

RADON HAZARD IN PERMAFROST CONDITIONS: CURRENT STATE OF RESEARCH

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ABSTRACT. In this paper, we review both practical and theoretical assessments for evaluating radon geohazards from permafrost landforms in northern environments (>60° N). Here, we show that polar amplification (i.e. climate change) leads to the development of thawing permafrost, ground subsidence, and thawed conduits (i.e. Taliks), which allow radon migration from the subsurface to near surface environment. Based on these survey results, we conjecture that abruptly thawing permafrost soils will allow radon migration to the near surface, and likely impacting human settlements located here. We analyze potential geohazards associated with elevated ground concentrations of natural radionuclides. From these results, we apply the main existing legislation governing the control of radon parameters in the design, construction and use of buildings, as well as existing technologies for assessing the radon hazard. We found that at present, these laws do not consider our findings, namely, that increasing supply of radon to the surface during thawing of permafrost will enhance radon exposure, thereby, changing prior assumptions from which the initial legislation was determined. Hence, the legislation will likely need to respond and reconsider risk assessments of public health in relation to radon exposure. We discuss the prospects for developing radon geohazard monitoring, methodical approaches, and share recommendations based on the current state of research in permafrost effected environments.

KEYWORDS: Radon hazard, radiation safety, permafrost, Arctic, climate warming, radon-hazardous territory, natural radioactivity, uranium ore, legislation, measurement method

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INTRODUCTION

At present, the problem of rapid warming in northern latitudes (>60° N) is quite acute, particularly for landscape changes, vegetation productivity, and ground subsidence or thawing of permafrost soils. Such changes lead to consequences for the population, infrastructure and the ecosystem as a whole (Zolkos et al. 2021). At the same time, the fact remains undeniable that climate warming trends over the past hundreds of years will continue in the future in accordance with the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014).

Recently, the most important indicator of global climate change was the phenomenon of permafrost degradation, which in turn causes the release of various substances into the atmosphere, for example, stored organic carbon. (Obu et al. 2019; Biscaborn et al. 2019). Permafrost is a key element of the cryosphere (Obu et al. 2019), occupying a significant part of the land and sea of the northern hemisphere (Brown et al. 1997; Rachold et al. 2007), and 17% of the Earth's land surface (Biscaborn et al. 2019). Recent studies indicate that the permafrost boundary is gradually shifting from south to north, and its depth is progressively increasing (Zhang et al. 2021). The indicators of such a phenomenon as the

degradation of permafrost are craters in Yamal (Buldovicz et al. 2018), man-made incidents (Norilsk) (Koptev, 2020), and changes in landform (Ji et al. 2019; Doloisio et al. 2020). Every year, new scientific studies enhance the concern of permafrost degradation across northern latitudes (Liu et al. 2021; Vaisanen et al. 2020; Heslop et al. 2019). One promising area of development is the assessment of radiation safety in conditions of thawing of soils, bedding of rocks with an increased content of radium-226, and subsequent release of radioactive radon gas to the near surface, but remains poorly understood (Glover 2006; Glover 2007).

The aim of this scientific work is to show the relevance and importance of a comprehensive study of the effect of thawing of permafrost on the radiation safety of the territory from the point of view of the radon hazard, as well as the need to take this predictor into account in the normative assessment of the potential radon hazard parameter. We find the lack of scientific literature in this area indicates a knowledge gap, if we are to safeguard public health in response to polar amplification, and its consequences, as mentioned. We discuss here the field studies of two parameters: the concentration of radon and pathway mechanisms involving permafrost thaw.

Our study examines four areas of inquiry (1-4):

(1) we show how radon is distributed in the conditions of the spread of permafrost soils, as well as their degradation due to progressive climate change.

(2) we identify territories where complex factors are widespread, for example, the presence of soils and rocks with an increased content of radium-226, as well as the population factor of the territory living on these permafrost landforms; the latter factor plays an important role, because if the major hypothesis of increased radon production developing from conditions of permafrost degradation is confirmed, this will ultimately lead to the re-evaluating methods for monitoring the potential radon effects on the public health of populated areas living near such geohazards.

(3) we apply the current legislation regarding the environmental radiation safety or standards in response to natural sources of ionizing radiation, in order to understand the need for further clarification and adjustment of the norms for the control of the potential radon hazard.

(4) Finally, it is important to study the recent developments, methods, and technologies for assessing the potential radon hazards, which are currently available; the parameters or predictors we must consider for effective public safety measures and the remaining hidden variables, which are poorly understood in this context.

PERMAFROST AS A BARRIER TO RADIOACTIVE RADON GAS

Radon is a member of the radioactive chain of uranium-238 and is continuously formed in all natural environments during the radioactive decay of its parent isotope, radium-226, which has a half-life of about 1600 years (Sabbarese et al. 2021; Giustini et al. 2019; Miklyaev et al. 2010; Baskaran et al. 2016; Daraktchieva et al. 2021). Due to its physical and chemical properties, as well as being an inert gas with a relatively long half-life (3.82 days), it is an optimal indicator for studying many processes occurring in the environment (Loisy et al. 2012, Kuo et al. 2014, Baskaran et al. 2016, Selvam et al. 2021), including in geological research, for example, for predicting seismic phenomena and other geodynamic processes (Sahoo et al. 2020; Kawabata et al. 2020). Free radon exhibits the ability to easily migrate in the geological environment in the gas phase or dissolved in pore waters. This is especially true

when the geological system is open or has conduits, for example, pores, cracks, and faults (e.g. Taliks) (Miklyaev et al. 2010; Moreno et al. 2018; Tsapalov et al. 2016; Yang et al. 2018). The process of release of radon-222 from solids to the surface (into the external space or into the open pore space) is called radon emanation, the quantitative characteristics of which are the intensity of emanation, emanation ability and the coefficient of emanation (Miklyaev et al. 2010; Nuccetelli et al. 2020; Domingos et al. 2018; Pinto et al. 2020).

The behavior of free radon can depend on a high degree of influencing factors, starting with climatic parameters (temperature, humidity, pressure) and physical parameters of the geological environment (for example, gas permeability of rocks, soils, porosity, density), as well as mineralogical composition and complex geochemical processes and relationships, on which the existence of both the parent radionuclide radium-226 and its daughter radionuclide, radon-222, depends (IAEA 2013; Krupp et al. 2017). Some authors (Banerjee et al. 2011; Pereira et al. 2017; Li et al. 2018; Coletti et al. 2020) indicate the importance of considering the parameters of porosity and density of the rock, which in turn depend on the temperature processes occurring after magmatic crystallization. Radon formed in a solid can enter the surrounding space both due to radioactive recoil and due to diffusion (Titaeva, 2000). In the case of radioactive recoil, the radon atoms formed during the radioactive decay of radium-226 acquire a certain recoil energy, which they subsequently lose while transporting. Part of the atoms remaining in the solid phase that make up bound radon. But the recoil energy of about 86 keV is quite enough for some of the atoms to be released outside the solid, forming free radon (IAEA 2013; Thu et al. 2020). Considering the above, there are three scenarios for the behavior of the radon atom after its formation as a result of the decay of the radium-226 atom. In the first case, the radon-222 atom remains in the solid phase. In the second case, the recoil energy is enough to overcome the boundaries of one grain of solid matter, to pass through the pore space, but to be included in the composition of another grain of solid matter. In the third case, the radon atom remains in the pore space and enters the environment, which in turn constitutes the process of radon emanation (Hassan et al. 2009; Eakin et al. 2016; Thu et al. 2020).

In order to understand the behavior of radon, scientists have developed and supplemented the previously existing models of radon transport in solid media. There are three groups of radon transport models: (1) diffusion (Telford et al. 1983; Pavlov et al. 1996; Minkin et al. 2002, 2003; Klimshin et al. 2010; Livshits et al. 2017); (2) convective (Rogers et al. 1991; Arvela et al. 1995) and diffusion-convective; and (3) diffusion-advective (Al-Ahmady et al. 1994). However, the latest results of mathematical calculations obtained from convective and diffusion-convective models have shown poor correlation with experimental data, since the calculated versions of the models are usually very simplified, and most of them require very specific input parameters, which in some cases unrealistic for determining in-situ (Bakaeva et al. 2016). The group (1-2) of diffusion models showed cogent results in convergence with experimental data, and at the moment the diffusion mechanism is considered to be the main one for the radon transfer process (Minkin et al. 2008, Livshchits et al. 2017). In the context of permafrost thawing and the dependence of radon flux on seasonal variations, the prior work of thermo diffusion model (Minkin et al. 2003) seems to be of interest here, where radon transfer in the absence of a

pressure difference occurs at a temperature gradient and therefore, during the mass transfer equation, where the radon flux includes two components:

(1) thermal diffusion radon flux and (2) flux concentration diffusion. Later, this theory was refined by the authors themselves, based on the already known temperature fluctuations in soils (Minkin et al. 2016; Shapovalov et al. 2016). Livshchits et al. 2017 also calculate radon transport using a diffusion model, but considers thermal diffusion in the form of an «equivalent» diffusion coefficient.

In fractured and fractured-porous geological areas, fracture geometry plays an important role in the study of radon flux. For such environments, among others, discrete fracture network (DFN) models have been created, which is generally considered one of the most effective methods for predicting the flow of fluids such as groundwater, carbon-dioxide, oil and natural gas (Blonsky et al. 2017). In the case of fractured porous media, a tetrahedral mesh is used for their geometric description. Tetrahedrons describe a porous matrix, while tetrahedron faces describe cracks. In the case of purely fractured media, the fractures are described by a two-dimensional triangular mesh matched at the intersection lines of the fractures. In this case, the gas flow is described as the sum of diffusion and advective flows. However, such a description of media does not consider the anisotropy, which is quite costly in terms of the required computational resources needed for modeling. In recent work (Feng et al. 2020), the author proposed to use fractals to describe the geometry of coupled fractures in the DFN model, which makes it possible to take into account the fractured anisotropy and optimizes the numerical calculation algorithm by presenting equations for the fracture network in matrix form.

Moving from the physical processes of radon transfer to the issue of the effect of permafrost on radon, it should be noted that as early as 1990, work was carried out to assess the distribution of permafrost based on the results of measuring the radon concentration as a tracer (Sellmann et al. 1990). Results showed that the radon concentration correlates well with frozen areas under conditions of permafrost cover. Low values of radon concentration were found where the permafrost thickness is high. And high values of radon concentration were found where there is a weak level of permafrost (or there is no permafrost at all). The authors concluded that permafrost has a significant impact on the dynamics of radon distribution. At the same time, it was not concluded that an increase in the amount of radon occurs at a higher level of thawing of frozen soils due to the release of radium-226 and radon from ice crystals. That is, the permafrost layer, on the one hand, retains radioactive substances, and on the other hand, it is an excellent barrier for mobile forms of radionuclides.

The need to consider permafrost factors when assessing the distribution of radon was first indicated by prior work (Evangelista et al. 2002) and conducted studies of the radon exhalation rate on King George Island and the Antarctic Peninsula. They assumed that surface ice and permafrost largely screen the radon flux to the Earth's surface.

Some theoretical studies in the field of assessing radon distribution under permafrost thawing conditions were started in 2006–2008 (Glover 2006; Glover 2007). The authors developed models showing the fact of an increase in the supply of radon to the surface, including buildings, in the process of permafrost degradation. They showed that with an average world content of radium-226 in soil with concentration of 40 Becquerels per kilogram ($\text{Bq}\cdot\text{kg}^{-1}$), a permafrost layer of 13 m can lead to a decrease in the

radon concentration in a building to 5–10 Becquerels per cubic metre ($\text{Bq}\cdot\text{m}^{-3}$) (model of an unventilated room). However, as a result of melting permafrost, the level of radon concentration can increase up to 100 times ($1000\text{--}1500 \text{ Bq}\cdot\text{m}^{-3}$). According to the model constructed by the authors, this level can persist for several years and then gradually decrease. The authors believe this fact is extremely relevant considering the control level of $100\text{--}300 \text{ Bq}\cdot\text{m}^{-3}$ (for different countries), as well as considering the extremely negative effect of radon on the incidence of cancer.

It is noted that the values of the radon concentration were obtained under the condition of the radium-226 content in the soil at a level of $40 \text{ Bq}\cdot\text{kg}^{-1}$. In the world as a whole, there are many territories having increased content of radium-226 in soils, rocks, but particularly interesting in the presence of permafrost up to 1500 m in layer thickness, and where human settlements and/or infrastructure exist. Some Russian scientists (Klimshin et al. 2010) have made conclusions about the significant effect of the level of seasonal soil freezing (up to 1 m) in winter on radon emanation to the earth's surface. Based on these results, appropriate guidelines were developed with criteria for assessing the potential radon hazard, considering the level of soil freezing. Recently, it was found by (Chuvilin et al. 2018) by experimental methods, soil freezing significantly affects gas permeability, depending on the initial value of moisture content. The authors investigated sand types and sandy-clay mixture mediums. For most sand samples with an initial moisture content of about 10%, permeability in thawed and frozen states differed within 1.5–4 times, whereas samples represented by silty sand, gas permeability in thawed and frozen states differed by more than 10 times.

As part of a series of international expeditions TROICA (Transcontinental Observations into the Chemistry of the Atmosphere), passing along the Trans-Siberian Railway from 1999 to 2007, an analysis of spatial and temporal variations in the concentration of radon-222 in the surface layer of the atmosphere over the continental part of Russia was carried out. Scientists (Berezina et al. 2009; Berezina 2014) noted a significant increase in the surface concentration of radioactive gas (approximately 3 times) with an increase in the depth of seasonal soil thawing from summer 1999 to autumn 2005 in the permafrost zone in the Eastern Siberia region Russia due to the intensive migration of radon-222, accumulated in frozen soils, into the near-surface layer of the soil and its subsequent exhalation into the atmosphere. All the above facts about climate warming, melting of permafrost and its barrier function for the entry of gases to the surface, an increase in the radon concentration during thawing of frozen soils, were based on a few studies, as well as the fact that radon has an extremely negative effect on human health from the point of view of oncology. This indicates the relevance and need for fundamental research in potentially hazardous areas and from the point of view of radiation safety or public health assessment but remains poorly understood. In such case of confirmation, a significant increase in the flow of radon to the earth's surface during thawing of frozen soils, it will then be necessary to recognize that permafrost is one of the predictors (indicators) that characterizes the territory in terms of potential radon hazard. Under such context and conclusions, this warrants further development of the regulatory legal framework in terms of radiation safety and radiation control when planning the construction of residential and industrial buildings, as well as their operation, and the methodology for assessing the potential radon hazard of the Arctic territories. It then become

necessary to consider certain geological parameters of the spread of permafrost (power, rate of degradation, etc.), which we will now consider.

DYNAMIC GEOHAZARDS: PARAMETERS OF RADON IN PERMAFROST LANDFORMS

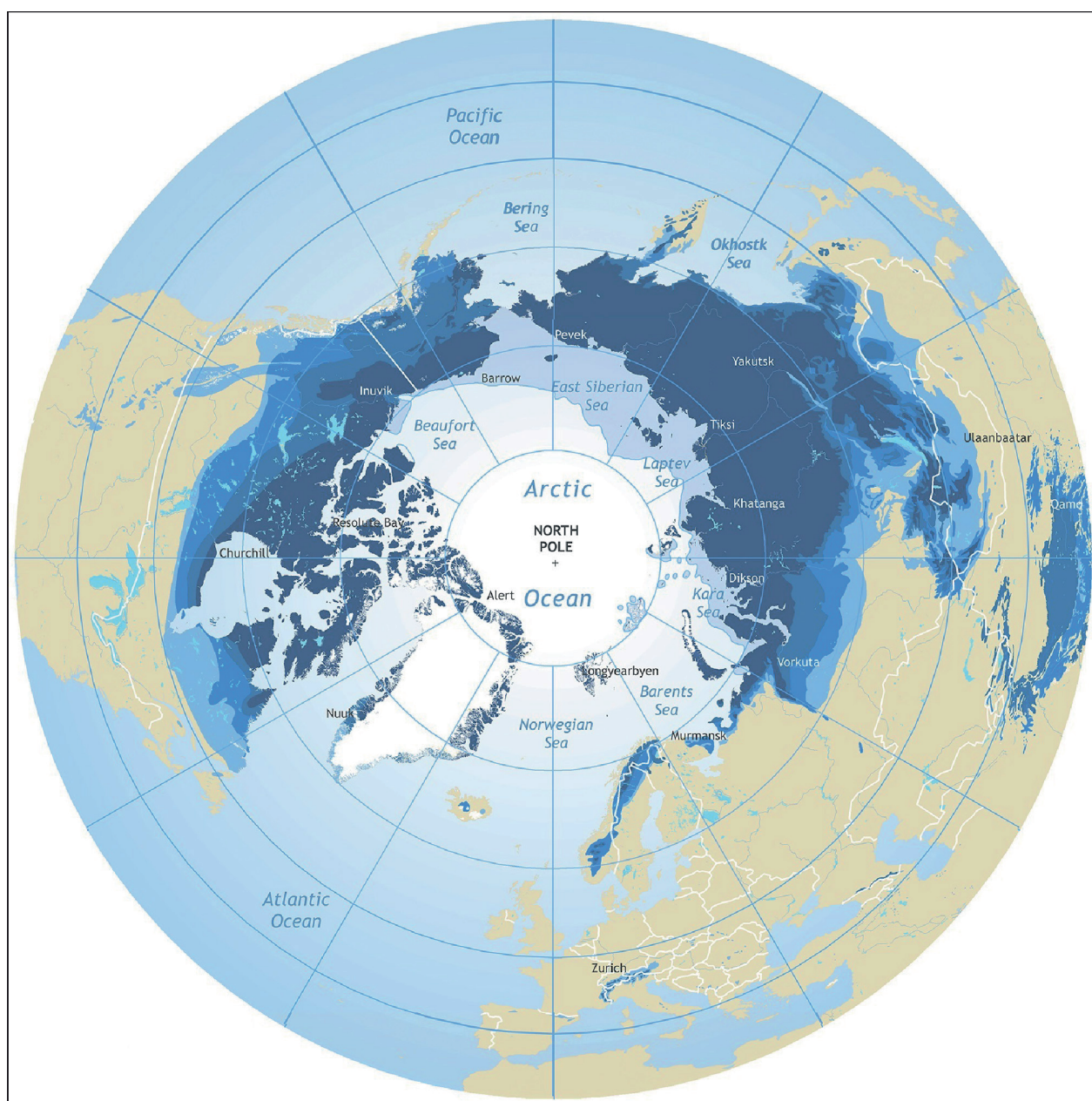
In order to understand the need and relevance of research on the subject of radon hazard of territories in the conditions of thawing permafrost, it is necessary to identify the territories in which the increased content of radioactive elements and the spread of permafrost are most pronounced, as well as characterized by the presence of settlements.

Figure 1 shows the distribution of permafrost over the earth's surface, which covers ~24% of the Northern Hemisphere surface area. The territories covered by

permafrost are represented by such countries/areas as the United States (Alaska), Canada, Scandinavia (e.g. Sweden) and Russia. Permafrost covers to a lesser area Mongolia, Greenland (Denmark), and Alpine regions.

Due to the fact that radon is a decay product in the uranium-238 chain (Baskaran et al. 2016), we will focus on uranium-containing ore fields to identify promising territories. From this point of view, two countries remain interesting for study: Russia and Canada.

On the territory of Russia, within the permafrost distribution, the following uranium-bearing ore fields can be distinguished: Polar-Ural field; Taimyr field; Chukchi field; Anabar field; Sayano-Yenisei field; North Baikal field; Vitimskoye deposit; East Transbaikalian field; Streltsovskoye deposit; Elkon field; East Aldan field. Figure 3 shows a diagram of the location of the main



Permafrost in the Northern hemisphere

Durability

Continuous permafrost

Discontinuous permafrost

Sporadic permafrost

Isolated patches

Subsea permafrost

© International Permafrost Association

Fig. 1. Distribution of permafrost on the earth's surface in the Northern Hemisphere
(based on materials from <https://www.eea.europa.eu>. Copyright holder: European Environment Agency (EEA))

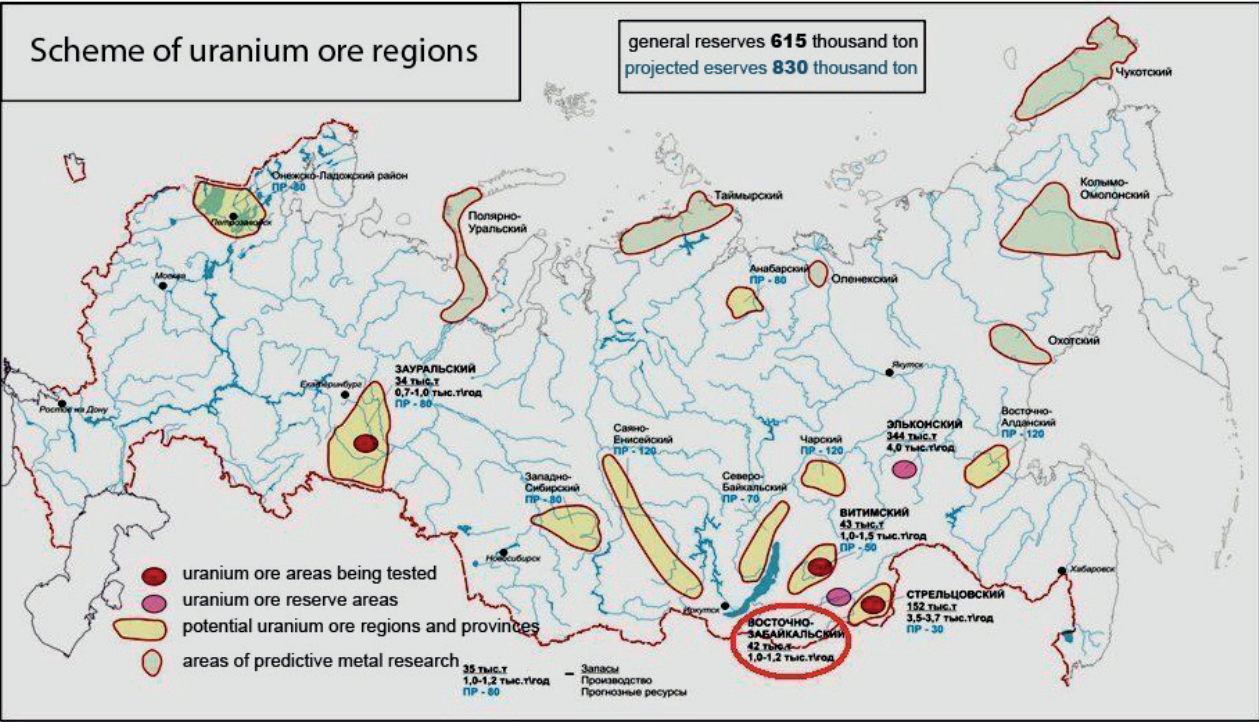


Fig. 2. The diagram of the location of the main uranium-containing regions of Russia (based on materials from <https://promtu.ru/dobyicha-resursov/dobyicha-urana-v-rossii-i-mire>)

uranium-containing regions of Russia (<https://promtu.ru/dobyicha-resursov/dobyicha-urana-v-rossii-i-mire>).

Ores vary in uranium content in the territory. Moreover, the distribution of uranium in the ore is described not by the normal (Gaussian) rule, but as logarithmic one, i.e. very rich ores are possible, but they are extremely rare. Uranium does not occur naturally as a native element. This is due to the fact that uranium can be in several stages of oxidation, it occurs in a very diverse geological setting (Nizinski et al. 2020).

From the ore fields presented above, two of the most interesting regions were identified, which are located on the territory of permafrost, near settlements and within the seismically active zone: the Polar-Ural field and the Republic of Buryatia, which includes the Severo-Baikalskoe field, Vitimskoe deposit, Streltsovskoe deposit and the Khiagda ore field. The Polar-Ural field is located within the Russian Arctic. These facts are confirmed by the information presented in Figures 3, 4. Buryatia especially stands out given the presence of permafrost, a seismically active zone and an increased dose of radon exposure.

From a historical perspective on the area, it should be noted that in 1960, large scale geological surveys were conducted within the Polar Urals, discovering the Kharbeysky molybdenite deposit and Novo-Kharbeysky uranium ore occurrence. These discoveries served as one of the initial beginnings of prospecting work in the northern Urals or

Study Area: Northern Regions of Russia & Permafrost Extent

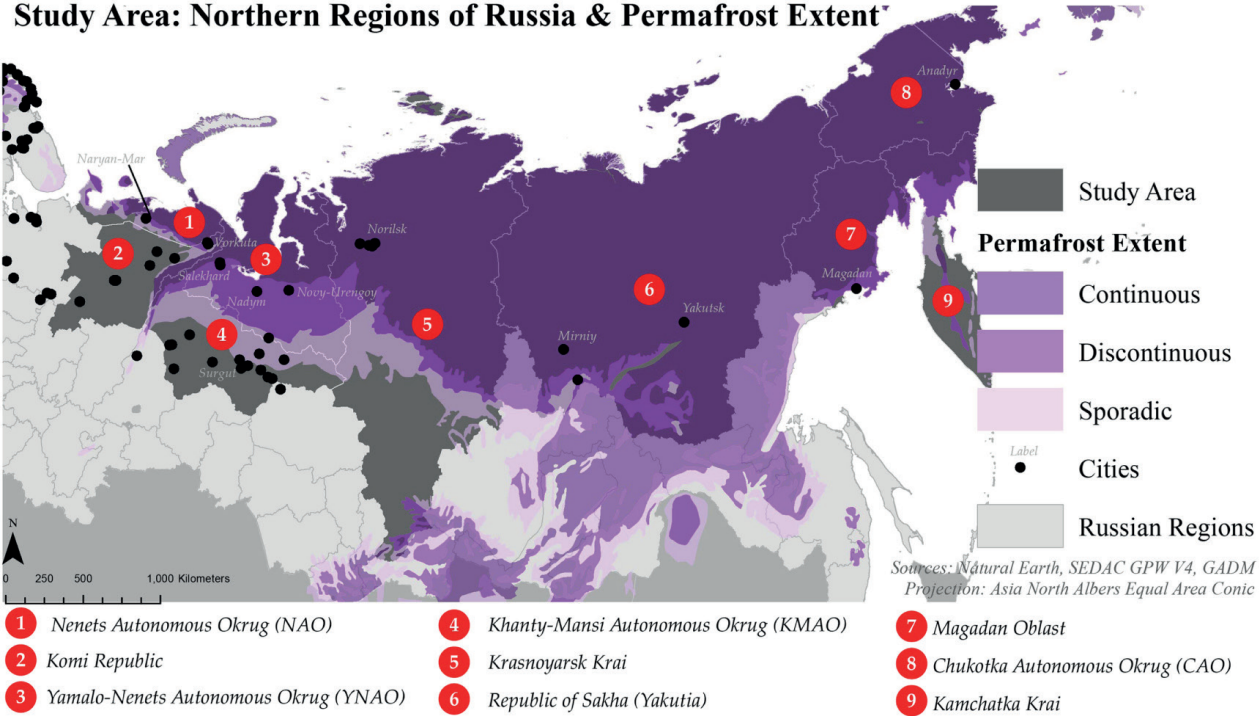


Fig. 3. Permafrost distribution and administrative division of Russia. The boundaries of nine administrative regions considered in this study are shown in gray. Location of major cities is shown with black circles (Streletskiy et al. 2019)

Average radiation doses from radon, mSv / year

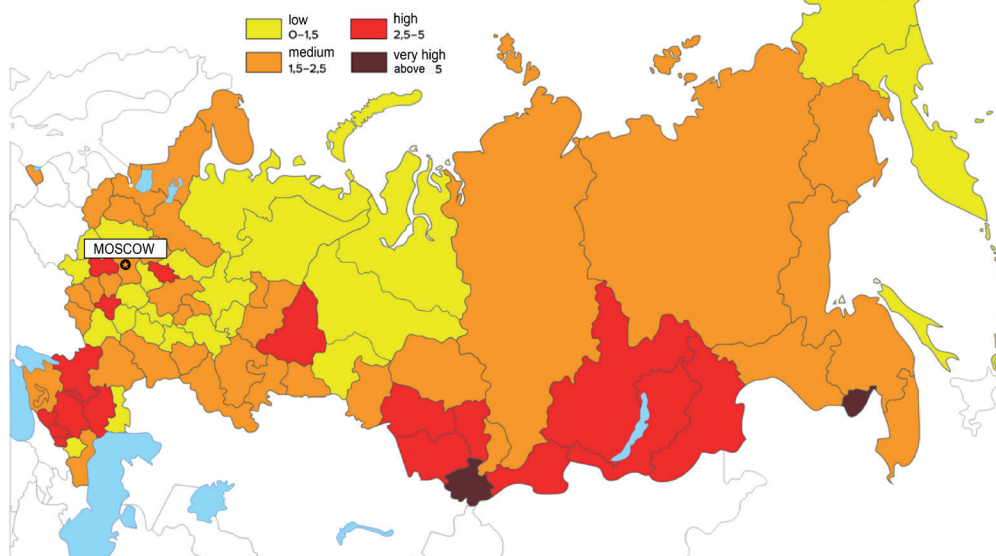


Fig. 4. Average radiation doses from radon in Russia (based on materials from <https://eksorb.com/radon>)

polar and sub-polar division. Here, between 1961 and 1965, Uranium-bearing ores were discovered (Verkhovtsev 2000).

A more detailed study in this area, discovered clastic diorites on the surface with the dose rate of gamma radiation reaching $612 \mu\text{R}\cdot\text{h}^{-1}$. The radioactivity was sourced in shallow deposition of a radioactive minerals from the near surface. Later, geophysicists during search routes on the southern slope of the mountain discovered a bedrock outcrop of dark gray chloritized rocks with resinous mineralization 0.7 m thick, having a gamma dose rate of over $7500 \mu\text{R}\cdot\text{h}^{-1}$ (Dushin et al. 1997).

As for the Republic of Buryatia, the unique position of the territory in the Trans-Baikal radio-geochemical province of the Sayano-Baikal folded seismically active region with a significant number of natural radioactive objects (deposits, ore occurrences and radioactive anomalies) and associated high levels of radiation background in terms of the exposure dose

rate of gamma radiation and radon allow us to objectively classify the territory of the Republic of Buryatia as a province of radiation distress, high radon risk with very high radon concentrations in the geological environment (rocks, faults, water and soil) and in residential buildings. It is necessary to conduct extensive radon metric studies in the geological environment, as well as studies of the air environment within the permafrost in order to identify risk groups of the population in accordance with dose loads due to radon (Astakhov et al. 2015), as well as to form predictive estimates for the development of radioecological situation in the region.

Canada is a good example of an area outside of Russia characterized by both permafrost and rock outcrops with increased levels of naturally occurring radionuclides. Canada is a vast country with most of the population living on a small portion of the land. But despite this, control over the radon hazard is carried out throughout the country as a whole (Chen

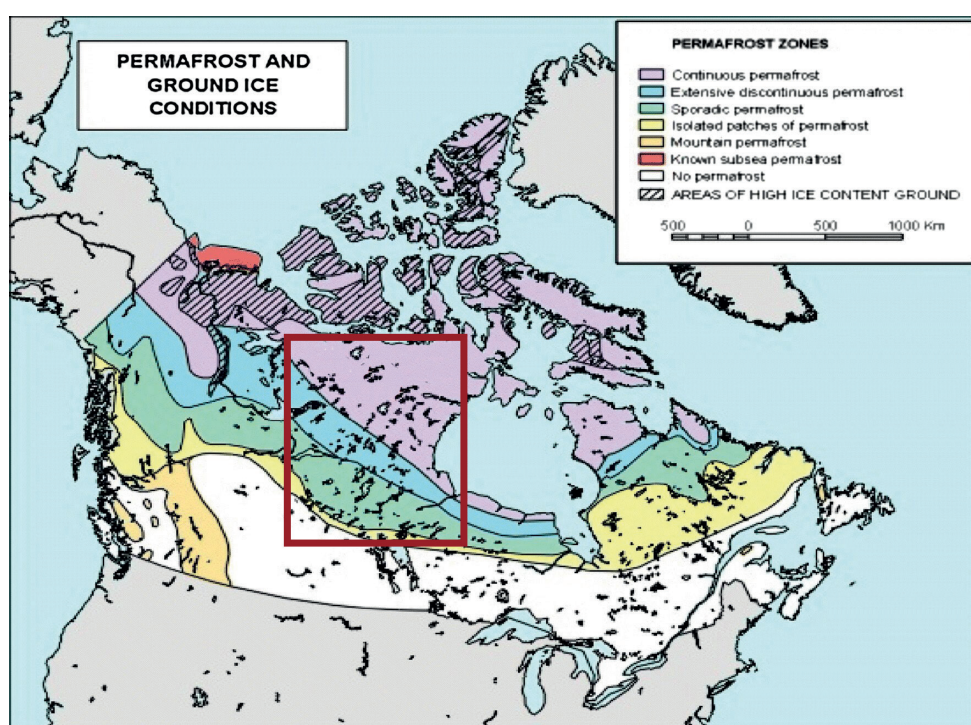


Fig. 5. Uranium-bearing ore field in Canada – northern part of Saskatchewan (based on materials from <http://gsc.nrcan.gc.ca>)

2009). One province are especially interesting in terms of potential radon hazard – the northern part of Saskatchewan shown in Fig. 5. This province is covered (from north to south) with continuous to discontinuous permafrost and also characterized by seismic hazard zones (Leonard et al. 2010; Chi et al. 2018).

The uranium ore deposits in this area are located on the Canadian Shield (Chi et al. 2018). They are associated with Precambrian quartz conglomerates containing brannerite, uraninite, and uranium-rich monzonite, with veins containing uranium tar, and pegmatite facies of syenite and granite with uraninite and uranotorite (Chi et al. 2018). The main deposits of uranium are known in the Elliot Lake (Blind River) area (Clulow et al. 1998). Deposits of the second type, initially mined for radium, are known in the structural provinces of Ber (the eastern coast of Lake Bolshoye Medvezhye and southeast of it) and Churchill (the northern coast of Lake Athabasca and areas southeast of Lake Slavolnichye) (Bridge et al. 2009); the main deposits are in the regions of Port Radium (Great Bear Lake) and Uranium City (Lake Athabasca) (<http://nuclearsafety.gc.ca/>).

The above facts indicate the presence of large territories in the world (mainly Russia, Canada and, probably, the United States (Alaska)) on which a combination of three factors is revealed: permafrost, uranium-containing ores, and human settlement or temporary residence of people in such territories. This conclusion indicates the need for research in the field of radon distribution in certain areas as mentioned. At the moment, we are working on a program for conducting scientific research in the territories of Russia (the Republic of Buryatia, the Nenets Autonomous Okrug) and the USA (Interior Alaska), landforms of which covered by permafrost.

LEGISLATIVE REGULATION AND ASSESSMENT POTENTIAL RADON HAZARD

Much attention is directed to the problem of radon hazard in aforementioned ecosystems. In 2009, UNSCEAR, based on a detailed scientific assessment of epidemiological data, made a statement at the UN General Assembly that there is direct evidence to support a detectable risk of lung cancer for the population from radon in dwellings. The statement concluding that there is no effective lower threshold of radon concentration, below which radon exposure poses no danger. Strong scientific evidence demonstrates that radon-induced lung cancer is a significant public health risk, with children at greater risk than adults (as is often the case with exposure to toxic substances/radiation) (Radon indoor air, Canada 2014). The presence of a carcinogenic effect was noted, particularly when such exposure to radon levels of concentration for dwellings exceeding 50–100 Bq·m⁻³. Most radon-induced lung cancers are due to low to moderate levels of radon concentration rather than high levels, because fewer people are generally exposed to high radon concentrations. Therefore, continuous low doses pose the major risk (UNSCEAR 2019).

Back in 2009, the World Health Organization published the book «WHO handbook on indoor radon: A public health perspective», where recommendations established a number of rules to reduce the level of radon hazard in rooms, for example, setting a control level for the radon concentration in buildings of no more than 100 Bq·m⁻³; the introduction of preventive measures to reduce the level of radon in the design and construction of buildings and structures; the improvement of technologies for monitoring the level of radon both in the territories and in buildings were recommended (World Health Organization, 2009).

The European directive (Council Directive 2013) establishes basic safety standards to protect various categories of the population and personnel from the dangers associated with human exposure to ionizing radiation. In this document, including the main categories of the population and personnel, reference levels of the radon concentration is again established at 100 Bq·m⁻³. If it is impossible to reach this level and in excess of 300 Bq·m⁻³, it is necessary to take measures for radon protection of the population and personnel. This document is distinguished by the involvement of a wide range of categories of the population and personnel in the process of standardizing the characteristics of ionizing radiation: children, students, pregnant women, adults, workers, etc.

Longstanding recognition of radon as a public health concern has been established internationally. For example, in Canada, this has led to the establishment of guideline norms for indoor air concentrations of radon, recommending no greater level of 200 Bq·m⁻³, established by Health Canada. This is 4-fold lower than a previous guideline reference level of 800 Bq·m⁻³, but still higher than the guidelines set by the World Health Organization (100 Bq·m⁻³) and in the United States (4 pCi·L⁻¹, equivalent to about 148 Bq·m⁻³) (Radon indoor air, Canada 2014). Health Canada's surveys of indoor radon levels in federally owned or operated buildings and of private homes across Canada indicate certain geographic areas in Canada of particular concern (parts of Manitoba, New Brunswick, Saskatchewan, and the Yukon), but also that high radon levels may be present anywhere and therefore that all buildings should be tested (Radon indoor air, Canada 2014).

ICRP publication 103 considers radon exposure in the context of the existing exposure situation. The introduction of a new concept of radiation protection in situations of existing exposure served as the basis for a modern strategy for the implementation of national programs to protect the population from radon. The current vision for solving the radon problem is to consider two related problems. The first is aimed at reducing the number of people exposed to unacceptably high individual risks associated with radon, the second is aimed at reducing the average value of individual radon risk for the entire population of the country. The systematic solution of both problems, calculated for the long-term perspective of its implementation, will allow to achieve the ultimate goal – to reduce the morbidity and mortality of the population from radon-induced lung cancers (ICRP 2007).

New recommendations from WHO, ICRP and IAEA have initiated the development of new or revision of existing radon programs in many countries. For the member states of the European Union, their development is mandatory in accordance with the approved (Council Directive 2013). According to (Marennyy et al. 2019), in world practice, the understanding that the national radon program should be carried out in the format of multi-level cooperation between organizations responsible for radiation protection and public health policy, public and private enterprises specializing in radiation measurements and engineering and construction activities by scientific organizations interested in informal and non-governmental organizations, emerging information policies in this area.

The experience of implementing a strategy for solving the radon problem, aimed at reducing individual risks from radon in existing buildings, has shown that the main difficulties in all countries are the extremely low awareness of the population about radon and its effects on the human body, as well as the lack of experience in the application of radon protection measures.

The requirements of Russian legislation are aimed at limiting the impact of ionizing radiation on humans from all types of radiation. Such requirements are reflected in the basic federal laws (Russian Federal Law N 3-FZ, 1996, Russian Federal Law N 384-FZ, 2009), as well as in the basic sanitary rules for ensuring radiation safety (NRB-99/2009, OSPORB-99/2010). In accordance with the requirements of the (NRB-99/2009), the reduction of exposure of the population is achieved by establishing a system of restrictions on exposure of the population from individual natural sources of radiation. At higher values of the radon concentration, protective measures should be taken to reduce the intake of radon into the air of buildings and improve ventilation of buildings (NRB-99/2009, OSPORB-99/2010). If it is impossible to reduce the values of one or both indicators to the standard level without violating the integrity of the building, the issue of relocation of residents and re-profiling of the building or part of the premises or the demolition of the building is considered.

To check the compliance of residential and public buildings with legal requirements at all stages of construction, reconstruction, overhaul and operation of residential and public buildings, radiation monitoring is carried out. In cases of detection of an excess of the standard values, an analysis of the reasons associated with this should be carried out and the necessary protective measures should be taken to reduce the dose rate of gamma radiation and / or the content of radon in the indoor air.

Assessment of the radiation situation at the site is part of the program of engineering and environmental surveys during construction work on the construction of residential and non-residential buildings, industrial development, linear and square structures, as well as during construction work on the dismantling of previously erected facilities.

The engineering and environmental surveys include a whole list of the main types of work, including the study and assessment of the radiation situation (SP 47.13330.2016).

In accordance with (SP 47.13330.2016), radiation and environmental studies should include an assessment of the gamma background on the construction site, determination of the radiation characteristics of water supply sources, an assessment of the radon hazard of the area. At the same time, the radon hazard of the territory is determined by the density of the radon flux from the soil surface and the radon content in the air of constructed buildings and structures. The assessment of the potential radon hazard of the territory is carried out according to a complex of geological and geophysical characteristics. Geological features include: the presence of certain petrographic types of rocks, faults, seismic activity of the territory, the presence of radon in groundwater and the outcrops of radon sources to the surface. Geophysical features include: high concentration of radium in the rocks composing the geological section; levels of radon concentration in soil air, equivalent equilibrium the radon concentration in buildings and structures operated in the study area and in the adjacent area. Therefore, at the pre-design stages, a preliminary assessment of the potential radon hazard of the territory should be carried out, and at the design stage, the radon hazard of the area is clarified and the class of the required anti-radon protection of buildings is determined.

For the implementation of engineering and environmental surveys for construction and sanitary supervision, unified approaches to the procedure for monitoring the potential radon hazard of land plots and

assessing the results of monitoring were developed (MU 2.6.1.038-2015). This document covers a significant list of geological and geophysical features that allow to reliably determine the potential radon hazard of a territory. It should be noted that, in accordance with this document, an assessment of the potential radon hazard is not carried out (not required) in areas located in the permafrost zone during construction without thawing of the base soils. However, in the calculations of the radon exhalation rate based on the results of field measurements, a soil freezing factor was introduced with a value of up to 1.7 when freezing more than 1 m, which indicates a significant screening of radon entry to the surface by frozen soils. Moreover, the guidelines indirectly take into account the sign of permafrost when assessing the radon hazard of a territory. This fact is indicated by the calculation of the radon exhalation rate based on the results of standard measurements of the characteristics of soil samples and the comparison of the calculation results with the permissible levels of the radon exhalation rate given in (NRB-99/2009, OSPORB-99/2010). But it does not take into account that the process of degradation of permafrost can lead to an increase in radon flux to the surface, which in turn can transfer the investigated area into the category of «abnormally radon hazardous area».

Thus, we wanted to show that a lot of attention is paid to the radon hazard problem in the world both at the level of research and at the level of legislative regulation. The main conclusion of the numerous documents is the fact that today scientists have studied radon production in populated areas thoroughly. However, they ignore individual territorial predictors such as permafrost. This stems from the fact that permafrost has only been extensively studied recently and does not immediately come into consideration.

EXISTING METHODS AND TECHNOLOGIES FOR ASSESSING THE POTENTIAL RADON HAZARD AND THEIR MODERNIZATION

Until now, a unified approach to the methodology for assessing the radon hazard of sites planned for development has not been developed (Ryzhakova et al. 2018), including due to a large number of factors affecting the formation of the radon field of the territory. We conducted a patent search for existing technologies and methods for assessing the radon hazard. In this section, we will describe some of these methods, which most fully take into account various indicators when assessing the potential for radon hazard.

European scientists are faced with a number of difficulties when using individual physical quantities as criteria for the radon hazard, on the basis of which the radon potential or radon index is calculated (Ryzhakova et al. 2018; Ciotoli 2017). For example, in the Czech Republic and Germany, a complex of two parameters is widely used – the gas permeability of the soil and the radon concentration in the subsoil air, with further calculation of the quantitative indicator – the radon potential (Neznal 2004). This method for assessing the radon hazard is based on measuring the radon concentration at a depth of 0.8 m after a short air sampling using a special rod with a syringe. In parallel with the radon concentration at the same depth, the gas permeability parameter is determined using the Radon-Jok installation. Further, using the classification table, the category of the radon index is determined – low, medium or high level of radon hazard.

A known method for assessing the radon hazard of building sites (Kropat et al. 2016) is a complicated process that includes several steps such as:

(1) Measuring the dose of gamma radiation at a height of 1 m from the earth's surface;

(2) Measuring the gas permeability of soils at depths from 0.8 m to 1 m using a device Radon-Jok;

(3) Studying the geological structure of the overburden based on regional databases to: a) identify geologically homogeneous units; b) determine the density of fault lines.

(4) Processing by means of logistic regression data on: a) types of geologically homogeneous units; (b) doses of gamma radiation; (c) gas permeability of soils and density of fault lines.

Russian scientists (Ryzhakova et al. 2018) have recently developed and patented a method for assessing the risk of radon, which entails choosing control points at the bottom of the foundation of a building under construction at the bottom of the excavation located at a distance of 10 m from each other. At the control points, the top layer with a thickness of 3 cm to 5 cm is removed, and the surface is carefully leveled out. A storage chamber with carbon adsorbers is installed at each point to accumulate radon for 1 hour, and the radon exhalation rate is determined by the beta radiation of short-lived daughter products of radon decay ^{214}Pb and ^{214}Bi . If the average value of the radon exhalation rate exceeds $80 \text{ mBq} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, then the territory is considered radon-hazardous, and if it is less than $80 \text{ mBq} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, then the territory is radon-safe.

The most detailed and comprehensive method for assessing the radon hazard of a territory is the radon exhalation rate method described in detail in (MR 2.6.1.038-2015 «Assessment of the potential radon danger of land plots for construction of residential, public and industrial buildings»). These guidelines cover a significant list of geological and geophysical signs (predictors) that allow to reliably determine the potential radon hazard of a territory. Among other things, the document contains recommendations for taking into account the level of soil freezing, which is significant in the context of the influence of the northern climate and the geographical location of the northern countries. It should be noted that in other countries except Russia, when assessing the potential radon hazard of a territory, this factor is not taken into account.

All of the above methods and technologies take into account a variety of factors and predictors of potential radon hazard, but the phenomenon of permafrost remains ignored. Only one document (MR 2.6.1.038-2015) takes into account the factor of seasonal soil freezing. But in our opinion, this factor has one negative feature. After the completion of the construction of the building, the factor of soil freezing will be absent due to the warming effect of the foundation. On the other hand, permafrost will remain. And despite the technologies that allow not to disturb this geological environment, climate warming will lead to thawing of permafrost and an increase in the flow of radon to the earth's surface.

In view of the above, we believe that the existing methods and technologies should be supplemented with an assessment of the level of permafrost degradation if an assessment of the potential radon hazard is carried out in such territories. To do this, we can choose ways to assess the permafrost level: electrical prospecting, the method of contactless measurement of the electric field, electromagnetic sounding, ground penetrating radar, seismic exploration, microgravimetry. Recently, the method of low-frequency electromagnetic mapping (VLF-method) seems to be of interest (Wright 1988, Oskooi and Pedersen 2006, Sundararajan et al 2007, Ramesh et al. 2007), which began to develop in Alaska from the 1970s (McNeill

1973; Hoekstra 1978). This method is also interesting for the detection of uranium ores, respectively, rocks with an increased content of natural radionuclides. In this case, the complex of methods of emanation survey, low-frequency magnetometry and, as an auxiliary, drilling and determination of the radiation and physical characteristics of the rock and soil core looks interesting. Such a set of methods will allow the most complete assessment of the potential radon hazard, taking into account all possible predictors.

CONCLUSIONS

The issue of assessing the radon hazard at the current moment in the whole world is quite deeply worked out. Organizations conducting radiation-ecological surveys have at their disposal modern instrumental and methodological complexes that take into account a significant number of factors affecting the behavior of radon in conditions of various soils.

But despite this, over time, events arise that lead to the need to adjust already created methods or develop new ones. One of such events was global warming and the associated phenomenon of melting permafrost. This process began to lead to the release of a significant amount of various kinds of substances (organic matter, methane, carbon dioxide), including radioactive ones. One of these radioactive substances was radon gas, which is still in the crystal lattice of ice, permafrost.

Perhaps in the absence of elevated radium-226 content in the soil, thawing of permafrost will not lead to a significant increase in the radon content in the near-surface soil layers, and, accordingly, in buildings. But in those territories where there are outcrops of rocks enriched in natural radionuclides, this predictor can play a significant role.

We assume that the greatest release of radon will be observed during thawing of icy dispersed sediments. The rocks with which uranium deposits are associated in most cases contain significantly less ice and their thawing is not accompanied by significant structural changes. Thus, during their thawing, the additional release of radon will be less significant. But if the rocks are covered with a layer of frozen soil, then it will be a barrier for radon. And when such a layer thaws, we will be able to observe an increased concentration of radon on the earth's surface.

The few facts and theoretical studies presented in this work on the effect of the thawing of permafrost on an increase in radon flux to the earth's surface show the relevance and need for full-fledged fundamental research work aimed at confirming the proposed theory. In addition, the fact of the increased interest of countries in the Arctic territory, its progressive development and settlement adds relevance to the conduct of such studies.

In case of a successful result of such work, it will be extremely necessary to revise the existing methods and methods for assessing the radon hazard of the Arctic territories, as well as those territories that are in the permafrost zone. Additionally, it will be extremely necessary to take into account the predictor presented in this work when correcting existing laws. Such changes in the legislation will lead to the prevention of a possible situation in the future associated with increased exposure of the population of the Arctic countries due to the natural radioactive background. ■

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