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# Modelling the source and mechanism of radon entry into the building

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**Abstract.** The problem of ensuring the radon safety of construction is currently far from being solved, which is explained by the lack of a unified opinion on the dominant mechanism of radon transport from the soil into indoor area. The modelling of the contributions of diffusion and convective radon fluxes into the buildings performed in the paper shows that convection starts playing a role at sufficiently high floor structure permeabilities (about  $10^{-12}$  m<sup>2</sup>). Modern construction technologies make it possible to provide lower permeabilities of the underground walling, excluding convective radon entry into the buildings. Based on the diffusion model of radon entry, the paper proposes a method for ensuring radon safety of buildings at the design stage.

## 1. Introduction

A sharp increase in the urban population in the second half of the twentieth century has led to the fact that about 3/4 of Russia and other industrialized countries population live in urbanized areas currently [1]. Modern cities have become places where basic human needs are met, practically all scientific and cultural society potential is concentrated in cities, and the urban way of life has become the dominant behaviour model in society [2,3].

However, the cities development at the expense of the biosphere and outside the biosphere compatibility principles has made them concentrators of large-scale environmental problems. At the same time, along with direct damage to the biosphere, a fundamentally new group of technogenically altered natural factors has emerged. Their negative impact on humans is manifested exclusively within urbanized areas. One of the most dangerous factors in this group is the human radiation exposure in buildings. The limitation of indoor radiation dose is currently an urgent scientific and practical problem of the environmental safety system of construction [4,5].

The radiation population exposure is a knowledge area that is highly susceptible to myths and misconceptions. Most people are sure that radiation poses a threat to their life and health only in case of accidents at nuclear power plants. This is easily explained by the consequences of accidents at the «Mayak» plant and the Chernobyl nuclear power plant, which still remind of themselves in the form of the East-Ural radioactive trace and unsuitable zones for life on the territory of Russia, Ukraine, and Belarus.

However, the real structure of population exposure in the world is currently different: artificial radiation sources do not make a significant contribution to the annual dose outside the previously



contaminated areas. In all Russian regions, radon and its short-lived progeny exposure in houses is the main dose-forming factor (Fig. 1). In the overwhelming majority of Russian Federation subjects, the radon exposure contribution to the annual individual dose exceeds 50%, and in radon-hazardous territories (Altai and Caucasian Mineral Waters region) it can reach 85%.

Radon is generated in the soil from radium, transfers to the daily surface, and enters the atmosphere, where it disperses to the negligible concentrations. But if the movement to the daily surface is impeded by the buildings underground walling, under certain conditions radon can penetrate through them and accumulate in indoor air in dangerous quantities. As a result, most of the individual annual radiation dose is formed in buildings.

Radon and its progeny affect the human respiratory system. S. Darby's studies have shown that indoor radon is responsible for 2,000 lung cancer deaths per year in the UK [6], another 150-200 radon deaths occur annually in Ireland [7]. In Germany, where uranium-rich polymetallic mines are located, about 3,400 lung cancer cases are currently associated with indoor exposure [8]. Even in the Netherlands, where high indoor radon concentrations are rare enough, about 400 deaths from lung cancer per year are caused by its action [9]. In Russia, such an assessment is difficult due to the enormous territory size and different population exposure conditions in the regions, the number of additional lung cancer cases from radon in Moscow is estimated as 242 cases per year [10].

Significant negative effect from radon exposure led to the introduction of its maximum permissible concentrations in indoor air by international and national organizations (Table 1).

**Table 1.** Radon control levels.

Organization or country	Recommended maximum radon concentration in indoor air, Bq·m <sup>-3</sup> <sup>a</sup>	
	existing buildings	projected buildings
United Kingdom	200	50
Finland	400	100
Germany		200
Croatia		68
USA		150
International Commission on Radiological Protection	400	200
World Health Organization		100

<sup>a</sup> Since the threat to health is created by extremely small mass radon concentrations in indoor air (about 10<sup>-17</sup>% of the air mass), then to estimate its content the activity is used, which is proportional to the mass and measured in Becquerels per cubic meter.

The process of radon accumulation in buildings is multifactorial, its nature is influenced by the geophysical characteristics of the soil under the building, the features of the design and operation of buildings, etc. Therefore, different countries have established their own maximum permissible values of radon concentration in indoor air. In the United States, the National Action Level is 4 pCi/l (150 Bq/m<sup>3</sup>). In Russia, there is a two-level National Standard: 500 Bq/m<sup>3</sup> for existing buildings and 250 Bq/m<sup>3</sup> for buildings under construction [11]. The World Health Organization proposed a radon reference level in dwellings of 100 Bq/m<sup>3</sup> [12]. Compliance with the specified radon levels is possible exclusively through construction technologies.

## 2. Methods

High radon levels in indoor air are possible only with the simultaneous presence of a radon source in the building vicinity, paths and driving forces of its transport to underground walling, as well as paths of entry directly into the building. The soil under the building is the only radon entry source capable of exceeding the established reference levels. The contribution of radon exhalation from building walling

materials (the second most powerful entry source) rarely exceeds 10% of the total radon activity in the indoor air. As a result, increased radon exposure most often occurs in the lower floor rooms, which is in direct contact with the soil base.

Understanding the dominant radon transport mechanism from the soil into a building is of paramount importance for developing an effective approach to creating a radiation-safe construction. The radon entry from the soil is possible by diffusion and advection, while each of the mechanisms can be dominant and requires its own set of protective measures.

Advective radon flux is controlled by a temperature-induced pressure gradient at the outer foundation boundaries, which value does not exceed 2 Pa/m [13]. The advective flux density is determined from Darcy's law:

$$q_{ad} = \frac{k}{\mu} \cdot \frac{\partial P}{\partial z} \cdot A, \quad (1)$$

where  $k$  is the soil permeability,  $m^2$ ;  $\mu = 1,8 \cdot 10^{-5}$  Pa·s is the dynamic viscosity of soil gas;  $P$  – pressure, Pa;  $A$  is the radon concentration in soil gas,  $Bq \cdot m^{-3}$ .

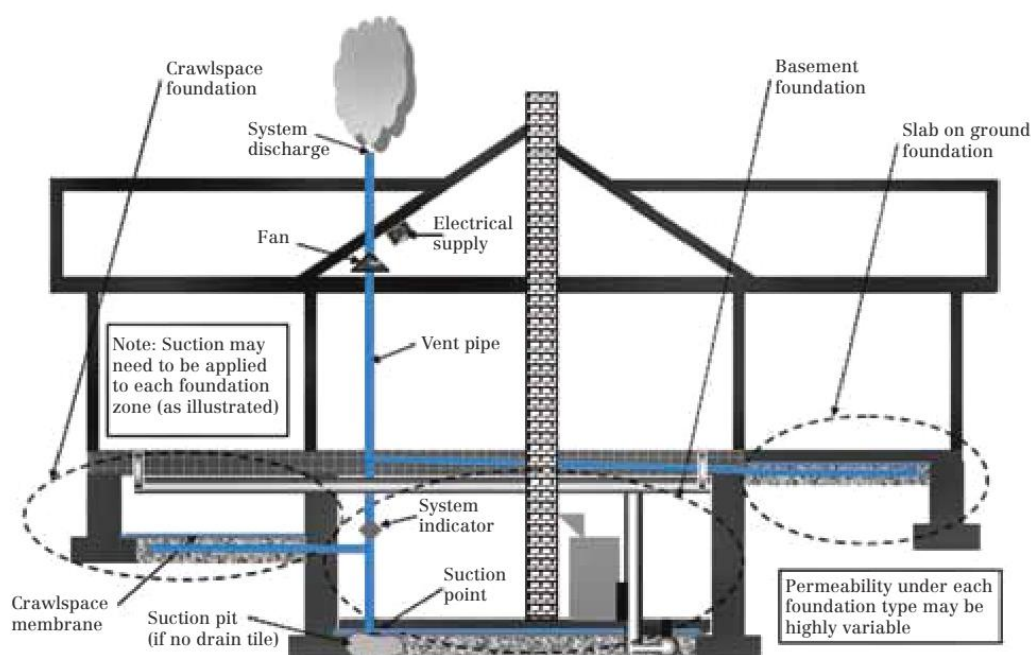
The advective radon flux density can vary over a very wide range; this is due to the large variations range in the permeability of soils and building materials – from  $10^{-9}$   $m^2$  for coarse sand to  $10^{-14}$   $m^2$  for uniform silt and  $10^{-16}$   $m^2$  for concrete.

Diffusive radon flux through underground walling remains practically constant. It does not depend on the pressure drop and air permeability of the transport medium, but is caused by the radon activities difference in the soil gas and indoor air. The diffusion flow density is determined by Fick's law:

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

where  $D_e$  is the effective radon diffusion coefficient,  $m^2 \cdot s^{-1}$ .

Advective transport ensures the flow of large radon volumes into buildings, but its implementation requires leaks in the underground shell, while diffusion occurs with any floor structure.



**Figure 1.** System of active soil depressurization [14].

For 30 years, intensive research has been carried out in the United States to establish the dominant mechanism for the radon entry into buildings. According to their results, the US EPA has stated that the radon flux into the premises has an advective nature and the radon safety of the building can be guaranteed only if the technology of active soil depressurization is used (Fig. 1).

Active radon protection technologies are effective in combating advective radon entry; however, the fact of the advective transport dominance is not generally accepted even among American scientists [16,17]. In addition, ASD-systems are expensive and energy-intensive, their elements are a source of constant noise and vibration and installation requires changes in the building structure. Therefore, the widespread use of active radon protection technologies can hardly be justified, and the search for more resource-efficient ways to ensure the buildings radon safety is urgent.

### 3. Results

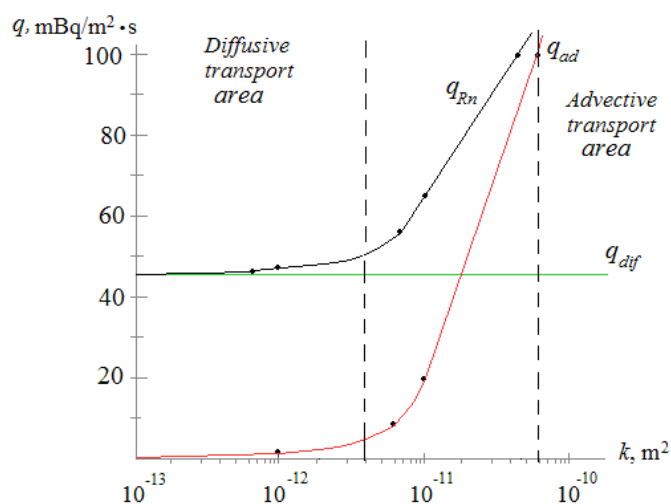
About 30 years, research on the radon problem in Russia has been conducted at the Research Institute of Building Physics and the Institute of Industrial Ecology of the Ural Branch of the Russian Academy of Sciences. Their result can be considered as the substantiation of the possibility of ensuring the buildings radiation safety with passive protective technologies by the buildings underground walling.

When developing a strategy for ensuring the safety of radon in buildings, it is of practical interest to assess the contributions of diffusion and advection to the transfer of radon from the soil to the building. Figure 2 shows results of modelling the ratio of the diffusive and advective radon fluxes densities depending on the air permeability of the transport medium. The radon diffusion coefficient was taken to be  $D_e = 1.0 \cdot 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$ , and the calculation of the advective flux density was carried out for the pressure gradient value  $\partial P / \partial z = 1.0 \text{ Pa} \cdot \text{m}^{-1}$ . The radon concentration in soil air  $A_{max}$  was calculated by the formula:

$$A_{max} = C_{Ra} \cdot \rho_g \cdot k_e \cdot \frac{1 - \varepsilon}{\varepsilon}, \quad (3)$$

where  $C_{Ra}$  is the specific radium activity in the soil,  $\text{Bq} \cdot \text{kg}^{-1}$ ;  $\rho_g = 2,700 \text{ kg} \cdot \text{m}^{-3}$  is the density soil grains;  $k_e$  is the coefficient of radon emanation;  $\varepsilon = 0.2 \dots 0.5$  is the porosity.

For the world average value of the specific radium activity in the soil  $C_{Ra} = 30 \text{ Bq} \cdot \text{kg}^{-1}$ , with coefficient of radon emanation  $k_e = 0.3$  and porosity  $\varepsilon = 0.4$  the radon concentration in soil air equaled  $A_{max} = 36,500 \text{ Bq} \cdot \text{m}^{-3}$ .



**Figure 2.** Dependence of the radon flux density from soil into the building on the floor construction permeability:  $q_{dif}$  – diffusive flux density;  $q_{ad}$  – advective flux density;  $q_{Rn}$  – total radon flux density.

As shown in Figure 2, the advective flow starts playing a significant role in radon entry into the building at base permeabilities  $(3...5) \cdot 10^{-12} \text{ m}^2$  and becomes dominant at permeabilities  $(3...5) \cdot 10^{-11} \text{ m}^2$ . Therefore, the main requirement for ensuring the radon safety of the lower floor premises is the absence of advective radon transport from the soil. This requirement is met when the air permeability of the floor structure is less than  $10^{-12} \text{ m}^2$ . Providing such permeability is not difficult, not only building materials, but also a number of clayey soils have a lower permeability (Table 2).

**Table 2.** Air permeability of some soil types [18].

Soil type	Air permeability, $\text{m}^2$
Clean fine sand	$10^{-12}$
Silty sand	$10^{-13}$
Homogeneous sludge	$10^{-14}$
Sandy clay	$10^{-15}$
Concrete	$10^{-14} \dots 10^{-16}$
Polymer insulating materials	below $10^{-16}$

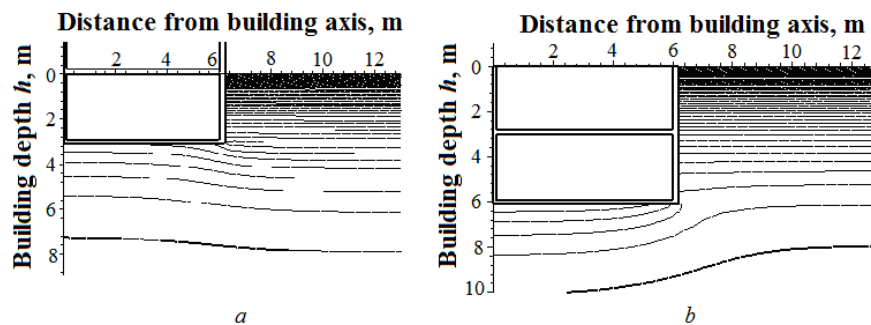
Thus, with a sealed building underground shell on clay soil, a diffusion model of radon transport in the medium system “soil-walling-indoor air” is presented. To describe the radon situation in this system the differential equations system of two-dimensional stationary diffusion radon transport can be used [19,20]:

$$D_i \cdot \left( \frac{\partial^2 A_i}{\partial x^2} + \frac{\partial^2 A_i}{\partial y^2} \right) - \lambda \cdot A_i(x, y) + W_i = 0, \quad (4)$$

where  $D_i$ ,  $A_i$ , and  $W_i$  are the diffusion coefficients, radon concentrations and radon generation rate in air, walling material and soil, respectively.

The boundary conditions represent the equality of fluxes at the boundaries of the corresponding areas, the conditions for gas exchange, and the absence of radon fluxes at the outer areas boundaries. The solution of the equations system (4) with the corresponding boundary conditions makes it possible to obtain the distribution of radon concentration in the soil under the building. Figure 3 shows the isolines of the radon concentration in the soil at the diffusion coefficient  $D_{soil} = 5 \cdot 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$  for building depths of 3 and 6 m, respectively. The lower line represents the soil radon potential of  $45\,000 \text{ Bq} \cdot \text{m}^{-3}$ , the remaining lines decrease towards the daily surface with a step of  $1\,000 \text{ Bq} \cdot \text{m}^{-3}$ .

As seen from Figure 3, the building significantly changes the natural radon distribution in the soil. Since the building prevents the radon discharge into the atmosphere, the radon concentration at the outer foundation boundary is less than the maximum radon activity in the soil (soil radon potential) by only 15–20%.



**Figure 3.** Radon concentration isolines: *a* – at the building depth 3 m; *b* – at the building depth 6 m.

The similar character of the radon concentration distribution in the soil under the building allows us to take the soil radon potential as the radon load on the underground walling of the building:

$$P_{Rn} = C_{Ra} \cdot \rho_s \cdot k_{em}, \quad (5)$$

where  $\rho_s$  is the soil density,  $\text{kg}\cdot\text{m}^{-3}$ ;  $k_{em}$  is the radon emanation coefficient.

The values in Eq. (5) are easily determined when analysing the soil from the building site. Overestimation of the real radon load by 15-20% forms a safety factor for the presence of microdefects in underground walling.

Then, under conditions of diffusive radon entry into a building to ensure its radon safety at the design stage it is necessary:

1) to set the acceptable radon concentration in the indoor air  $A_a$  after the building is put into operation and calculate the maximum permissible value of the radon flux density into the building:

$$q_{Rn} = \frac{A_a \cdot (\lambda + n) \cdot h}{F}, \quad (6)$$

where  $\lambda$  is the radon decay constant,  $\text{s}^{-1}$ ;  $n$  is the air exchange rate,  $\text{s}^{-1}$ ;  $h$  is the room height, m;  $F = 0.4-0.5$  is the equilibrium factor.

2) to determine the minimum sufficient radon resistance of the floor structure according to the formula:

$$R_{min} = \frac{P_{Rn}}{q_{Rn}}. \quad (7)$$

3) to make a transition from the calculated value of radon resistance to the base plate thickness:

$$R_{min} = \frac{1}{\sqrt{\lambda \cdot D}} \cdot sh \left( H \cdot \sqrt{\frac{\lambda}{D}} \right) \rightarrow H_{min} = \sqrt{\frac{D}{\lambda}} \cdot \text{arcsh} \left( R_{min} \cdot \sqrt{\lambda \cdot D} \right). \quad (8)$$

4) to introduce the second layer with a higher radon resistance into the floor structure, if the required thickness of the base slab significantly exceeds the dimensions required to ensure the main bearing functions. Most often it is a hydro-gas insulating polymer material with a thickness of 2-3 mm.

#### 4. Conclusion

The studies carried out allow us to note the lack of a generally accepted approach to the protection of buildings from radon, which indicates the need for further study of the patterns of soil gas entry into buildings. However, the limited conditions for advective radon transport into buildings indicate the possibility of providing a favourable radon environment in buildings using passive technologies exclusively.

Under the conditions of the buildings underground shell tightness, the radon soil transport through underground walling can be described by a stationary diffusion model. The technique developed on its basis makes it possible to ensure the required radon levels in buildings at the design stage without measuring the radon flux density from the surface of the building site, which should be excluded from the radon hazard criteria of a building site in Russia.

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