https://doi.org/10.1051/e3sconf/202345702041

Prediction of the Radon Situation in Buildings Constructed Under the Renovation Program

Valery Telichenko[1], *Vladimir* Rimshin[1, 2,*], *Alexander* Kalaydo[2, 3] and *Marya* Semenova[2]

[1]Moscow State University of Civil Engineering, 26, Yaroslavskoye shosse, Moscow, 129337, Russia
[2]Scientific Research Institute of Building Physics of Russian Academy of Architecture and Construction Sciences, 127238 Moscow, Russia

[3]Lugansk State Pedagogical University, 291011 Lugansk, Russia

Abstract. The paper is devoted to the study of the regularities of the radon situation formation in modern multi-storey buildings at the design stage. Calculation schemes for radon entry into the premises of the lower and upper floors are constructed, a method for determination of radon concentration in the building after its erection is proposed. It is based on a joint analysis of the soil base physical and mechanical characteristics of and the design features of the underground shell of the building. According to the calculations results, a significant role of air exchange in the formation of a favorable radon situation in the building was noted.

1 Introduction

Radioactive gas radon is one of the pollutants that are invariably present in indoor air of any design and service life constructions. Thus far, it has been established that radon and its progeny in buildings form more than half of the annual individual exposure dose of the Russian Federation population [1-2]. In open areas radon does not pose a threat to the population collective health in open areas since it cannot accumulate to dangerous concentrations there.

Radon is a colorless and odorless natural radionuclide which is generated in all radioactive families from radium. It has three natural isotopes: ^{222}Rn (radon Rn), ^{220}Rn (thoron Tn) and ^{219}Rn (actinon An) with half-lives $T_{1/2}$ of 3.82 days, 55.6 s and 3.9 s, respectively [3]. The first two isotopes pose a danger to the indoor air environment of buildings, and if thoron can be formed only in the materials of building walling, then radon-222 can also entry into the lower floor premises from the soil base. Obviously, the danger of these two isotopes is incommensurable and the main threat to humans is posed by the much longer-lived radon-222.

Although it is customary to talk about radon exposure to, its contribution to the internal human exposure dose does not exceed 2%, the remaining 98% form short-lived progeny: polonium-218, lead-214 and bismuth-214 for radon-222; lead-212 and bismuth-212 for radon-220. However, radon progeny, being heavy metals, is practically unable to migrate in the environment, while gaseous radon can entry into buildings from a depth of up to 10 m [4].

* Corresponding author: v.rimshin@niisf.ru

The radon levels in the air of the premises of the Russian Federation is characterized by the equivalent equilibrium radon concentration (EERC) of the progeny of its two main isotopes - radon-222 and radon-220 (thoron)

$$EERC = EERC_{Rn} + 4{,}6 \cdot EERC_{Tn},$$

where each of the terms on the right-hand side is expressed in terms of the most dangerous short-lived progeny's activities, namely

$$EERC_{Rn} = 0{,}10 \cdot EERC_{Po\text{-}218} + 0{,}52 \cdot EERC_{Pb\text{-}214} + 0{,}38 \cdot EERC_{Bi\text{-}214};$$

$$EERC_{Tn} = 0{,}91 \cdot EERC_{Pb\text{-}212} + 0{,}09 \cdot EERC_{Bi\text{-}212},$$

where the coefficients in front of the terms on the right side show the contribution of this daughter product to the total internal dose from radon or thoron.

The radon concentration in indoor air is directly proportional to the probability of lung cancer occurrence in the future, therefore, the sanitary legislation of the Russian Federation establishes EERC levels, which excess is unacceptable [5-6]. In particular, for buildings under construction EERC after commissioning should not exceed 100 $Bq \cdot m^{-3}$. At the same time, this level should not be taken as the maximum permissible concentration, below which a negative impact on health cannot be detected by modern medical equipment. Radon belongs to the carcinogens group, which does not have the maximum permissible concentration, and this control level is technologically and economically justified at this stage of construction industry development, but one should strive to reduce the EERC in indoor air as much as possible.

Indoor radon in is a controllable component of the radiation load on the population, since the intensity of its entry into a building can be regulated over a wide range by construction tools and technologies. Since the radon-protective resource of any structure is laid at the design stage, it is of some scientific and practical interest to predict the radon situation in a building designed with using modern technologies, as well as to assess the power of the main radon sources in the indoor air.

2 Methods and object of study

The methodology of this investigation included systemic and abstract-logical approaches. Of the experimental methods, modeling was used, and of the theoretical methods, idealization and formalization were used.

The object of the study was the project of a residential building, completed by AMC-PROJECT LLC, being built as part of the renovation program at the address: Moscow, Danilovskoye intr. form., Vostochnaya str., 1.

The object was a complex shape structure - a three-section residential building of variable storey's number (12, 18 and 19 floors) with built-in non-residential premises on the ground floor and a single-level underground parking lot. Overall dimensions of the underground part - 108.8 × 59.1 m, above-ground part - 95.9 × 22.5 m, maximum height - 64.4 m, planned inhabitants number - 695.

It is now generally recognized that in large cities the sources of radon entry into buildings and structures are the soil base and the emanation from the materials of the building walling. At the same time, it is considered that about 90% of radon entry in indoor air from the soil, up to 10% - by emanation from internal and external building walling, and another 1–2% with external air due to infiltration [7].

In the context of studying the soil radon entry dynamics, the structure underground part is important. It is represented as a one-story volume under a residential building, in which technical rooms and a parking lot are located. The underground parking of the facility is located on the same level under the courtyard area of the residential building and adjoins the residential building through the expansion joint, making up a single volume with it.

Thus, in order to assess the contributions of each of the radon entry and predict the radon situation in it after commissioning, it was decided, based on the design documentation, to perform a model study of radon concentration: in the territory of the parking lot, which is in direct contact with the soil foundation, and in a one-room apartment on the second floor, which separated from the ground base by the technical floor.

3 Results

At the initial stage of the radon situation modeling, design schemes for an underground parking lot and an apartment were built. For an underground car parking (Fig. 1, *a*) the horizontal radon transport from the soil is not considered, since the air permeability of the sandy soil with a loam layer located at the building base is 3-4 orders of magnitude higher than B35, W6, F75 concrete used in the vertical underground walling [20-22]. In such a situation, the horizontal radon transport is negligible and all soil radon at the side underground shell is freely discharged into the atmosphere.

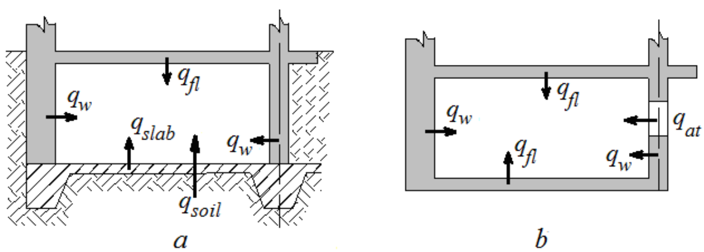

Fig. 1. Calculation schemes for radon entry: *a* – into the underground parking lot; *b* – in the second floor apartment.

The difference between the calculation scheme for an apartment (Fig. 1, b) is the absence of radon transport through a horizontal floor slab. The fact is that the radon levels in the premises of the first and second floors differ by units or tens of $Bq \cdot m^{-3}$, and not by 100–1,000 times, as in the case of ground air and underground parking air. Therefore, such a difference in concentrations is not enough to ensure any significant radon transport through a reinforced concrete slab 200 mm thick [17-19].

The constructed design schemes make it possible to proceed to determining the dependence of the EERC levels in the future building premises on the design features of this residential building and physical and mechanical characteristics of the underlying soil. It is advisable to build this dependence for an underground parking lot, and then obtain a similar dependence for an apartment from it, excluding the radon flux density from the soil q_{soil}. During the obtaining of the calculated dependence, the following assumptions were made:

– there is no radon entry with water and household gas, which is true in the metropolis conditions;

– the radon transport in the material of the underground horizontal building slab is carried out exclusively by diffusion, the convective component of the transport is zero. The substantiation of this assumption is presented in the works [8–9].

The whole process of modeling the radon situation in the designed building included three stages described below.

A. Calculation of geometric and radon protective walling characteristics

Geometrical characteristics of the investigated premises:

– volume $V = a \cdot b \cdot h$;

– internal wall area $S_{in.w} = 2h \cdot (a+b) - S_d$;

– external wall area $S_{ex.w} = 2h \cdot (a+b) - S_w$;

– floor and ceiling area $S_{fl} = S_{cel} = a \cdot b$,

where a, b and h are the length, width and height of the premise, m; S_w and S_d are the total windows and doors area, m^2.

The main radon-protective characteristic of the underground shell is the floor structure radon resistance, which, assuming the diffusion nature of radon transport in reinforced concrete, is determined by the formula

$$R = (\lambda \cdot D_{con})^{-1/2} \cdot sh\left[h_{sl} \cdot (\lambda / D_{con})^{1/2}\right],$$

where h_{sl} is the base slab thickness, m; λ = 2,1·10^{-6} s^{-1} – radon decay constant; D_{con} = 1,1·10^{-7} m^2·s^{-1} is the radon diffusion coefficient in reinforced concrete.

B. Calculation of radon flux densities into the premise

Radon flux density from soil through a horizontal underground walling [9; 11-16]

$$q_{soil} = C^{s}_{Ra} \cdot \rho_s \cdot k_{em} / R,$$

where C^{s}_{Ra} is the radon specific activity in soil, Bq·kg^{-1}; ρ_s = 2 600 kg·m^{-3} is the density of the soil solid phase (grains); k_{em} = 0,3 is the coefficient of radon emanation by soil.

Radon flux density from exterior wall material

$$q_w = C^{c}_{Ra} \cdot \rho_{con} \cdot k_{em} \cdot (\lambda \cdot D_{con})^{1/2} \cdot \tanh\left[0{,}5h_{fl} \cdot (\lambda / D_{con})^{1/2}\right],$$

where C^{c}_{Ra} = 15…30 Bq·kg^{-1} is the radium specific activity in reinforced concrete [10]; ρ_{con} = 2 500 kg·m^{-3} is the density of reinforced concrete; h_w is the wall thickness, m.

Radon flux density from the floor material

$$q_{fl} = C^{c}_{Ra} \cdot \rho_{con} \cdot k_{em} \cdot (\lambda \cdot D_{con})^{1/2} \cdot \tanh\left[0{,}5h_{fl} \cdot (\lambda / D_{con})^{1/2}\right],$$

where h_{fl} is the floor material thickness, m.

Radon flux density from the base slab

$$q_{slab} = C^{c}_{Ra} \cdot \rho_{con} \cdot k_{em} \cdot (\lambda \cdot D_{con})^{1/2} \cdot \tanh\left[0{,}5h_{sl} \cdot (\lambda / D_{con})^{1/2}\right],$$

where h_{sl} is the slab thickness, m.

C. Calculation of the predicted progeny EERC in the study premise

The predicted ERRC levels in an underground car parking was determined from the radon balance equation

$$EERC_{park} = \left(\frac{q_w \cdot (S_{in.w} + S_{ex.w}) + q_{fl} \cdot S_{fl} + (q_{soil} + q_{slab}) \cdot S_{fl}}{V \cdot (\lambda + n)} \right) \cdot F, \qquad (1)$$

where F = 0,4…0,5 is the equilibrium factor; n is the air exchange rate in the parking, s^{-1}.

Similarly, the predicted ERRC levels for an apartment

$$EERC_{ap} = \left(\frac{q_w \cdot (S_{in.w} + S_{ex.w}) + 2q_{fl} \cdot S_{fl}}{V \cdot (\lambda + n)} + \frac{EERC_{out} \cdot n}{\lambda + n} \right) \cdot F, \qquad (2)$$

where $EERC_{out}$ = 5 Bq·m^{-3} is the average EERC in outdoor air.

When calculating the radon situation in the underground parking lot (Fig. 2), its structural dimensions were used from the project documentation of a residential building developed by AMC-PROEKT LLC were used. Taking into account the complex shape of the car parking, to simplify the calculations, the dimensions of the parking were taken in plan: length a = 108,8 m; width b = 59,1 m; height h = 3,2 м; walls thickness h_{wall} = 0,25 m; total doors area S_d = 186,3 m^2; total windows area S_w = 0 м^2; base slab thickness h_{slab} = 0,60 m and floor thickness h_{floor} = 0,20 m.

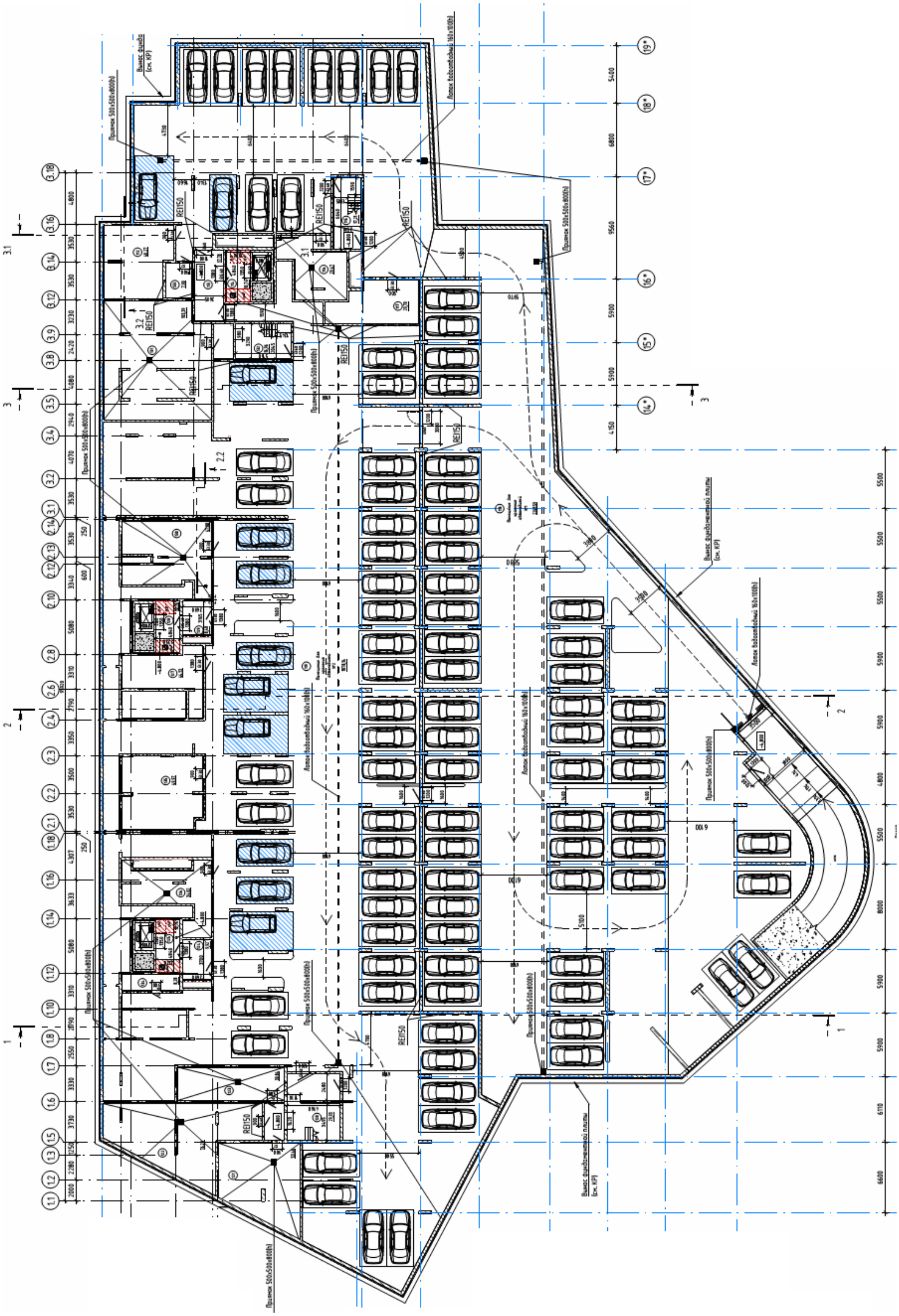

Fig. 2. Heated underground parking plan

The radium concentration in the building walling materials was assumed to be C_{Ra} = 20 Bq/kg; the calculation was performed in MS Excel spreadsheet editor. The dependence of the estimated radon EERC on the air exchange rate for an underground heated parking lot is presented in Table. 1.

Table 1. Results of a numerical study of the dependence of EERC in an underground car parking on the air exchange rate *n*

Air exchange rate n, h^{-1}	***0***	***0,05***	***0,1***	***0,15***	***0,2***	***0,25***
EERC in an underground car parking, Bq·m^{-3}	682	89	48	32	25	20

As can be seen from Table. 1, a favorable radon situation on parking territory will be provided already at low air exchange rates of 0.15 ... 0.2 h^{-1}, and an acceptable radon situation will be provided with a minimum air exchange rate 0,05…0,1 h^{-1}.

According to the project documentation, it is planned to use base slabs of three different thicknesses for this residential building: a 600 mm thick slab for a parking lot; 900 mm thick under section 1 and 1,200 mm thick under sections 2 and 3 of a residential building. The calculation presented above was carried out for the smallest thickness foundation slab, as a result, for the lower floors of sections 1-3, slightly lower EERC levels should be expected at the air exchange rates given in Table 1.

The last study stage was the assessment of the future radon situation in a one-room apartment on the second floor (Fig. 3). The ERRC was calculated only in the residential area, since in small areas (43.6 m^2) there is a uniform radon distribution.

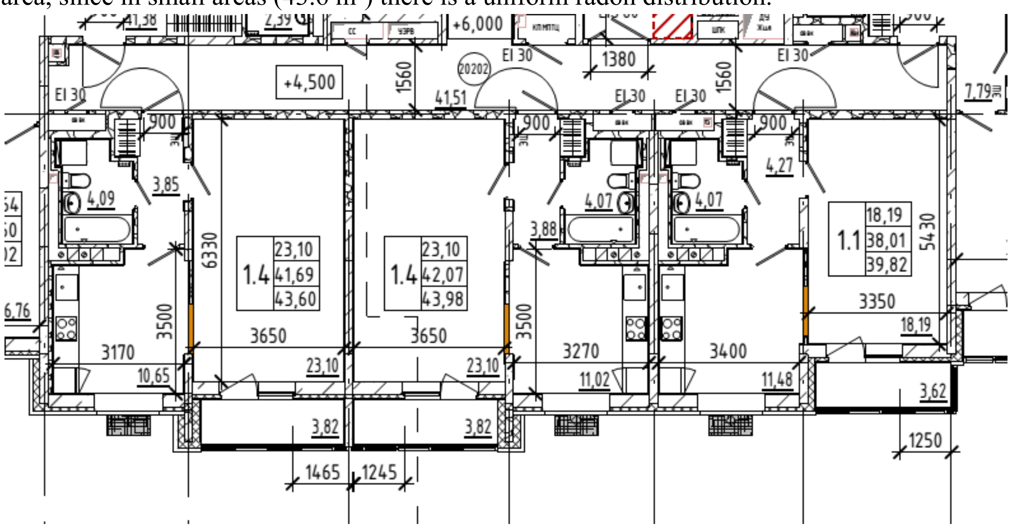

Fig. 3. Fragment of the 2nd floor plan with one-room apartments

Initial data for calculation according to fig. 3: length a = 6,33 m; width b = 3,65 m; height h = 3,0 m; walls thickness h_{wall} = 0,25 m; total doors area S_d = 3,2 m^2; total windows area $S_{ок}$ = 2,0 m^2; thickness of top and bottom floors $h_{пер}$ = 0,20 m.

The dependence of the estimated EERC on the air exchange rate in a one-room apartment on the second floor is presented in Table. 2.

Table 2. Results of a numerical study of the dependence of EERC in a one-room apartment on the second floor on the air exchange rate *n*

Air exchange rate n, h^{-1}	***0***	***0,05***	***0,1***	***0,15***	***0,2***	***0,25***	***0,4***
EERC in a one-room apartment, $Bq{\cdot}m^{-3}$	714	95	52	36	28	23	15

As can be seen from Table 2, while ensuring the normatively fixed air exchange rate for this type of premises ($n \geq 0.4$ h^{-1}), the EERC in the apartments will be close in value to its activity in the outside air.

4 Discussion

The model experiment results showed that the radon situation in the building is determined by two processes - the soil radon transport through horizontal underground building slab and its emanation from the walling materials. At the same time, it is impossible to state in advance which of the two above-mentioned processes has the main influence on the formation of radon levels in indoor air.

In this case, for a building on soils with background radium content with a thick foundation the radon flux density (RFD) from the soil into the air of the underground car parking was 1,4 $mBq{\cdot}m^{-2}{\cdot}s^{-1}$, while the RFD from the walls was 3,6 $mBq{\cdot}m^{-2}{\cdot}s^{-1}$, from the floor plate was 3,0 $mBq{\cdot}m^{-2}{\cdot}s^{-1}$, from the base slab was 3,7 $mBq{\cdot}m^{-2}{\cdot}s^{-1}$. Thus, after the construction of this building, it can be expected that no more than 12% of radon will enter the air of the underground parking from the soil.

Also, the key role of air exchange in the radon situation formation in the building is obvious. Even with the minimum air exchange rate $n = 0.05$ h^{-1}, EERC decreases by almost 8 times compared to a “closed” premise.

5 Conclusions

1. Radon and its progeny are invariably present in buildings and their concentration reducing to acceptable levels is possible only by construction methods and means.

2. The main radon sources in the air of the lower floor premises are the soil under the building and emanation from the walling materials and each of these processes can be dominant. On the upper floors, all radon comes exclusively from building walling.

3. A monolithic reinforced concrete foundation of great thickness (600 mm or more) is the most effective means of protecting the indoor air from soil radon. Further radon levels reduction in rooms with a long stay of people is possible due to rationally organized air exchange.

4. The performed modeling study confirmed the prospects of using passive radon protection technologies, in which the radon barrier is the elements of the building underground shell which perform the main bearing functions.

5. The proposed calculation method can be used at the design stage of buildings to determine the structural dimensions of the foundation elements according to a predetermined EERC levels in the building under construction.

References

1. T. A. Kormanovskaya, R. R. Akhmatdinov, G. A. Gorsky Results of 20 years of functioning of the Federal data bank on doses of natural irradiation of the population of the Russian Federation *Radiation Hygiene,* **14** No. 3 (2021) Pp. 112–125. – DOI 10.21514/1998-426X-2021-14-3-112-125.
2. I. V. Yarmoshenko Radon as a factor in the exposure of the population of Russia *Biospheric compatibility: man, region, technologies*, **2 (18)** (2017) Pp. 108–116.

3. Chemical Encyclopedia / Editorial Board: Knunyants I. L. et al. - Moscow: Soviet Encyclopedia. Vol. 4 (1995). – 639 p.
4. L. A. Gulabyants, B. Yu. Zabolotsky. The power of the "active" layer of soil during the diffusion transfer of radon in the soil foundation of the building *Equipment and News of Radiation Measurements*. **4 (27)** (2001) Pp. 38–40.
5. Basic rules for ensuring radiation safety (OSPORB-99/2010). Sanitary rules and regulations SP 2.6.1.2612–10.
6. Radiation safety standards (NRB-99/2009). Sanitary rules and regulations SanPin 2.6.1.2523-09.
7. O. P Sidelnikova. Natural radionuclides in building materials and industrial wastes of the Volgograd region *Vestnik VolgGASU: Construction and architecture* **44–2 (63)** (2016) Pp. 52–60.
8. A. V. Kalaido, V. I. Rimshin, M. N. Semenova Evaluation of the contributions of diffusive and convective radon entry into buildings *Housing construction* **7** (2021) Pp. 48–54.
9. L. A. Gulabyants, A. V. Kalaido. Radon protection of residential and public buildings: Monograph, ed. Shubin I. L. – Moscow; Berlin: Direct-Media (2020) 232 p.
10. O. P. Sidelnikova, Yu. D. Kozlov. Effective specific activity of natural radionuclides in building materials of the Volgograd region *Internet Bulletin of VolgGASU* **2 (27)** (2013) Pp. 1–4.
11. V. I. Rimshin, A. V. Kalaido, M. N. Semenova, V. A. Borshch Building technologies for ensuring the radon safety of buildings *Building materials* **6** (2023) Pp. 33–38.
12. V. I. Rimshin, M. N. Semenova. Designing radon protection of buildings *Bulletin of the Lugansk State Pedagogical University. Series 5. Humanities. Technical science* **1 (79)** (2022) Pp. 91–98.
13. V. I. Rimshin, A. V. Kalaido, M. N. Semenova. Technology for designing radon-safe buildings *Bulletin of the Luhansk State Pedagogical University. Series 5. Humanities. Technical science* **4 (92)** (2022) Pp. 88–93.
14. A. V. Kalaido, V. I. Rimshin, M. N. Semenova. Ensuring acceptable levels of radon exposure in buildings with passive radon protective technologies *BST: Bulletin of Construction Equipment* **6 (1042)** (2021) Pp. 20–22.
15. V. I. Rimshin, A. V. Kalaido, M. N. Semenova. Technology for protecting the air environment of buildings from the ingress of radioactive radon gas *Bulletin of the Luhansk State Pedagogical University. Series 5. Humanities. Technical science* **3 (68)** 2021 pp. 98-104.
16. A. V. Kalaydo Passive Technologies for Providing Radiation Safety of Buildings at the Design Stage *Civil Engineering Research Journal* **11 (2)** (2020) Pp. 001–004. DOI: 10.19080.
17. Vu Dinh Tho, E. A. Korol, V. I. Rimshin, Pham Tuan Anh. Model of stress-strain state of three-layered reinforced concrete structure by the finite element methods *International Journal for Computational Civil and Structural Engineering* **18 (2)** (2022) Pp. 62–73.
18. V. I. Rimshin, V. L. Kurbatov, V. T. Erofeev, E. S. Ketsko. Degradation damages survey of the silt reservoir structures *Building and Reconstruction* **2 (100) (**2022) Pp. 65–74.
19. V. I. Rimshin, P S. Truntov, I. S. Kuzina, S. I. Roshchina, E. S. Ketsko Engineering calculations of acidifier retaining walls during water treatment facilities designing *Lecture Notes in Civil Engineering* **182** (2022) Pp. 55–73.

20. V. I. Rimshin, V. I. Telichenko, P. S. Truntov, A. L. Krishan, G. S. Bykov. Assessment of the impact of high temperature on the strength of reinforced concrete structures during operation *Key Engineering Materials* **887** (2021) Pp. 460–465.
21. V. I. Rimshin, E. S. Kuzina, I. L. Shubin. Analysis of the structures in water treatment and sanitation facilities for their strengthening *Journal of Physics: Conference Series. International Scientific Conference on Modelling and Methods of Structural Analysis 2019* (2020) Pp. 012074.
22. S. Merkulov, V. Rimshin, E. Akimov, V. Kurbatov, S. Roschina. Regulatory support for the use of composite rod reinforcement in concrete structures *IOP Conference Series: Materials Science and Engineering. International Conference on Materials Physics, Building Structures and Technologies in Construction, Industrial and Production Engineering, MPCPE 2020* (2020) Pp. 012022.