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PREDICTION OF RADON CONCENTRATIONS IN ABOVE-GROUND APARTMENTS

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The estimate of radiation safety in existing buildings by indoor radon levels measuring requires considerable time and financial costs, at stage of the constructions design it is not possible generally. So the prediction of radon concentrations in new and existing buildings on the basis of mathematical modeling is the actual problem. The semi-empirical model of radon levels prediction in the above-ground apartments presents in the paper. The model structure is the result of theoretical studies of soil gas transport mechanism in a porous media and the empirical constants determined based on the radiation monitoring results of the buildings and territory of the University.

Key words: Radon, Radiation safety, Progeny, Equivalent, Equilibrium, Radon, Concentration (EERC), Construction

INTRODUCTION

Forty years ago in the publication of the UN Scientific Committee on the Effects of Atomic Radiation radon was recognized as the most important source of radiation risk for the population. The analysis of the residential radiation monitoring results in the Russian Federation and abroad shows the indoor radon exposure contribution ranged from 55 to 95% the annual individual dose from all ionizing radiation sources [01-05].

The criterion of indoor radiation safety in Russia is the equivalent equilibrium radon concentration (EERC). The Radiation Safety Standard sets for EERC two control levels (100 and 200 Bq·m-3 for new and existing buildings, respectively). The radon concentration level is related to the effective radiation dose with a conversion multiplier of 11.9 nSv·m3/(Bq·h) [06; 07].

The radon generation occurs in the soil during the decay of the radionuclide 226Ra and further exhalation into the pores and microcracks. With the soil air radon forms a binary mixture with negligible mole fractions (of the order of 10-16) and moves to the ground surface and building substructures, which overlap the free soil gas entry in the atmosphere. The maximum concentration of radon per soil volume unit is called the soil radon potential (PRn, Bq·m-3) and depends on the radium content in soil CRa, the soil density ρsoil and the radon emanation coefficient k

$$P_{Rn} = C_{Ra} \cdot \rho_{soil} \cdot k \qquad 1)$$

The radon concentration in gas increases with depth and established at several meters under the daily surface [8] in ranges from 10,000 to more than 150,000 Bq·m-3 [09]. With a sufficient accuracy it can be taken equal to the radon activities difference in the external and internal borders of underground walling [10].

The correlation between indoor radon levels and specific radium content CRa in the underlying soils was found. It can be attributed CRa (with high air permeability) to the potential radon risk factors. The subsurface soil permeability determines the maximum depth of radon migration from soil to horizontal building substructures. Most of the Russian Federation territory is located of dispersed clay-sandy sedimentary rocks with low air permeability. The molecular diffusion is the single mechanism of radon transport in such conditions and the maximum depth of radon migration does not exceed 3-5 m [05]. The conditions for advective soil gas transport take place in the fractured rocks with the collector properties and active microgeodynamic areas

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under the buildings, in this case the radon migration depth can reach tens or hundreds meters.

PROBLEMS OF RADON ENTRY DESCRIPTION

Soil gas is the main source of radon entry in indoor air. The modern walling constructions are the concrete slabs with a low permeability (10-14 – 10-16 m2). The radon transport through these structures is possible only by a molecular diffusion. In this case, the soil gas flow through the horizontal substructures

$$q_{\text{soil}} = \frac{P_{Rn}}{R_{\Sigma}} \qquad 2)$$

where R_{Σ} is the total construction radon resistance, $s \cdot m^{-1}$.

The specific radon flux from the soil can be determined as

$$a_{\text{soil}} = q_{soil} \cdot \frac{A}{V} = \frac{P_{Rn}}{R_{\Sigma}} \cdot \frac{A}{V} \qquad 3)$$

where A is the floor area, m^2; V is the room volume, m^3.

The modern building foundations consist 3-7 layers with different physical characteristics, however radon resistance to determine the layers with lowest permeability (concrete and gas/liquid isolation layers usually). The building substructures has small layers thickness, because the total radon resistance of two different layers can be written in the form [10]

$$R_{\Sigma} = R_1 + R_2 = \frac{1}{\sqrt{\lambda D_1}} \cdot sh\left(H_1\sqrt{\frac{\lambda}{D_1}}\right) + \frac{1}{\sqrt{\lambda D_2}} \cdot sh\left(H_2\sqrt{\frac{\lambda}{D_2}}\right) \qquad 4)$$

where *H1* and *H2* are the thickness layers with the highest radon resistance, m; $\lambda = 2{,}1 \cdot 10^{-6}\ s^{-1}$ is a radon decay constant; D1 and D2 are the bulk radon diffusion coefficient in these layers materials, $m^2 \cdot s^{-1}$.

Eq. (4) is obtained under the assumption of diffusive radon transport through the building substructures, which is fair for permeabilities less than $10^{-12}\ m^2$. Advection starts to play a significant role in the radon transport at air permeability ranged from 10^{-10} to $10^{-12}\ m^2$. At the air permeability more than $10^{-10}\ m^2$ advection becomes the dominant transport mechanism even at low pressure differences [11; 12].

The soil gas flow also depends on the floor construction. So, a supported slab (Figure. 1, a), has a greater radon resistance than the floating slab (Figure 1, b).

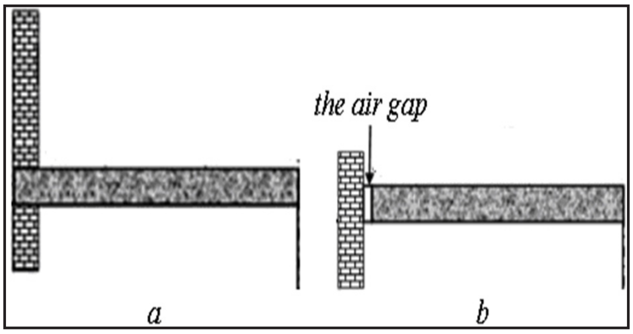

Figure 1. The floor constructions: a – the supported slab; b – the floating slab

Furthermore, micro-cracks always present in the concrete floor structures and it number increases with the building age. Accounting the gaps influence in building substructures on a radon entry rate can be produced by the introduction of effective radon diffusion coefficient of the foundation materials

$$D_e = \frac{D_{air} \cdot A_g + D_{con} \cdot (A - A_g)}{A} \qquad 5)$$

where D_{air} and D_{con} are the bulk radon diffusion coefficients of the air and of the concrete, respectively, $m^2 \cdot s^{-1}$; A is the total area of the inner surface of the horizontal building envelope, m^2; Sg is the leakage area (cracks and gaps), m^2.

Eq. (2) - (5) can be used for description of radon entry into the most buildings. The exceptions are the buildings with defective substructures and with crawl space (ground) floor, which is already quite longer applied even in the dwelling constructions.

The second largest source of radon entry into the buildings is the exhalation from the walling materials, which exceed about 3 $mBq \cdot m^{-2} \cdot s^{-1}$ [10]. The rate of radon exhalation determined by the building materials properties: the specific radium activity, porosity and emanation coefficient.

$$q_{\text{wall}} = C_{Ra} \cdot \rho \cdot E \sqrt{\frac{\lambda D_e}{\varepsilon}} \tanh\left(\frac{h}{2} \cdot \sqrt{\frac{\lambda \varepsilon}{D_e}}\right) \qquad 6)$$

where E is the radon emanation coefficient; h is the thickness of material layer, m; ε – porosity.

RESULTS

However, in existing buildings the walling materials properties is not known often, so the real radon entry rate can be found experimentally. In this work the estimate of radon entry rate from walling materials produced by the following method: initial EERC Q0 was measured in a 5-th floor University apartment before it transition from operating mode to closed mode. In closed apartment each hour in automatic mode were measured EERC, the measurement results are shown in Figure 2.

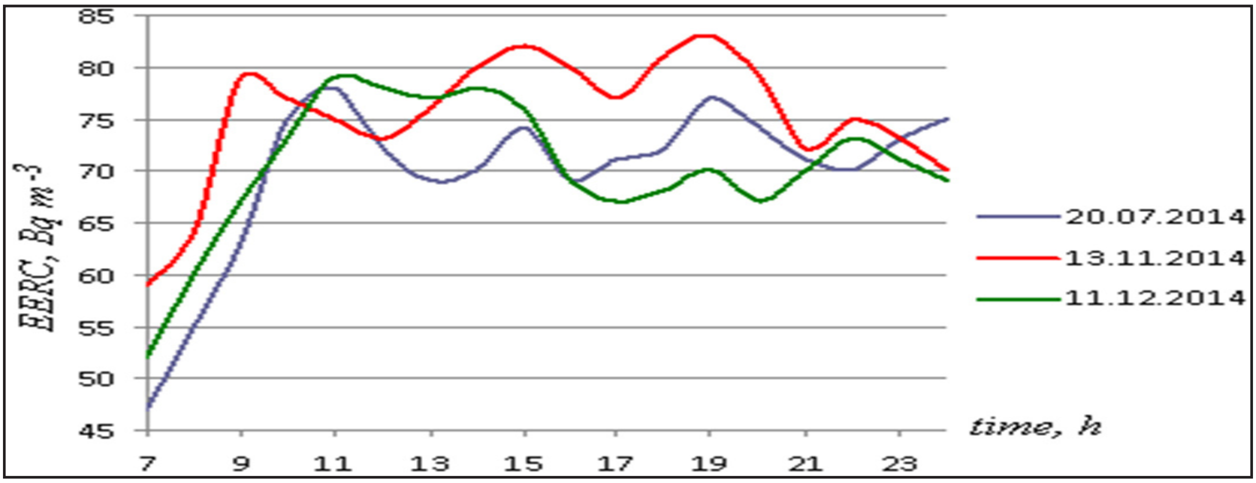

Figure 2: Radon levels measurement in the experimental room

All measurements showed the process with the saturation effect after a few hours of measurement start and a further radon concentration oscillation around the steady-state level. Specific radon exhalation flux from the walling materials can be written in the form [09]:

$$a_{\text{wall}} = \frac{\lambda \cdot (Q(t) - Q_0) \cdot e^{-\lambda t}}{1 - e^{-\lambda t}} \quad 7)$$

where t is the time to saturation, s; Q(t) is the EERC in the room in the given time t, $Bq \cdot m^{-3}$.

The result of calculation of the average specific radon entry flux from the walling materials is awall = 0.0026 $Bq \cdot m^{-3} \cdot s^{-1}$, that is equivalent to an average radon exhalation rate (at room volume 39 m^3 and the emanation surfaces area 72.4 m^2)

$$q_{wall} = a_{wall} \cdot \frac{V}{A} = 0.0026 \cdot \frac{39}{72.4} = 0.0014 Bq \cdot m^{-2} \cdot s^{-1} = 1.4\ mBq \cdot m^{-2} \cdot s^{-1}$$

The last significant source of radon entry into the houses is the radon infiltration with outdoor air. Assuming that infiltration exceeds the soil gas diffusion flux greatly, the specific infiltration radon flux per volume unit

$$a_{atm} = C_{atm} \cdot \lambda_{air} \quad 8)$$

where λ_{air} is the air exchange rate, s^{-1}.

There are no widely researches of the EERC in outdoor air in scientific literature. For this purpose, three cycles of radon levels measurements in outdoor air have been made on the Luhansk Taras Shevchenko National University campus. The measurements produced on warm and cold period of the year (July and November) and after deposition of the snow cover with a 40 cm thickness. Measurements were carried out at intervals of one hour from 7 a.m. to 7 p.m. on the distance more than 40 m from the building to avoid the influence of wind flows. The results of the study did not reveal any diurnal and seasonal patterns, as well as the correlation of radon levels with climate parameters. The average value of EERC in the outdoor air in Luhansk was

$$C_{atm} = 14.4 \pm 5.9\ Bq \cdot m^{-3}$$

For July, November and December EERC in the outdoor air was 13.7 ± 4.8; 13.1 ± 9.5 and 16.4 ± 4.4 $Bq \cdot m^{-3}$, respectively. You should expect similar results for most part of the territory of the Russian Federation without the uranium-rich soils and active microgeodynamic areas.

In some studies water and natural gas indicate as a sufficient radon sources. But in typical conditions for residential areas (the centralized water supply and gas aging in underground storages) these radon sources contribution are to be neglected.

With mechanisms of indoor radon accumulation take place the mechanisms of its activity reduction, such as a radioactive decay and ventilation [14]. Specific radon concentration reduction caused by these mechanisms

$$a_{red} = C \cdot (\lambda + \lambda_{air}) \qquad 9)$$

Finally, the radon concentration in indoor air may be expressed in the form

$$\frac{dC}{dt} = \sum_{i=1}^{3} a_i - C(\lambda + \lambda_{air}) = a_{soil} + a_{wall} + a_{amM} - C(\lambda + \lambda_{air}) \qquad 10)$$

We obtain the solution to Eq. (10)

$$C = \frac{\sum_{i=1}^{3} a_i}{\lambda_в + \lambda} \cdot \left(1 - e^{-(\lambda + \lambda_в)t}\right) + C_0 e^{-(\lambda + \lambda_в)t} \qquad 11)$$

where C0 is the EERC in the room at the initial time moment, Bq·m^{-3}.

The greatest interest in the prediction of radiation situation in above-ground apartments presents the determination of the maximum EERC under the steady-state conditions (t → ∞). Since the real air exchange rate is always greater the radon decay constant (λair >> λ), we can be written finally

$$C = \frac{\sum_{i=1}^{3} a_i}{\lambda_{air}} = \frac{a_{soil} + a_{wall} + a_{atm}}{\lambda_{air}} \qquad 12)$$

COMPARISON OF THEORY AND EXPERIMENT

Validation of the proposed model to the real conditions of radon entry was carried out by comparison with the results of the annual measurements EERC in the ground floor University laboratory, the technique of EERC measurements described in [13]. Figure 3 shown the results EERC measurements for warm and cold periods: radon concentrations value are 71.3 ± 4.6, and 125.5 ± 7.9 Bq·m^{-3}, respectively.

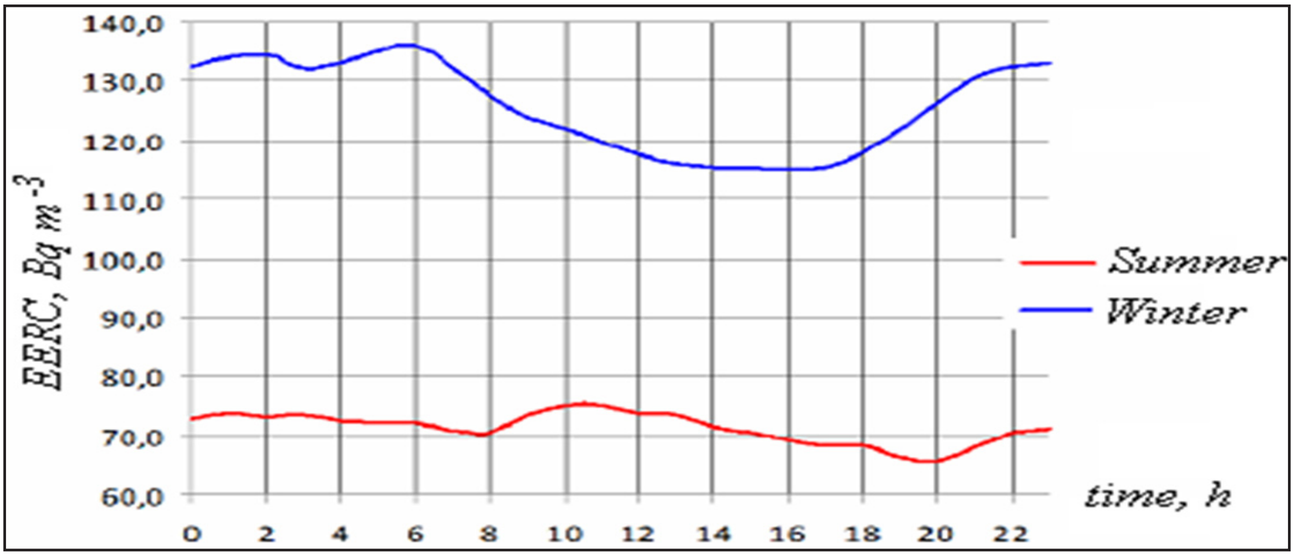

Figure 3 – Results of EERC measurements in the ground floor laboratory

The floor construction in Luhansk Taras Shevchenko National University laboratory is the 200 mm concrete floating slab. For this case Eq. (12) with C_{atm} and a_{wall} has the form:

In Table 1 shows the results of the maximum EERC calculation in the laboratory.

$$C = \frac{P_{Rn}}{sh\left(H\sqrt{\frac{\lambda}{D_e}}\right)} \cdot \frac{A}{V} \cdot \frac{\sqrt{\lambda D_e}}{\lambda_{air}} + \frac{0.0026}{\lambda_{air}} + 14.4. \qquad 13)$$

Table 1: Results of EERC calculations in experimental laboratory under the different air exchange rates

V, m^3	A, m^2	H, m	De, $m^2 \cdot s^{-1}$ [4]	P, $Bq \cdot m^{-3}$	λair, S^{-1}	EERC, $Bq \cdot m^{-3}$
60	91.5	0.2	$5.3 \cdot 10^{-8}$	50,000	$2.78 \cdot 10^{-5}$ (0,1 h^{-1})	673.7
					$5.56 \cdot 10^{-5}$(0,2 h^{-1})	344.0
					$8.83 \cdot 10^{-5}$ (0,3 h^{-1})	234.2
					$1.11 \cdot 10^{-4}$ (0,4 h^{-1})	179.2
					$1.39 \cdot 10^{-4}$ (0,5 h^{-1})	146.3

The proposed approach also allows assessing the different radon sources contribution in the formation of indoor radon levels (Table 2).

Table 2: Contribution of different sources in radon entry (at λair = 0.1 and 0.4 h^{-1})

Radon entry sources	**Formula**	**a, $mBq \cdot m^{-3} \cdot s$-1**	**Contribution**
Diffusion with soil gas		15.7	84% 79%
Exhalation from the walling materials	experiment	2.6	14% 13%
Entry with outdoor air	$14.4 \cdot \lambda_{air}$	0.4 (λair = 0,1 h^{-1}) 1.6 (λair = 0,4 h^{-1})	2% 8%

CONCLUSION

Analysis of experimental data and the current theory indicate that:

1) Under the low ventilation rates take place a significant excess of the reference level (200 $Bq \cdot m^{-3}$) in above-ground apartments by the diffusive radon transport through the sub-slab structures with high radon resistance.
2) The principal mechanism of radon entry in indoor air of the above-ground apartments is pure diffusion through horizontal sub-slab structures under the action of the radon concentration differences. The contribution of molecular diffusion is not less than 80% for all sources of radon entry.
3) The comparison between the developed model and experiments is satisfactory.
4) The proposed model can be used to calculation of radon concentrations in above-ground apartments of the buildings. For improving of the calculation results accuracy it is necessary to refinement of the input model parameters: radon concentration in the soil air near the building basement, the radon diffusion coefficient of the walling materials, etc.

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