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ORIGINAL ARTICLE

Radon ecology danger and the ways of its minimization in Rivne City (Ukraine)

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The presence of high concentrations of radioactive gas Radon-222 in residential and production premises exerts negative influence on the health state of the population and boosts the risk of coming into existence of respiratory system cancer. In this research, the analysis of main factors that exert influence on the content of Radon in premises of Rivne city is presented and the set of measures that minimize negative consequences of Radon influence on the health of the population both in the premises that are exploited and in the ones that are on the design stage is offered. We divide the city into the regions with different levels of radon danger that depend on the values of Radon volume activity (VA) in premises and the density of Radon flux (DRF) from the soil. The city territory was divided into 12 proving grounds and 48 sub regions for this purpose. Measuring VA in premises was performed in the time frame from 2013 to 2017 with the reliance on the express method and the Radon radiometer "Alpharad plus". In total 600 premises were investigated. 185 of them are located under the ground level. 215 of them are only partially under the ground level. 200 of them are located on the first floor. VA of Radon-222, DRF from the ground, Radon concentration in the ground gas and water were determined experimentally. Risks of acquiring lung cancer on the part of the population of Rivne city were calculated. It is determined that the values of Radon VA in the premises under investigation range from 25 Bq/m^3 to 1000 Bq/m^3, the values of DRF from the soil range from 16 to 173 mBq/(m^2 × s). Since the construction standard of the Radon flux from the ground is set at the level of 80 mBq/(m^2 × s); 34%, 44%, and 22% of city premises have respectively low, medium, and high levels of safety. The results of this research imply that the regional and state programs of creating standards and collecting data for the analysis of the state of radioactive safety and for making practical decisions regarding measures that subdue risks due to population exposure to natural irradiation should be developed.
Keywords: Radon; flux density; volume activity; antiradon protection; population health

Introduction

The choice of physical parameter that is the best in characterizing radon as a factor of negative influence on the health of human being indoors is not unique. It was experimentally determined that the population exposure to radon irradiation can be characterized by several parameters: volume activity (VA) of radon in the premises where a human spends the largest portion of his or her time, effective dose due to radon the lungs obtain, the density of flux of radon (DFR) from the ground under a building, etc. The relation between them has to do with some uncertainties. For the transition from VA of radon to the effective dose one has to use coefficients that characterize the shift of the equilibrium between derivative products of decay (DPD) of radon, biological kinetics of DPD in respiratory tract, the relative biological effectiveness and radio sensitivity of organs. The majority of the mentioned coefficients depend on time, the portion of them are determined too roughly, their values are made more precise on the regularly basis (Yarmoshenko et al., 2014). At the same time, VA of radon and DFR are quantities that are measured directly. Therefore, the recommendations of taking antiradon protection measures in residential premises of populated areas are based on investigation of these parameters.

It is known that the structural peculiarities of the underlaying soils and the main geological rock under buildings located on territories unsafe due to radon frequently determine a critical situation with the radon concentration inside a building (Keller et al., 2001; Lebed & Klymenko et al., 2018; Akerblom et al., 1984). Geological peculiarities of such the concentration can be determined by the content of Radium-226 in soils beneath the building and hermeticity of its building shell that determines the intensity of entering from the ground on the part of Radon-222. Sometimes such the relation is not observed, for instance, when the peculiarities of constructing the building determine the minimization of the radon concentration in it thanks to hermeticity. (Albering et al., 1996; Amponsah et al., 2008; Grodzinskiy, 1987). The internal concentration of radon in the building premises is unstable due to external meteorological conditions and the speed of air convection, which in its turn influences the behavior of dwellers that perform ventilation of a premise and its heating. (Mullerova et al., 2018; Mazur & Kozak, 2014; Barazza et al., 2018). It is obligatory to perform estimations of exposure to radon when determining its influence on the increase of risks of acquiring lung cancer during a long period of time that should be at least one year. In this research, the determination of the value of DFR from the soils of Rivne city was carried out. Obtained data determine possibilities of construction of residential premises since a number of documents of world organizations in which new stricter requirements regarding radioactive pollution of territories of residing in Europe and the world, for instance, Council Directive 2013/59/EURATOM (Council of the European Union, 2014) and the ones WHO developped were adopted recently (Zeeb & Shannoun, 2009). In these documents, the special attention is paid to investigating radon fields of the cities with large population densities located on platform territories that are problematic with regard to the content of the radioactive elements (the Rivne city is located on Ukrainian crystal shield enriched with beds of uranium ore). This directive is adopted in national legislations of the countries that are members of EU, in which it was expected that some measures aimed at resolving the general problem of the influence of exposure to radon on global state of health of the European population will be taken by February 2018 According to this directive, the base level of averaged over a year radon concentration of 300 Bq/m^3 for residential premises and work places is introduced and the member countries are offered to develop “the plans of activities with regard to radon”. It should be noted that the US requirements are much stricter (the level of action is set to approximately 4 pKi/l ≈ 148 Bq/m^3) (United States Environmental Protection Agency, 1991). European standards expect the development of the methods and indicators of measurement and estimation of radon concentration. In relation to this, the necessity of performing special complex investigations of radon concentrations of European platform regions (including Rivne city as radon unsafe European territory) for the development of the system of standardization and estimation of the potential ecological danger of territories arises since it is known that radon is the gas that is carcinogenic to the great extent. Inhaling it causes oncological diseases of trachea, bronchi, and lungs and acquiring mainly the adenocarcinoma, the squamous cell carcinoma, and the sarcoma of lymph nodes (Field et al., 2000).

The aim of this research consists in determining the level of radon danger for dwellers of Rivne city, analyzing main factors of influence on the radon content in premises, and offering measures aimed at minimization of negative consequences of radon influence on the health of population both in the premises that are exploited and during designing new constructions.

Materials and methods

The factors that influence the radon content in the air of the premises to the great extent are the following: 1) radiological characteristics of underlying grounds and construction materials (coefficient of emanation of radon from soils, there gas permeability, etc); 2) characteristics of ventilation systems of buildings and the regimes of airing them up; 3) design features of buildings (storeyness, the type of foundation, the presence of aerodynamic connection between floors, location of communication systems in the building contour, etc); 4) type of window glazing (the degree of their hermticity, the presence of ventilation valves, etc); 5) type of heating (stove heating, electrical heating, gas heating, or the central one); 6) the level of floor in the premises: basements, semi-basements, the first floor relative to the surface of the ground (Svetovidov et al., 2009). We performed the investigation of the influence of these factors on the increase of the risk of acquiring lung cancer on the part of the dwellers of Rivne city during the time frame from 2013 to 2017 in Rivne city and in the suburban area (figure 1). We determined experimentally the following: concentration of Radon-222 in the city premises: basements, semi-basements, and the premises of the first floors of buildings (Klymenko & Lebed, 2017; Lebed et al., 2016; Lebed & Klymenko, 2017; Lebed & Myslinchuk, 2017), the density of radon flux from the ground (Lebed, 2018), radon concentration in the ground gas (Lebed & Lysytsya et al., 2018), water (Lebed & Myslinchuk et al., 2018) and calculated the risks of acquiring the lung cancer on the part of the dwellers of the city of Rivne (Lebed & Klymenko et al., 2018; Lebed & Trusheva et al., 2019; Lebed et al., 2017).

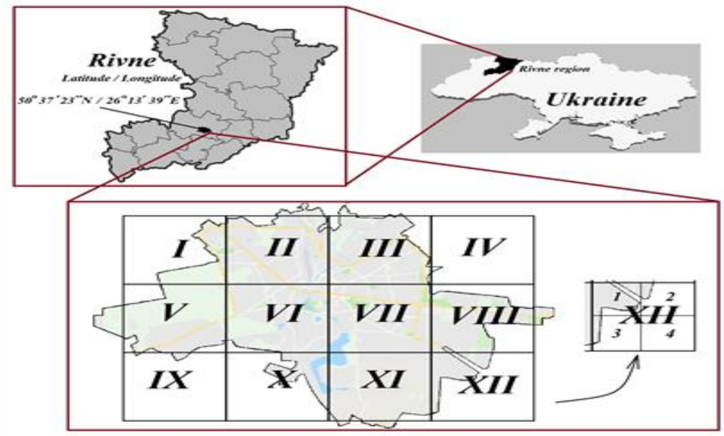

Figure 1. Proving grounds of Rivne city created to conduct comprehensive research on the influence of radon exposure in homes on the increase of the risk of of acquiring lung cancer on the part of the population.

The territory of the city was divided into 12 proving grounds. Each of them was divided into 4 sub regions. Hence, there are 48 sub regions in total. The measurement of radon VA was performed with the reliance on the express method and the use of the Radon radiometer “Alpharad plus” during a day with subsequent averaging. Such the measurements were carried out 4 times per year in each season. Averaged data of the radon concentration in the premises displayed slight deviation between seasons (about 15%). It should be noted that we did not detect the presence of Radon-220 (thoron) in each of the measurement probes taken from premises air, water, and ground water. There were 600 measurements in total. 185 of them were performed beneath the ground level. 215 of them were performed in the premises located only partially under the ground level and 200 of them were performed in the premises located on the first floor. Besides 144 measurements of DFR from the soils of Rivne city were performed during the time of the investigation and 48 measurements of the content of radon in the ground gas were performed with reliance on the methodologies described in (Lebed & Lysytsya et al., 2018; Lebed, 2018). The characteristic feature of measuring DFR in the city is the following. Significant variation of the measured value of DFR with the changes in the atmospheric pressure was not observed (the variations of DFR, the air temperature, and the ground temperature did not exceed respectively 5%, 10%, and 10%). For different seasons (spring, summer, and autumn) and years fluctuations in DFR for specific points of measurement were equal to approximately 10%.

Results and discussion

The investigation of 600 premises of Rivne city showed that the spectrum of values of VA in the premises under scrutiny was broad. Specifically they varied in the range from 25 Bq/m^3 to 1,000 Bq/m^3. The dependence of the frequency of the quantity of premises on radon concentration has obviously lognormal type (Klymenko & Lebed, 2017) with arithmetic mean of VA in all premises under investigation equal to 262.5 Bq/m^3 and the standard deviation equal to 194.4 Bq/m^3. The geometric mean was equal to 200 Bq/m^3 and the geometric standard deviation had such the value σ=0.7865. The value of VA that corresponds to 3σ deviation was equal to 1,420 Bq/m^3 (It means that there are premises, which we did not observed and in which the value of VA can be as high as 1,420 Bq/m^3).

Obtained values of DFR (Lebed, 2018) indicate that the radon situation in the city is difficult and the investigation of radon activity in the premises located fully and partially under the ground level as well as in the residential ones located on the first floor support such the conclusion. The considerable range of DFR (from 16 to 173 mBq/(m^2 × s)) is obviously determined by geological, meteorological, climatic, and biotic factors. Approximately one third of the city territory is characterized by the density of the radon flux from the ground that exceeds the construction norm equal to 80 mBq/(m^2 × s). The obtained statistics indicates that the radon fluxes from the city soils are comparable with the ones registered in broadly recognized as dangerous with respect to radon places of the world such as Caucasus, Irkutsk region, Tatarstan, Krasnoyarsk territory (Russia), Illinois (USA).

The investigation of radon concentration in the ground gas indicates that the levels of the concentration for this locality are low (1.4-17.7 kBq/m^3) with the arithmetic mean equal to 11.13 kBq/m^3 (Lebed & Lysytsya et al., 2018). However, they are sufficiently high for creation of radon VA in the buildings as high as 1,420 Bq/m^3. These data we recorded in 2017. Complex determination of radon in physical media of the territory under scrutiny showed that the territory of Rivne city is unsafe with respect to radon with being in the range from 4% to 11% for lifetime exposure to VA equal to 2,000 Bq/m^3 on the part of the value of the additional relative risk (R). If VA equals 1,420 Bq/m^3, then R is in the range from 20% to 50% (Lebed & Klymenko et al., 2018; Lebed & Trusheva et al., 2019; Lebed et al., 2017).

Obtained results of the research raised the question regarding measures related to the decrease of the impact of radon on the health of the population of Rivne city.

In an attempt of achieving this goal we divided the city into the regions with regard to the categories of “radon safety" and “radon danger” according to the values of radon VA in the premises and DFR from the soil. During dividing the city into the regions determining the damage to the human health due to stay in the premises with determined radon concentration in the air of the premises we were using the radiation and hygiene regulations of the fourth group of population as a guide (Radiation Safety Standards of Ukraine, 2000). We offer to perform the classification of the ecological risk gradation (regarding radon) with respect values of VA in the air of the premises according to the following. The low level, the medium level, the level that is higher than the medium one, and the high level correspond respectively to such the ranges from 0 Bq/m^3 to 50 Bq/m^3, from 50 Bq/m^3 to 100 Bq/m^3, from 100 Bq/m^3 to 200 Bq/m^3, as well as 200 Bq/m^3 and higher (see table 1). The chosen ranges correspond to the ones specified in the norms of radiation safety of Ukraine approved in 1997 (NRSU-97) with respect to the level of action for the equivalent volume activity at equilibrium (EVAE). Since the value of the coefficient of the equilibrium between radon and its DPD for the majority of the world territories is not determined (the value of the coefficient equal to 0.4 is offered for US and the one equal to 0.5 is offered for Russia, according to some publications the last value lies in the range from 0.2 to 0.7), we offer to use the value of F equal to 1 as a guide. Although it is probably too high, it takes into account boosted risk of radon impact on ecological safety of the population of Rivne city. In this case, the values of EVAE and VA are identical.

Table 1. Classification of residential premises of Rivne city with respect to ecological radon danger.

Indices of radon VA in a premise	**Characteristic of the radiogenic load with respect to VA in the premises**				
	Low level, I	**Medium level, II**	**Level III that is higher than the medium one**	**High level, IV**	**Not investigated**

The number of the proving ground	I.1; IV.1; VI.1,2,3,4; X.1,2,3,4	I.3,4; III.1,2,3,4; IV.3; V.1,2,3,4; XI.1,2	–	VII.1,2,3, 4; VIII.1, 3	I.2; II. 1,2,3,4; IV.2,4; VIII.2, 4; IX.1,2,3,4; XI.3,4; XII.1,2,3,4
The relative quantity of premises in percent	21	27	0	13	39

If one enumerates the relative quantity of premises, in which the measurements were performed, in accordance with indicators of radon VA in them and conducts the classification according to the level of radon danger in them, then he or she will find out that 34%, 44%, 22% of premises have respectively the low, medium, and high levels of the safety. It should be noted that the percentage of the territories in which premises the investigation was not conducted due to some reasons (utility rooms, disinterest of the inhabitants, etc) is high.
If one classifies the radon danger of the territory of Rivne city with respect to the indicators of DFR from the soils of the territory, which is decisive for the norms DBN B.1.4-2.01-97, DBN B.1.4-1.01-97 and DBN B.1.4-1.03-97, then he or she can determine the following gradation with respect to the levels of safety-danger. The low level, the medium level, the level that is higher than the medium one, and the high level correspond respectively to such the ranges from 0 mBq/($m^2 \times s$) to 25 mBq/($m^2 \times s$), from 25 mBq/($m^2 \times s$) to 50 mBq/($m^2 \times s$), from 50 mBq/($m^2 \times s$) to 75 mBq/($m^2 \times s$), as well as 75 mBq/($m^2 \times s$) and higher (see Table 2).

Table 2. Classification of Rivne city territory with respect to ecological radon danger (with respect to indicators of DFR).

Indicators of DFR from the ground	**Characteristic of the radiogenic load with respect to DFR from the ground**			
	Low level, I	**Medium level, II**	**The level III, that is higher than the medium one**	**High level, IV**
The number of the proving ground	II.2,3,4; IV.1,4; VI.1,2,3,4; IX.1,2,3,4; X.1,2,4	II.1; IV.2,3; V.1,2,3,4; X.3	I.1,2,3,4; III.3; VII.1; XII.4	III.2,3,4; VII.2,3,4; VIII.1,2,3,4; XI.1,2,3,4; XII.1,2,3
The relative area of the grounds of the city of Rivne	33	17	15	35

Taking into account conducted research one can realize that drastic decrease of the radon content in the internal air of the premises can be achieved thanks to the following:
1) choosing the site with low going out of the ground on the part of radon for construction;
2) the use of protective structures that prevent radon from penetrating into a building effectively;
3) removal of radon from internal air of premises.
For satisfaction of these requirements the obligatory effective parallel monitoring of radiation safety indicators with respect to VA and DFR is necessary, which values have to be used for sanitary and epidemiological assessment of land for construction and environmental safety of residing in the premises. As additional parameters for controlling potential radon danger the following ones can be used:
1) radon VA in the air of basement premises or/and premises of the first floors of neighboring buildings;
2) radon VA in ground air at a depth of 0.5-1.0 m from the surface of soils on the construction site;
3) geological and geophysical characteristics of the site (the presence of faults, etc.);
4) specific activity of Ra-226 in the underlying rocks.
We believe that the control of indicators of radon hazard should be separated with respect to (separately) DFR in the areas where residential development is planned and (separately) VA in the air of buildings that are exploited currently. For all measurable indicators, common requirements for measuring instruments are mandatory. They are the following:
1) in the established order they must be metrologically certified (standardized);
2) measurement means used to control the indicators of radiation safety of land plots (with respect to DFR) and the environmental safety of residing in premises (with respect to VA) have to have valid verification certificates.
At the same time, at all proving grounds used for the determination of DFR from the surface of the city soils in places, where no residential development is carried out, and from the surface of soils on land plots measuring instruments with the following technical characteristics have to be used:
1) the lower limit of the measurement range of the DFR from the soil surface has to be at a level that does not exceed 20 mBq/($m^2 \times s$) with an error of not more than 50%;
2) the measurement error of the DFR has to be at a level of 75 mBq/($m^2 \times s$) and above - no more than 30%.
Measurement of DFR from the surface of the soil, the search and detection of local radiation anomalies are recommended (Kuznetsov, 1998) to conduct at a positive air temperature as well as: 1) at the thickness of the snow cover on the territory less than 0.1 m; 2) at freezing of soils to a depth of less than 0.1 m; 3) after establishing the soil moisture (in the autumn and spring periods or after intense rains) to a typical condition for the given area. It should be understood that measures for protecting the building, which are carried out at the stages of its design and construction, are more efficient and are less costly than measures to reduce the amount of radon in an already constructed building are (Vasiliev et al., 2018). In the construction on radon-hazardous areas, the main principle of antiradon protection of the building should be recognized as prevention of radon intake in the premises. Measurement of the DFR on the land plot for construction, we recommend to conduct at the nodes of the network of control points, the locations of which can be selected as follows. If the location of the

contours of the projected objects on the site is not specified (pre-design stage), the control points network is selected in increments of 20 × 20 m or more depending on the area of the site:
1) up to 3 hectares - the number of control points is taken at a density of not less than 10 per 1 hectare;
2) from 3 to 10 hectares - at least 10 points per 1 hectare, but not less than 100 points per plot;
3) more than 10 hectares - at least 10 points per 1 hectare, but not less than 150 points per plot.
In this case, the total number of points for determining the DFR at the site must be not less than 20, regardless of its area. If there is an anchorage of a projected building on a plot of land for construction; then measurements are made only within the contour of the building, the increments of the network of control points should not exceed 10 × 10 m, and the total number of points must be not less than 15, independently from the building area of the structure. Besides, they have to be placed as uniformly as possible in the area of development. The value of the DFR from the soil surface on the investigated area of the site is taken as the arithmetic mean of Raverage according to the measurements at all control points, the absolute error δ of the value of Raverage is calculated with reliance on the Student method. If according to the results of the determination of the DFR from the surface of the ground on the investigated area of land for the construction of residential buildings, public buildings and structures in Rivne, the expression Raverage ≤ 75 mBq/(m^2 × s) is valid at all points and the following condition is fulfilled:

$$R_{average}+\delta \leq 75 \text{ mBq/(m}^2 \times \text{s)} \quad (1)$$

then the land plot meets the requirements of sanitary rules and hygienic standards for this indicator.
If the difference between the value of DFR and 75 mBq/(m^2 × s) is positive in more than 20% of the control points in the investigated area of the site for construction of residential and public buildings as well as structures within their area of construction, and for Raverage the following condition is satisfied:

$$50 \leq R_{average}+\delta \leq 75 \text{ mBq/(m}^2 \times \text{s)} \quad (2)$$

then a final estimation of the conformity of the assessment area with the requirements of sanitary rules and hygienic standards that correspond to this indicator for the construction of these facilities should be accepted only if the results of the determination of DFR on the level of laying the foundation sole are taken into account and in the projects engineering and construction measures aimed at reducing the flow of radon in buildings and structures from the ground.are provided. When designing antiradon protection systems, it is recommended to use optimal technical solutions or their combination, depending on the specific conditions.
Such the technical solutions are (Allowable levels, 1997). We believe that the most expedient effective radon protection measures that can be implemented in Rivne are the following:
1) Impregnation is a process in which a liquid substance (a suspension or emulsion based on bitumen, latex, polymer, etc.) passes into pores and cavities of a layer of porous or loose material by injection into a material or after application onto its surface. Some impregnations form a solid film on the surface of the material and, at the same time, serve as a coating. It is recommended to use impregnation to reduce the radon permeability of such finely divided materials as, for example, clay or sand in the exploited basements of buildings with a slight depression. The insulating effect of impregnation can be increased due to the layered formation of a bed of material with successive treatment of each layer. As an impregnating liquid for radon safety of houses, the most effective are the hydrophobic polymer Silano gidrofob 1H, the water-based hydrophobic silano gidrofob 1H and the polyurethane compound LAK PUR 2K manufactured by LLC "HIDROIZOL", Dnipro or Elakor PU Grunt/2K (polyurethane impregnation), Elakor ED Soil-2K/100 (epoxy impregnation), Elakor MB2 (acrylic impregnation).
2) Coverage is a mixture that is applied in a liquid state to a thin layer on a solid surface of the element of a fencing structure. The coating may simultaneously serve as a steamproofing or waterproofing layer. Multilayer coatings are more effective than the single-layered ones are and can be used simultaneously for decorative finishing of these surfaces. In this case, to fill the cracks and for leveling the surface, it is recommended to apply a layer of putty, mastics or mixtures on an epoxy basis, which is then covered with the layers of paint on an epoxy, chlorine-urea, polyvinyl chloride or alkyd-urethane basis. In our opinion, the best coating in the implementation of anti-radon measures is a mastic of bitumen-butyl rubber (cold) "Venta" (TU 21-27-39-77), which is produced in the city of Dnepr. This is a multi-component homogeneous liquid mass of oil bitumen, butyl rubber, antiseptics, fillers, solvents and vulcanising agent. Good results are also given by the use of BLEM mastic (TU 21-27-76-88, production of LLC "HIDROIZOL", the city of Dnipro).
3) Membranes (radon-insulating) - used to cover foundation plates, walls and ceilings of cellars made of monolithic reinforced concrete or prefabricated reinforced concrete elements to prevent the transfer of radon through pores, cracks, joints and air cavities in these structures. As a antiradon protective sufficiently effective membrane, “Dniproflex G” (TU 5774-531-00284718-95, Dnipro, Ukraine) can be offered. This is a surfacing roll material that is applied to the surface after melting. It is based on fiberglass, polyester cloth or fiberglass, with an elastic covering content that includes a specialized modifier type SBS "KRATON" produced by the company "SHELL" (England - Holland). For this membrane, its radon defense characteristics - radon diffusion coefficient in the material have been determined by experimental methods. The research showed that it is 30 times lower for this material than for heavy concrete and provides a length of Radon diffusion in a membrane material of about 0.4 cm, which ensures a decrease in its inflow into the premises by more than 4 times with a thickness of 4 mm.
4) Antiradon barrier - solid, monolithic reinforced concrete slab that can be the foundation of the house, the floor or ceiling of the basement. The protective effect of the barrier is higher, the closer it is to the soil base and the less disturbed its integrity is.
5) The Radon Collector is a system that freely conducts gas-radon from the ground under the building through the structural elements in the foundation of the structure, which ensures its collection and release into the atmosphere, bypassing the premises of the building.

6) The depression of the soil ground floor base is the creation of a zone of reduced pressure with the usage of a radon collector and a special forced ventilation system, which is not connected with ventilation of premises, on the soil base of the ground floor or a basement. Such the measure provides the best antiradon protection.

7) Sealing - sealing of cracks, joints, seams, and communication holes in enclosing structures on the way of radon movement from the source to the premises of the house, which is carried out using self-adhesive, elastic, plastic, foam, etc. materials.

Below, we provide technical recommendations for measures of antiradon protection for constructing residential buildings in the city.

1. Proving grounds with low level of DFR from the ground (II.2,3,4; IV.1,4; VI.1,2,3,4; IX.1,2,3,4; X.1,2,4).

a) Multifamily residential units with concrete basement depending on the depth of the basement:

- natural ventilation of basements with a depth of up to 3 m (ventilation openings in the basement walls that provide multiplicity of air exchange in the winter time not less than 30 minutes^{-1});
- forced ventilation of basements with a depth of up to 5 m (forced exhaust ventilation system that provides multiplicity of air exchange in the winter time of not less than 60 minutes^{-1}).

b) Private sector buildings depending on possible financing:

- coating (protective layer of concrete, protective layer of cement-sand solution, coating of mastic material, leveling layer of cement-sandy solution, concrete preparation);
- membrane (protective layer of concrete, protective layer of cement-sand solution, 1-2 layers of roll waterproofing material, leveling layer of cement-sandy solution, concrete preparation).

2. Proving grounds with the average level of DFR from the ground (II.1; IV.2,3; V.1, 2,3,4; X.3).

a) Multifamily residential units with concrete basement depending on the depth of the basement:

- coating (protective layer of concrete, protective layer of cement-sand solution, coating of mastic material, leveling layer of cement-sandy solution, concrete preparation);
- membrane (protective layer of concrete, protective layer from cement-sandy solution, 1-2 layers of roll waterproofing material, leveling layer from cement-sandy solution, concrete preparation):

b) Private sector buildings depending on possible financing:

- barrier+coating (solid monolithic slab from cracked concrete, protective layer from cement-sandy solution, 2-3 layers of mastic material, leveling layer from cement-sandy solution, concrete preparation);

– barrier+membrane (solid monolithic slab from concrete protected from cracks, protective layer from cement-sand solution, 2-3 layers of roll waterproofing material, leveling layer from cement-sandy solution, concrete preparation);

- barrier+membrane (coating)+radon collector+depression of the collector by natural extraction of ground gas (solid monolithic plate made of monolithic reinforced concrete, protective layer of cement-sandy solution, 2-3 layers of roll waterproofing material (or rubber material), leveling a layer of cement-sand solution, a screed from depleted concrete, a layer of gravel+exhaust pipes, adding sand).

3. Proving grounds with the level of DFR from the ground that is higher than the average one is (I.1,2,3,4; III.3; VII.1; XII.4).

a) Multifamily residential units with concrete basement depending on the depth of the basement:

- barrier+membrane (solid monolithic slab from concrete protected from cracks, protective layer from cement-sandy solution, 2-3 layers of roll waterproofing material, leveling layer from cement-sandy solution, concrete preparation);
- barrier+membrane (coating)+radon collector+depression of the collector by natural extraction of ground gas (solid monolithic plate made of monolithic reinforced concrete, protective layer of cement-sandy solution, 2-3 layers of roll waterproofing material (or rubber material), leveling a layer of cement-sand solution, a scraper of thin concrete, a layer of gravel+exhaust pipes, adding sand);
- the same thing+depression of the collector by forced extraction of ground gas (the same+ventilation equipment).

b) Private sector buildings:

- barrier+membrane (coating)+radon collector+depression of the collector by natural extraction of ground gas (solid monolithic plate made of monolithic reinforced concrete, protective layer of cement-sandy solution, 2-3 layers of roll waterproofing material (or rubber material), leveling a layer of cement-sand soolution, a scraper of thin concrete, a layer of gravel+exhaust pipes, adding sand);
- the same thing+depression of the collector by forced extraction of ground gas (the same+ventilation equipment).

Construction of kindergartens is possible only on the territories of the proving grounds of medium and low levels. For them, we recommend that you always perform antiradon protection in the form of:

- barrier+membrane (coating)+radon collector+depression of the collector by forced extraction of ground gas by air pump (solid monolithic plate made of monolithic reinforced concrete, protective layer of cement-sand solution, 2-3 layers of roll waterproofing material (or rubber material) , a leveling layer from a cement-sand solution, a scraper of thin concrete, a layer of gravel+exhaust pipes with ventilation equipment, adding sand).

For buildings that are exploited, we offer a number of antiradon protective measures presented in Table 3.

Table 3. Recommendations of measures of environmental radon safety of residential premises in Rivne city.

Characteristics of radiogenic loading with regard to VA in premises			
Low level, I	**Average level, II**	**The level III that is higher than the average one is**	**High level, IV**
I.1; IV.1; VI.1,2,3,4; X.1,2,3,4	I.3,4; III.1,2,3,4; IV.3; V.1,2,3,4; XI.1,2	–	VII.1,2,3,4; VIII.1,3

Ventilation of premises of the first floors through the windows for at least 2 hours a day. Isolation of the basement floor by means of impregnation, coating or membranes.	Sealing of cracks, seams, joints and communication holes. Isolation of the floor of the first floor using membranes. Isolation of the basement floor by means of impregnation or coating. Natural ventilation of basements.	Sealing of cracks, seams, joints and communication holes. Isolation of floors of the first floor and basement with the help of membranes. Forced ventilation of basements.	The first floor is desirable to use for stores, catering establishments, warehouses, etc. All first floors and basements should be equipped with forced ventilation. Isolation of floors of the first floor and basement with the help of membranes.

Conclusion

Our research shows that Ukraine needs an effective system of monitoring the radiation safety of the population from the effects of radioactive natural sources of radiation in residential areas, communal and production conditions. The main problems with high levels of natural radiation exposure in Rivne city are related to the high emissions of radon from the city's soils in residential and industrial premises and concentrating in them on the part of radon (especially in old-built buildings). The radon concentration reduction measures proposed in this study are local in nature; they can be optimally applied to the results of our research program only in the buildings of the region in accordance with specifics of respective proving grounds. Probably, the system of measures aimed at reducing the levels of the country population exposure to radiation should be planned and carried out within the framework of a higher level program, for example, similar to Russian FCP Radon, American Indoor Radon Abatement Act of 1988 or EU countries, "Council Directive 2013/59 / EURATOM ", which would include a number of activities, including measures to reduce the levels of exposure of separate groups of populations to high doses and would allow assessing the effectiveness of protective measures. Then, in the framework of such the program, the regulatory system and data collection system should be the most important tool for analyzing the state of radiation safety and making practical decisions regarding the main measures aimed at reducing the levels and the adverse effects of natural radiation exposure of the population.

References

Akerblom, G., Andersson, P., & Clevensjo, B. (1984). Soil Gas Radon - a Source for Indoor Radon Daughters. Radiation Protection Dosimetry, 7 (1-4), 49-54.

Albering, H. J., Hoogewerff, J. A., & Kleinjans, J. C. S. (1996). Survey of Rn-222 concentrations in dwellings and soils in the Dutch Belgian Border region. Health Phys., 70, 64-69. doi: 10.1097/00004032-199601000-00010

Allowable levels of ionizing radiation and radon in construction sites. Moscow city building codes (MGSN 2.02-97). Adopted and enforced by Decree No 57 of the Government of Moscow dated February 4, 1997. [in Russian].

Amponsah, P., Banoeng-Yakubo, B., Andam, A., & Asiedu, D. (2008). Soil radon concentration along fault systems in parts of south eastern Ghana. Journal of African Earth Sciences, 51, 39-48. doi: 10.1016/j.jafrearsci.2007.11.004

Barazza, F., Murith, C., Palacios, M., Gfeller, W., & Christen, E. (2018). A national survey on radon remediation in Switzerland. Journal of Radiological Protection, 38(1), 25-33. doi: 10.1088/1361-6498/aa979a

Council of the European Union. (2014). Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation. Brussels: O.J. EU. Available at: https://publications.europa.eu/en/publication-detail/-/publication/65527fd1-7f55-11e3-b889-01aa75ed71a1/language-en/ Accessed on 25.12.2017

Field, R. W., Steck, D. J., Smith, B. J., Brus, C. P., Fisher, E. L., Neuberger, J. S., Platz, C. E., Robinson, R. A., Woolson, R. F., & Lynch, C. F. (2000). Residential Radon Gas Exposure and Lung Cancer. American Journal of Epidemiology, 151(11), 1091-1102.

Grodzinskiy, D. M. (1987). Otsenka prirodnoy radioaktivnosti ob"yektov okruzhayushchey sredy: Metodicheskiye rekomendatsii [Assessment of the natural radioactivity of environmental objects: Methodical recommendations]. Kiev, 119 p. [in Russian].

Keller, G., Hoffmann, B., & Feigenspan, T. (2001). Radon permeability and radon exhalation of building materials. Science of the Total Environment, 272(1-3), 85-89. doi: 10.1016/S0048-9697(01)00669-6

Klymenko, M. O., & Lebed, O. O. (2017). Investigation of volumetric activity of the radon of the internal house air of Rivne city. Bulletin of the Kremenchug National University n. Mikhail Ostrogradsky, 3(104), 124-129 [in Ukrainian].

Kuznetsov, Yu. V. (1998). On the issue of radon flux density measurement methods. ANRI, 4. [in Russian].

Lebed, O. O. (2018). The concentration of Rivne city by the density of the radon stream from the soil. Materials of the IX International Scientific Conference "Relaxation, Nonlinear, Acoustic, Optical Processes and Materials", Lutsk, PF "Vezha-Druk", 125-127. [in Ukrainian].

Lebed, O. O., & Klymenko, M. O. (2017). Determination of volumetric activity of radon in the air of basements. Collection of articles of the Scientific-practical conference "Radioecology-2017" with international participation, Kyiv, pp. 127-129. [in Ukrainian].

Lebed, O. O., Klymenko, M. O., Lysytsya, A. V., & Myslinchuk, V. O. (2018). Effect of Radon on oncological morbidity of the population: comparative analysis of some region of Ukraine and France. Ukrainian Journal of Ecology, 8(1), 585-595. doi: 10.15421/2017_253.

Lebed, O. O., Lysytsya, A. V., Myslinchuk, V. O., Pryshchepa, A. M., & Dejneka, O. Y. (2018). Measurement of radon

concentration in soil gas of Rivne city (Ukraine). Ukrainian Journal of Ecology, 8(4), 158-164. Available at: https://www.ujecology.com/articles/measurement-of-radon-concentration-in-soil-gas-of-the-city-of-rivne-ukraine.pdf
Lebed, O. O., & Myslinchuk, V. O. (2017). Determination of the bulk activity of radon in the air of the semi-basements of Rivne city. Actual problems of fundamental sciences: materials of the II International scientific conference, Lutsk: PF "Vezha-Druk", 63-65. [in Ukrainian].
Lebed, O. O., Myslinchuk, V. O., & Andreev, O. A. (2017). Radon: monitoring and geoecological analysis of its impact on the ecosystem of Rivne city. Monograph. Rivne, 208 p. [in Ukrainian].
Lebed, O. O., Myslinchuk, V. O., & Kochergina, O. D. (2016). Dynamics of arrival of Radon-222 in living quarters. Materials of the International Internet Conference of Young Scientists and Students "Actual Problems of Fundamental and Applied Research", Lutsk, P. 56-57. [in Ukrainian].
Lebed, O. O., Myslinchuk, V. O., Trusheva, S. S., Mandyhra, Y. M., & Lysytsya, A. V. (2018). Radon in the spring water of the Zdolbuniv Region, Ukraine. Ukrainian Journal of Ecology, 8(3), 82-89. Available at: https://www.ujecology.com/articles/radon-in-the-spring-water-of-the-zdolbuniv-region-ukraine.pdf
Lebed, O. O., Pryshchepa, A. M., Klymenko, O. M., & Kovalchuk, N. S. (2018). Determination of oncological disease risks caused by radon in urban ecosystems of Rivne. Ukrainian Journal of Ecology, 8(4), 175-182.
Lebed, O. O., Trusheva, S. S., & Lysytsya, A. V. (2019). Impact of radon exposure upon dynamics of mortality rate from lung cancer for population of Rivne city, Ukraine. Ukrainian Journal of Ecology, 9(1), 25-34. Available at: https://www.ujecology.com/articles/impact-of-radon-exposure-upon-dynamics-of-mortality-rate-from-lung-cancer-for-population-of-rivne-city-ukraine.pdf
Mazur, J., & Kozak, K. (2014). Complementary system for long term measurements of radon exhalation rate from soil. Review of Scientific Instruments. 85(2), No.022104. doi: 10.1063/1.4865156
Mullerova, M., Holy, K., Blahusiak, P., & Bulko, M. (2018). Study of radon exhalation from the soil. Journal of Radioanalytical and Nuclear Chemistry, 315(2), 237-241. doi: 10.1007/s10967-017-5657-4
Radiation control of building materials and construction objects (DBN B.1.4-2.01-97). Approved by the Order № 124 of the State Committee for the Construction of Ukraine from July 24, 1997, and entered into force on January 1, 1998 [in Ukrainian].
Radiation Safety Standards of Ukraine; addition: "Radiation protection from sources of potential radiation" ("NRBU-97 / D-2000"). Approved by the decision No 116 of the Chief State Sanitary Doctor of Ukraine on July 12, 2000 [in Ukrainian].
Regulated Radiation Parameters. Let's have a level. (DBN B.1.4-1.01-97). Approved by the Order № 124 of the State Committee for the Construction of Ukraine from July 24, 1997, and entered into force on January 1, 1998 [in Ukrainian].
Svetovidov, A. V., Venkov, V. A., & Gorsky, G. A. (2009). Experience in carrying out radon-protective measures in buildings in operation. Radiation Hygiene, 2 (4), 35-39 [in Russian].
System of norms and rules of reducing the level of ionizing radiation of natural radionuclides in construction (DBN B.1.4-1.03-97). Approved by Order No 124 of the State Committee for Ukraine on July 24, 1997 and introduced in operation since January 1, 1998 [in Ukrainian].
United States Environmental Protection Agency (1991). Office of Radiation Programs, National residential radon survey, statistical analysis, National and regional estimates. Vol. 1. Washington, DC: US Environmental Protection Agency.
Vasiliev, A. V., Yarmoshenko, I. V., & Zhukovsky, M. V. (2018). Radon safety of modern multi-storey buildings of various energy efficiency classes. Radiation hygiene, 11(1), 80-84. doi: 10.21514/1998-426X-2018-11-1-80-84 [in Russian].
Yarmoshenko, I. V., Onishchenko, A. D., & Zhukovsky, M. V. (2014). Problems of optimization of radon protection and the introduction of the reference level in the Russian Federation. Radiation hygiene, 7 (4), 67-70 [in Russian].
Zeeb, H., & Shannoun, F. (2009). WHO handbook on indoor radon: a public health perspective. Geneva: WHO.

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