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Comparison of Approaches to Ensuring the Radon Safety of Designed Buildings in Russia and USA

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Abstract. Indoor radon and its progeny exposure poses a significant threat to the population collective health of most countries in the world. Modern construction technologies make it possible to regulate the radon entry from the soil within a wide range, but at present there is no universal approach to ensuring the radon safety of buildings. This situation is partly explained by the multifactorial nature of the process of the radon situation formation in the lower floor premises, which does not allow to unambiguously establishing the dominant mechanism of radon entry. The article discusses technologies for ensuring the radon safety of buildings in Russia and the United States, shows their fundamental differences, advantages and disadvantages.

1. Introduction

For several centuries urbanization processes have been an invariable attribute of the society development, as a result the artificially created urban environment has become the main sphere of human life. Currently, more than 3/4 of the Russian Federation and industrialized foreign countries population live in cities and settlements [1].

Modern cities are the centers of the economic, political and social life of each state separately and of all mankind as a whole, practically all the scientific and cultural society potential is concentrated in them [2]. The city, in the current view, is a place for meeting the most significant human needs: biological, social, spiritual, etc. [3].

However, along with human-developing functions, modern cities are centers for the emergence of large-scale environmental problems as well. The constantly growing load on the Biosphere within the urbanized territories has led to the emergence of a fundamentally new group of technogenically altered natural factors that negatively affect humans, exclusively in the objects of the technosphere. The most significant of these factors for the damage to the collective health of the population is indoor exposure to radon and its progeny [4-5].

Radon is a noble radioactive gas which is generated in the geological environment from parent radium. Standing out from the soil into the atmosphere, radon instantly disperses to negligible concentrations that are not capable of causing harm to human health. But the main natural isotope ^{222}Rn has a half-life of 3.8 days, which allows it to enter buildings from the outside and accumulate in the air of the lower floor premises in dangerous quantities. Thus, increased radon exposure is possible only in buildings where a modern person spends about 80% of the time.

Radon and its progeny negatively affect the human respiratory organs, indoor radon exposure is recognized as the second most severe factor after smoking, leading to lung cancer, and radon itself is attributed to the carcinogens of the first most dangerous group for humans [6]. The Environmental Protection Agency (US EPA) estimates that about 21,000 lung cancer deaths in the United States each year can be caused by radon and its decay products in indoor air [7].

A real threat to human health is created by extremely small mass radon concentrations in indoor air ($\sim 10^{-17}\%$ of the air mass), therefore activity is used to assess its content, which is proportional to the mass. In European countries and the USA radon concentration (C_{Rn}) is used, in Russia and the post-Soviet countries – the equivalent equilibrium radon concentration (*EERC*) of radon progeny. Both quantities are measured in Becquerels per cubic meter (Bq/m^3) and are related by the ratio

$$EERC = F \cdot C_{Rn}, \tag{1}$$

where F·is the equilibrium factor.

There is no unambiguous transition for the values of C_{Rn} and *EERC*, since the F-factor depends on the conditions of air exchange in a particular room and can be in the range $0 < F < 1$. If the value of F is unknown, then, according to the recommendations of international organizations, in calculations its value should be taken equal to 0.4–0.5 [8].

The problem of ensuring the buildings and structures radiation safety is to ensure, through construction technologies, the radon content in the indoor air, which will not exceed national reference levels (action levels). The national level value depends on a number of factors, such as the radon hazard of the territory, the structure of the housing stock, the country level of socio-economic development, etc. In the USA, the maximum permissible radon concentration in indoor air is 150 Bq/m^3 [9], in Russia there is a two-level standard, according to which the value of the radon *EERC* should not exceed 200 Bq/m^3 for existing buildings and 100 Bq/m^3 for designing construction (approximately 400 and 200 Bq/m^3 in C_{Rn} units) [10], the World Health Organization (WHO) recommends striving to ensure the radon reference level in the premises $C_{Rn} = 100$ Bq/m^3 [11].

The study of the radon problem in the world has been going on for more than 50 years, but there is still no single approach to ensuring the radon safety of buildings. This is partly due to the multifactorial nature of the process of radon transport from the soil to the indoor air; its character is influenced by the geophysical characteristics of the soil under the building, the design and operation of the building, etc. [12-13]. In this regard, it is of interest to analyze the approaches to the design of radon-safe buildings in Russia and the United States – countries that occupy leading places in the world in terms of the scale of radon research.

2. Methods

The main point in effectively limiting the radon entry into buildings is understanding its transport mechanism in the soil and materials of underground walling. As you know, radon in porous media can be transported by means of two different mechanisms – convection and diffusion [14-15].

Convective transport occurs due to external forces, it is caused by a temperature-induced pressure gradient at the outer boundaries of the underground building shell. The density of the soil gas convective flux is determined from Darcy's law

$$q_{con} = \frac{k}{\mu} \cdot \frac{\partial P}{\partial z} \cdot C_{Rn}, \tag{2}$$

where k is the medium permeability, m^2; μ is the dynamic viscosity of soil gas, Pa·s; P is the air pressure, Pa.

The density of the convective radon flux can vary over a very wide range, which is caused by a huge range of possible values of the porous media permeability (from 10^{-9} to 10^{-16} m^2 and below).

The *diffusive radon transport* from the soil into the building proceeds due to a change in the internal substance energy and is caused by the radon concentrations difference in the soil gas and the indoor air. The diffusion flux density is determined from Fick's law

$$q_{dif} = D_{ef} \cdot \frac{\partial C_{Rn}}{\partial z}, \tag{3}$$

where D_{ef} is the effective diffusion coefficient of radon in the medium layer, m^2/s.

The range of changes in the radon diffusion coefficient in soils and building materials is significantly less than that of soil permeability (no more than two orders of magnitude).

Each of the mechanisms for the radon entry into buildings requires its own set of radon protection measures. So, sealing the underground building shell is an effective means of limiting the convective radon transport, but practically does not affect the diffusion intensity. It is the peculiarities of understanding the dominant mechanism of radon transport in porous media that explain the current difference in approaches to ensuring the radon safety of buildings in Russia and the United States.

In the USA the basic principle of building radon safety is to eliminate the potential hazard of increased indoor exposure in order to avoid the actual hazard. For 30 years intensive research has been conducted in the United States to establish the dominant radon transport mechanism into buildings, funded by the US EPA and the Department of Energy. Based on their results, the US EPA was proposed to recognize the dominant convective radon entry into rooms through cracks in the foundation slabs. This statement was enshrined in law along with the provision that the radon safety of a building can be fully guaranteed only in the case of using active radon protection technologies [16].

At present, the radon safety of American buildings is ensured through the use of active soil depressurization (ASD) technology – a system of measures to limit the intake of radon by creating a fan zone of low pressure in the soil under a slab or membrane, which provides favorable conditions for the radon accumulation and its subsequent removal by mechanical ventilation means (figure 1) [16].

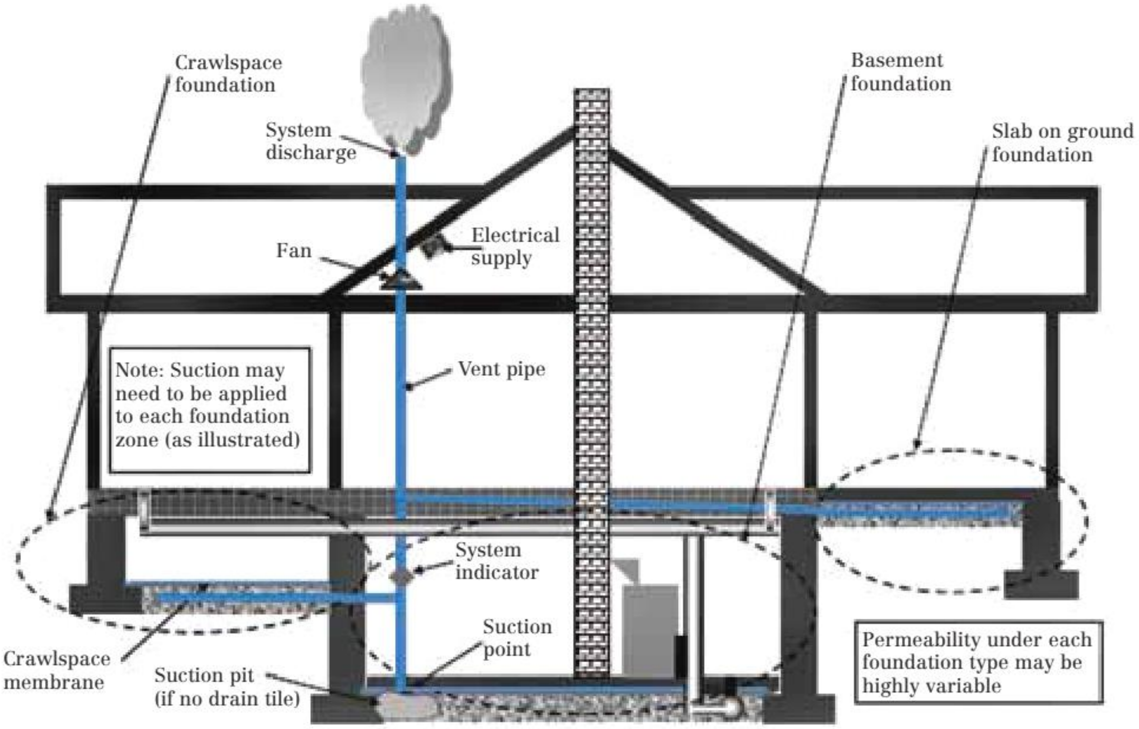


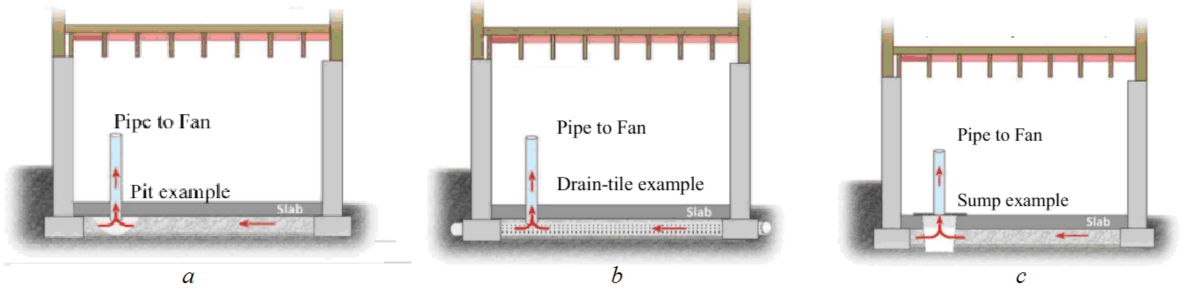
Figure 1. System of active soil depressurization [11].

Sub-slab depressurization is used for floor structures with a monolithic base slab (slab-on-grade, supported slab, slab above crawlspace) – a method of radon entry reducing by maintaining a lower air pressure under the base slab than above it. This method has the following constructive variations:

1. *Suction pit* is a cavity with a volume of at least 7 dm^3 (7 liters) which is created under the base slab at the point of suction pipe entry (figure 2, *a*). For more effective radon removal, the layer under the slab must have high permeability (about $10^{-9}…10^{-10}$ m^2), to ensure these conditions a gravel layer 10...15 cm thick is most suitable. To avoid radon entering the residential area, leaks at the entry point the suction pipes are sealed with epoxy resin or polymer mastic.

2. *Drain-tile* –in this case the suction pipe directly draws soil air from the drainage layer formed by a material with high permeability (figure 2, *b*). It is customary to use coarse gravel or geotextiles as drainage material.

3. *Sump* is the cavity with soil air not directly connected to the suction pipe, the inlet of which is sealed with a cover made of flexible elastic material (figure 2, *c*). The disadvantage of this scheme is the noise from the ASD system and the soil air leakage into the living quarters.



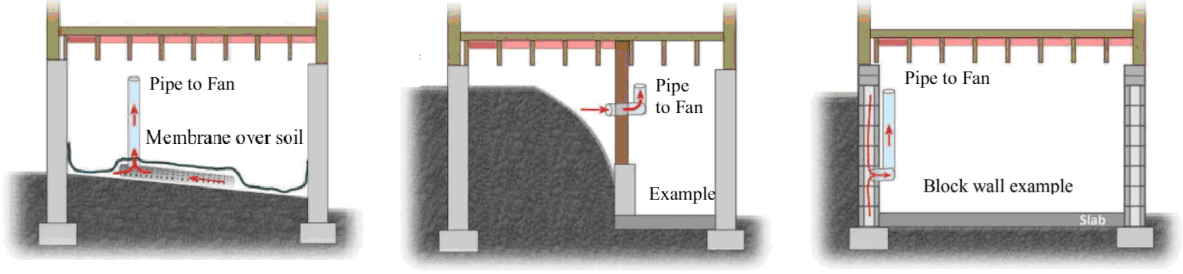
a *b* *c*

Figure 2. Methods of depressurization under the base slab: *a* – suction pit; *b* – drain-tile; *c* – sump.

When using a polymer sheet (membrane) in the floor structure, placed on the building foundation, the method of reducing the radon entry from the soil is called *sub-membrane depressurization*. The principle of operation of this method is completely similar to the previous one (figure 3, *a*).

Non-habitable air depressurization is used if there is a crawlspace in the building structure – an open area under the living zone formed by a concrete base slab and soil (figure 3, *b*). The crawlspace most often has a height of 10 cm to 1 m, it can be ventilated with outside air or be sealed. This method is not used to reduce the radon entry into buildings if the radon is not isolated from the outside air.

Block wall depressurization is used in the presence of air cavities in them, and the location of the suction pipe in this case is determined by the placement of these voids in the walls and the possibility of their sealing (figure 3, *c*). When using this method, voids in the walls must be reliably isolated from the room air entry, only the side adjacent to the soil mass remains open.



a *b* *c*

Figure 3. Methods of depressurization: *a* – sub-membrane; *b* – non-habitable air; *c* – block wall.

The above-described active radon protection technologies are effective in combating the intense convective radon entry, but the fact of the convective transport dominance is not generally recognized even among American scientists [17-18]. In addition, ASD-systems are expensive and energy consuming, their elements are the constant noise and vibration source and installation requires changes in the building structure. Therefore, the widespread use of active radon protection technologies can hardly be considered as justified.

3. Results

In Russia, the study of the patterns of radon entry into buildings has been carried out for more than 30 years in the laboratory of radiation safety in the construction of the Russian Academy of Architecture and Building Science Research Institute of Building Physics, a significant contribution to the understanding of the peculiarities of the radon environment formation in the building was made by scientists from the Institute of Industrial Ecology of the Ural Branch of the Russian Academy of Sciences, researchers from a number of academic institutes and lecturers of higher education institutions. At the moment, there is no doubt that the dominant mechanism of radon transport is determined by the current state of the media system "soil-building-atmosphere". Therefore, it is of practical interest to compare the contributions of diffusion and convection to the radon transport from the soil in indoor air of the ground floor rooms.

Figure 4 shows the result of calculating the densities of the diffusion and convective components of the radon flux depending on the permeability of the transport medium. The calculations used the conservative values of the effective diffusion coefficient (D_{ef} = 1.0·10^{-6} m^2/s) and pressure gradient ($\partial P/\partial z$ = 1.0 Pa/m). The maximum radon concentration in the soil air was taken to be $C_{Rn\ max}$ = 36,500 Bq/m^3, which corresponds to the world average value of the radium specific activity in the soil C_{Ra} = 30 Bq/kg with radon emanation coefficient k_{em} = 0.3 and medium porosity ε = 0.4.

As seen from figure 4, the convective flux begins to play a significant role in the radon entry into a buildings at their underground shell permeabilities of (3…5)·10^{-12} m^2, and at permeabilities from 3·10^{-11} to 5·10^{-11} m^2 it becomes dominant.

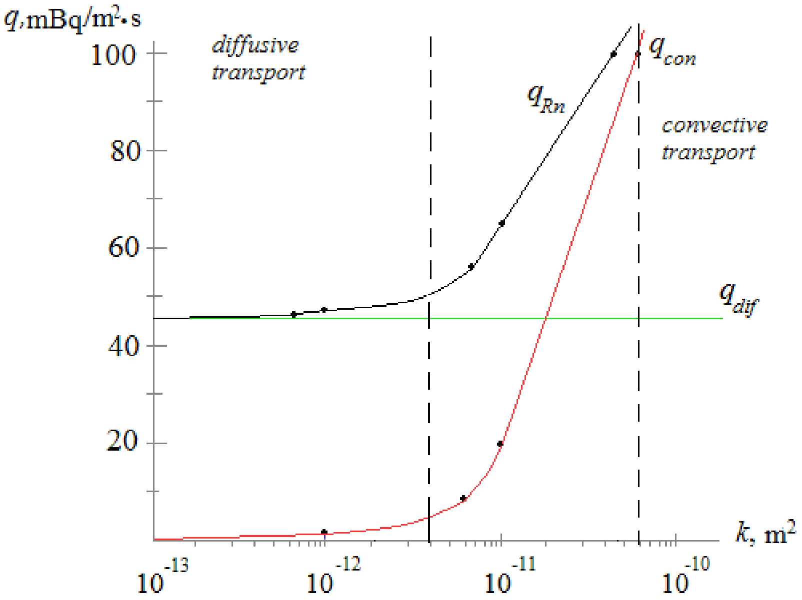


Figure 4. Dependence of the radon flux density from the soil into the building on the floor structure permeability: q_{dif} is the diffusion flux density; q_{con} is the convective flux density; q_{Rn} is the total radon flux density.

Thus, a prerequisite for ensuring the radon safety of the lower floor premises is the absence of convective radon entry from the soil, which occurs when the floor structure permeability no more than 10^{-12} m^2. It should be noted that the achievement of such permeability does not present any difficulties (table 1).

As you can see from the table 1, convective entry can be virtually nullified by using a traditional foundation structure with a concrete base slab and sealing joints and joints in the underground building envelope. Then, in conditions of purely diffusive radon transport the radiation safety of the living environment can be ensured by using exclusively passive protective technologies.

Table 1. Permeability of soils and building materials [19].

Type of soil or building material	**Permeability** ***k*, m^2**
Well-graded gravel	10^{-8}
Uniform coarse sand	10^{-9}
Uniform medium sand	10^{-10}
Clean well-graded sand and gravel	10^{-11}
Uniform fine sand	10^{-12}
Silty sand	10^{-13}
Uniform silt	10^{-14}
Concrete slab	$10^{-15}…10^{-16}$
Polymer film materials (membranes)	lower 10^{-16}

To do this at the design stage, you must consistently perform the following steps:

1. Set the acceptable radon concentration *EERC* in indoor air after the building is put into operation and determine from it the maximum permissible value of the radon flux density through horizontal underground walling using the formula

$$q_{Rn} = \frac{EERC \cdot (\lambda + n) \cdot h}{F}, \tag{4}$$

where $\lambda = 2{,}1 \cdot 10^{-6}$ s^{-1} is the radon decay constant; n is the air exchange rate in room, s^{-1}; h is the room height, m.

2. Using the gamma-spectrometric method of soil analysis from the place of laying the foundation, determine the specific radium activity C_{Ra} in it and the radon emanation coefficient k_{em}, and then calculate the maximum possible radon load on the building underground shell using the formula

$$C_{Rn\max} = C_{Ra} \cdot \rho_g \cdot k_{em} \cdot \frac{1-\varepsilon}{\varepsilon}, \tag{5}$$

where $\rho_g \approx 2\ 700$ kg/m^3 is the density of soil solid phase (grains); ε is the porosity.

3. Calculate the minimum sufficient radon resistance of the floor structure using the formula

$$R_{min} = \frac{C_{Rn\max}}{q_{dif}}. \tag{6}$$

4. Check the possibility of providing this radon resistance with one concrete layer (base slab). The radon resistance of a homogeneous material layer is determined by the formula [20]

$$R = \frac{1}{\sqrt{\lambda \cdot D}} \cdot sh\left(H \cdot \sqrt{\frac{\lambda}{D}}\right) \to H_{\min} = \sqrt{\frac{D}{\lambda}} \cdot arcsh\left(R_{\min} \cdot \sqrt{\lambda \cdot D}\right). \tag{7}$$

5. If the required thickness of the base slab significantly exceeds the dimensions required to ensure the main bearing functions, then a second layer with a higher radon resistance should be introduced into the floor structure, which is most often a hydro-gas insulating polymer material 2...3 mm thick with a radon diffusion coefficient of 1 10^{-11} m^2/s. For a two-layer structure, the total radon resistance is expressed by the formula [9]

$$R_{\Sigma} \approx R_1 + R_2 = \sum_{i=1}^{2} \frac{1}{\sqrt{\lambda \cdot D_i}} \cdot sh\left(H_i \cdot \sqrt{\frac{\lambda}{D_i}}\right), \tag{8}$$

where $i = 1, 2$ is the number of the protective layer in the floor structure.

4. Conclusions

The use of the proposed technique, developed at the Russian Academy of Architecture and Building Science Research Institute of Building Physics allows at the design stage to provide the required radon protection resource of buildings exclusively through the use of passive technologies that do not require energy supply and installation of additional equipment.

The studies carried out clearly show that the world has not developed a unified approach to ensuring the radon safety of buildings so far. In the United States, the use of active technologies for protection against radon is legislatively enshrined, while among Russian specialists in the field of building physics the point of view dominates that acceptable radon levels in buildings of most territories can be ensured through rational design of horizontal underground building walling that perform load-bearing functions. This difference in approaches indicates the need for further study of the radon transport patterns in porous media in order to build a universal and adequate model of its entry into buildings.

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