Master thesis

Comparative analysis of radon intake in residential buildings in Austria, Germany and Russia

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

Date 18.07.2023 Signature

Preface, Dedication, Acknowledgement

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Abstract

The final qualification work is presented on 70 pages, contains 30 figures, 6 tables, 54 sources of the literature.

Key words: radon; radiation; construction; radiation sources; environmental safety; air exchange; radioactive decay; ionizing radiation; α-particles.

The object of the study is low-rise house construction in the Russian Federation, Austria and Germany.

The objective of the study was to compare the characteristics of radon accumulation in low-rise buildings in the cities of Tyumen, Leoben and Schneeberg.

The indoor radon levels in low-rise residential buildings were measured in Austria, Germany and Russia, specifically in the basement, ground floor, and first floor. The results indicated that most of the houses examined exceeded the permissible limits by 1-1.5 times in Russia and 3 times in Germany. However, no exceedances were observed in low-rise houses in Austria. The causes of high radon levels in these residences are attributed to poor ventilation, low-quality floor concreting, gaps, loose joints, seams, and technological openings in basements. It is important for residents to take preventive measures such as improving ventilation and ensuring the building is airtight to prevent radon entry.

Zusammenfassung

Die abschließende Qualifikationsarbeit umfasst 70 Seiten, enthält 30 Abbildungen, 6 Tabellen und 54 Literaturquellen.

Schlüsselwörter: Radon; Strahlung; Bauwesen; Strahlungsquellen; Umweltsicherheit; Luftaustausch; radioaktiver Zerfall; ionisierende Strahlung; α-Teilchen.

Gegenstand der Studie ist der Bau von Flachbauten in der Russischen Föderation, Österreich und Deutschland.

Ziel der Studie war es, die Merkmale der Radonakkumulation in Flachbauten in den Städten Tjumen, Leoben und Schneeberg zu vergleichen.

Die Radonwerte in Innenräumen von Flachbauten wurden in Österreich, Deutschland und Russland gemessen, insbesondere im Keller, im Erdgeschoss und im ersten Stock. Die Ergebnisse zeigten, dass die meisten der untersuchten Häuser die zulässigen Grenzwerte um das 1-1,5-fache in Russland und das 3-fache in Deutschland überschritten. In Österreich wurden jedoch in niedrigen Häusern keine Überschreitungen festgestellt. Die Ursachen für die hohen Radonwerte in diesen Häusern werden auf schlechte Belüftung, minderwertige Betonböden, Lücken, lose Fugen, Nähte und technische Öffnungen in Kellern zurückgeführt. Es ist wichtig, dass die Bewohner vorbeugende Maßnahmen ergreifen, wie z. B. die Verbesserung der Belüftung und die Gewährleistung der Luftdichtheit des Gebäudes, um das Eindringen von Radon zu verhindern.

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1 Theoretical aspects of radon entering residential buildings

Pollution occurs when physical particles, chemicals or organisms enter the environment and cause damage to the living environment and material values. It is widely known that gases, dust, sulphur, lead and other substances entering the atmosphere represent a danger to human health and affect various components of the Earth's ecosystem. These pollutants and toxic substances can spread over long distances. Through the water cycle they reach the oceans, surface water and groundwater via precipitation. These substances then penetrate into the soil, where plants extract nutrients from it and animals, birds and insects then feed on them. The pollutants thus poison the environment, harm plant and animal life, and have a negative impact on the planet's climate overall.

Environmental protection, also known as nature protection or environmentalism, is a set of measures aimed at limiting the negative impact of human activities on nature.

Sometimes our knowledge and understanding of potentially dangerous phenomena is not enough to take them seriously. Although not worrying about it may make our lives easier but at a critical moment we may find that we are totally unprepared to protect our health. Such is the case with radon, which many people have heard of but few know what it is.

Nowadays, after the long term cessation of nuclear testing by the world's leading powers, most people associate the risk of receiving a significant dose of radiation with the activities of nuclear power plants, especially after the Chernobyl disaster. However, it is worth knowing that there is a risk of radiation exposure even if one is in one's own home. The natural gas radon and its decay products, such as heavy metals, are a threat to mankind throughout existence.

Radon is an inert noble gas that is becoming increasingly important in people's daily lives. Unfortunately, its effects are mostly negative as radon is radioactive and therefore dangerous. As radon is continuously released from the ground and spreads throughout the earth's crust, groundwater, surface water and the atmosphere, it can be assumed that it is present in every home located in areas with a potential for spreading this gas in depth.

Society has already realised the need to recognise the radon hazard as a large and complex problem. Given that radon causes radioecological processes at three structural levels of matter - nuclear, atomic-molecular and macroscopic, the solution to this problem includes the challenges of diagnosing and developing technologies to neutralise the effects of radon on humans and biological objects.

The aim of this final qualification work is to investigate features of radon accumulation in residential buildings and propose measures for its reduction.

The objects of the research are residential buildings, including both old and new low-rise construction.

In order to achieve the objective, the following goals need to be achieved:

1. To measure radon content in low-rise buildings in towns in Russia, Austria and Germany.
2. Determine the dependence of radon concentration on the level of air exchange in low-rise houses.
3. Compare the obtained data on radon concentrations in low-rise houses.
4. Propose measures to reduce radon concentrations in low-rise buildings.

1.1 General information on radiation

From the very beginning, life on Earth has developed in the presence of an always-present radiation background. The most familiar source of radiation is sunlight, without which there would be no life on our planet. Over time, however, it has become clear that large amounts of radiation are harmful and, even more so, can be hazardous to human health, so it is worth protecting ourselves by controlling our exposure to it.

Solar light, as illustrated in Figure 1, consists of radiation in a wavelength range from longwave infrared to shortwave ultraviolet.

Figure 1: Energy spectrum

In other words, the energy spectrum consists of low frequency radiation - radio waves, microwaves, infrared radiation, visible light - and high frequency radiation - ultraviolet, X-rays, gamma rays and cosmic rays.

What is beyond UV in Figure 1 is the higher-energy radiation, which is used in medicine and which is received by everyone on the planet, as it is emitted in small doses to human skin, passing through space, air and radiating from the earth and rocks. Taken together, these types of radiation can be combined and called ionising radiation.

Radioactivity is defined as the process of releasing high-energy radiation in the form of electromagnetic waves or moving subatomic particles when atomic nuclei are converted into other nuclei without external influences. Radiation is energy emitted by a source that passes through a medium, such as air, and is able to penetrate into various materials.

Radioactive decay is important because this process releases ionising radiation, such as alpha, beta, gamma or neutron radiation, which emits large amounts of energy. This energy can be used for energy production or in medicine. It should be noted that due to the short lifetime of radon products, the total activity in a given volume can increase several times. In addition, the final product in the uranium decay chain is stable lead (Pb-206), which can serve as a shield against environmental radiation. Radioactive decay can also be used in astrophysical measurements or to determine the age of materials such as water or rocks.

Alternative applications of radioactive decay include determining the age of the Earth, rocks, groundwater and prehistoric cave art [1].

Humans are always exposed to radiation because there is background radiation all around us (Figure 2).

Элементы списка иллюстраций не найдены.

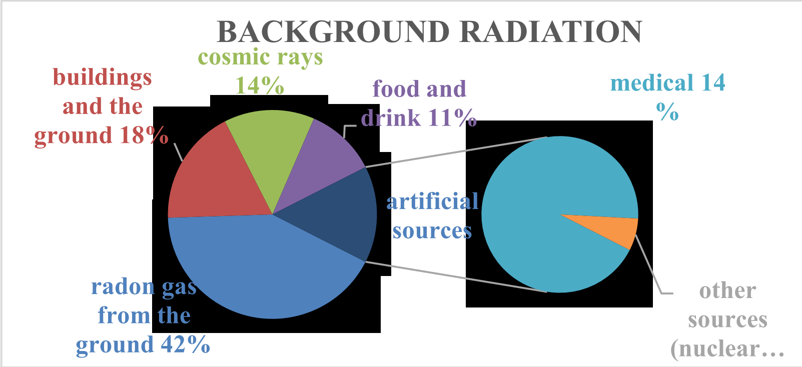

Figure 2: Background radiation

Thus, anyone on planet Earth is exposed to background radiation and, according to Figure 2, the main source is the emanation of radon gas that enters the atmosphere from the depths of the Earth's crust. The next cause is poorly tested building materials, which will consequently surround a person for the entire time he or she stays in a room in which the previously mentioned materials have been used. Next in percentage are named artificial sources of background radiation - X-rays, mammography and CT scans, which are used in medicine and, for example, nuclear reactors (accident) when nuclear power is considered. Last on the list are radiation in space, solar cosmic rays and food and water saturated with radiation that could potentially be consumed in the diet.

A more specific example from everyday life is radiation exposure in high-flying aircraft (Table 1). Factors influencing the increase in radiation dose:

- Altitude above sea level (rule of thumb: radiation doubles with increasing altitude for every 2 000 m);
- Latitude (dose rates at 70° north and south latitude are about 4 times higher than at 25°);
- Solar activity (solar flares can increase cosmic radiation levels);
- Flight duration.

	Personnel	Frequent flyers	Irregular flyers
Duration of flight (days)	40	10	2
Exposure dose	52* x (40/365) = 5,7 mSv/year	52 x (10/365) = 1,4 mSv/year	52 x (40/365) = 0,3 mSv/year

*At an altitude of 10,000 m, the radiation dose is 52 mSv/year

Table 1: Exposure dose to a human during an aircraft flight

1.2 The main types of emissions

Radioactivity refers to the property of atomic nuclei to change into other nuclei for no other reason than to emit high-energy radiation. It cannot be seen with the naked eye or felt without special equipment, but humans are always exposed to such exposure (Figure 3).

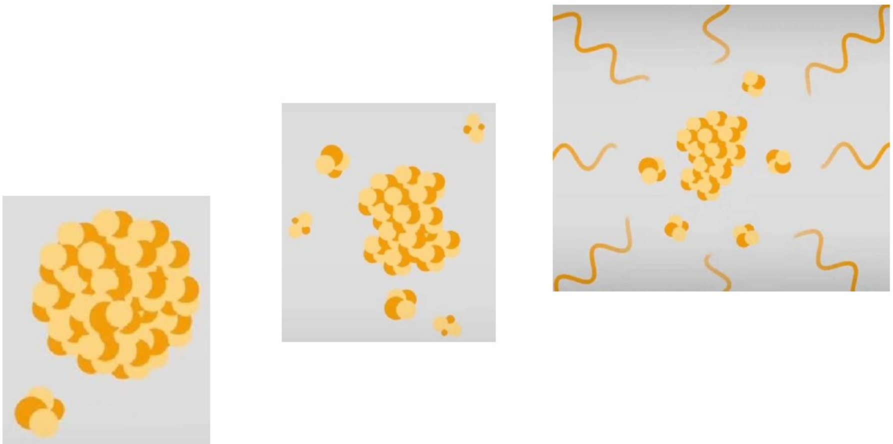

Figure 3: Schematic drawing of nuclear decay

During radioactive decay, the following types of ionising radiation can be emitted: alpha, beta, gamma and neutron radiation. Each of these will be considered in more detail.

Alpha radiation (Figure 4) is radiation from positively charged particles consisting of nuclei of the element helium (alpha particles).

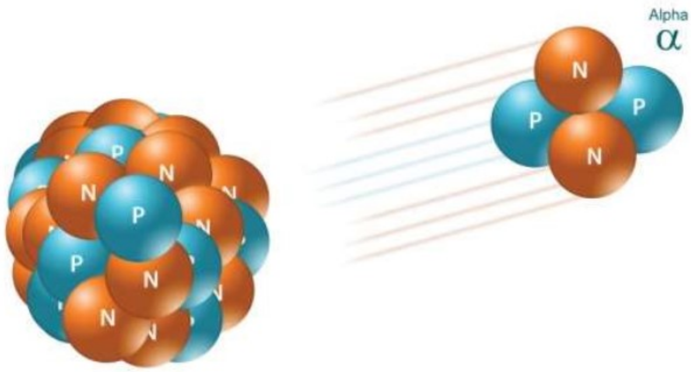

Figure 4: Alpha emission

Features:

- very short radius of action (a few cm in air, <1 mm in water);
- can be protected with a piece of paper;

– does not penetrate the outer layers of the skin;
– high short-range energy transmission, alpha particles cause particularly serious tissue damage (high biological effectiveness). Absorption of radon and its daughter products with air or food is a typical example of ingestion of alpha particles.

Beta radiation (Figure 5) is radiation from particles consisting of electrons (beta particles), or less commonly, positrons.

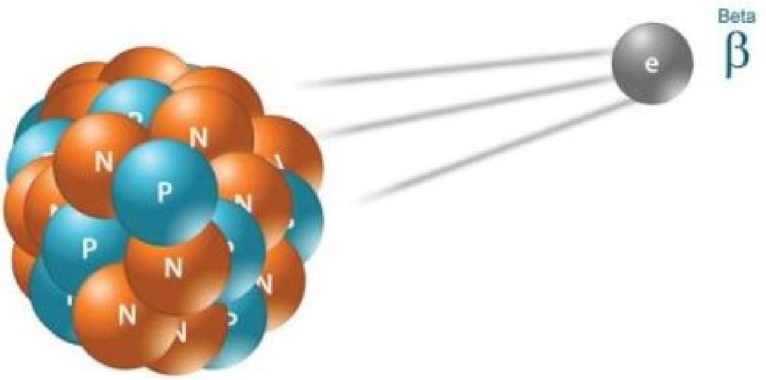

Figure 5: Beta radiation

Features:

– penetration in air ranges from a few cm to m, in soft tissues or synthetic materials from a few mm to cm;
– can be protected by an aluminium plate;
– radionuclides entering the body can cause significant radiation exposure. Entering with food or inhaled air, the radionuclides reach the blood and tissue through the intestines or lungs, resulting in irradiation of the body's cells.

Gamma radiation is electromagnetic radiation (Figure 6).

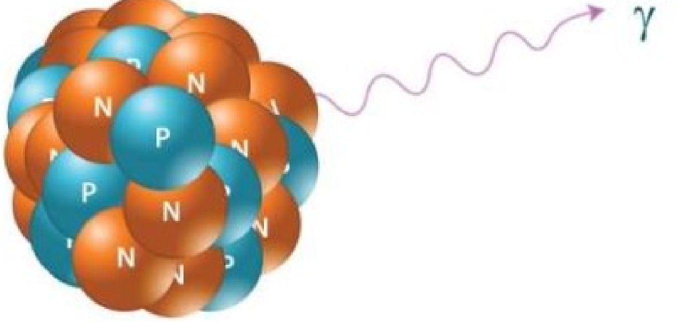

Figure 6: Gamma radiation

Features:

- is physically similar to visible light, but has higher energy and greater penetration, comparable to X-rays;
- can be shielded by heavy and dense materials such as lead and concrete;
- radionuclides entering the body can cause significant radiation exposure. When ingested with food or inhaled, they reach the blood and body tissues through the intestines or lungs, resulting in irradiation of cells.

Neutron radiation (Figure 7) is radiation that consists of uncharged particles or neutrons.

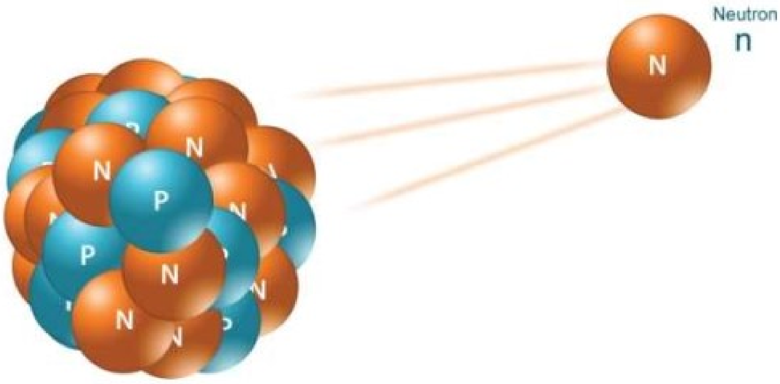

Figure 7: Neutron radiation

Features:

- almost unaffected by air;
- neutrons can be trapped with an absorber (boron, cadmium);
- can be protected with materials that have a high proportion of hydrogen in their composition (paraffin, polyethylene, water) to slow down neutrons;
- neutrons are released during nuclear fission, which is a special form of nuclear transformation. Nuclear fission is only characteristic of heavy atomic nuclei, e.g. nuclei of the element uranium.

An illustrative example of shielding from different types of radiation is shown below (Figure 8).

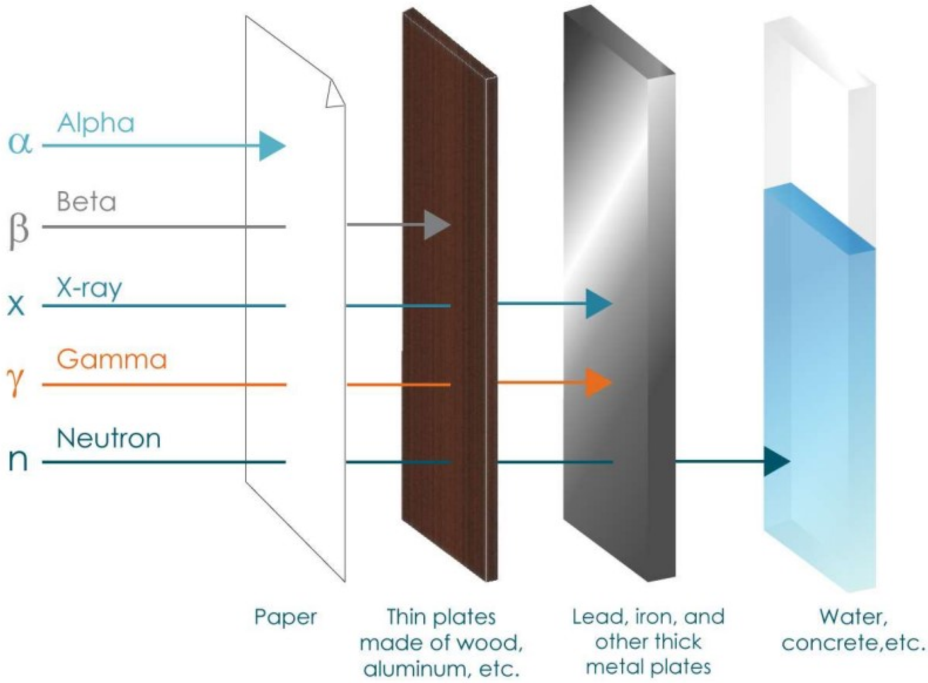

Figure 8: Types of radiation and penetration

1.3 Half-life

Radon is a noble gas with the symbol Rn and atomic number 86, which is radioactive, colourless, odourless and tasteless. In nature, it occurs in small quantities as an intermediate product in the radioactive decay chain, where thorium and uranium are gradually transformed into various short-lived radioactive elements and eventually into stable lead. Radon is the direct decay product of radium. The most stable isotope of radon, 222Rn, has a half-life of only 3.8 days and is one of the rarest elements. Thorium and uranium, on the other hand, are the most abundant radioactive isotopes on Earth, with half-lives measured in billions of years, which means that radon will be present on Earth for a long time, despite its short half-life. The decay of radon produces other short-lived nuclides, called "radon daughter elements", which eventually turn into stable lead isotopes.

Unlike other intermediate elements in the decay chain, radon is in a gaseous state under standard conditions and can therefore easily be inhaled, causing health hazards. The level of human exposure to radon gas varies from place to place due to regional differences in the geological environment. The main source of radon is uranium-containing minerals in the ground, so it accumulates in underground spaces such as basements. Radon may also be present in some groundwater such as wells and hot springs. With climate change and thawing permafrost, radon previously trapped underground can be released. The air in buildings can be tested for the presence of radon and exposure levels can be reduced, for example by depressurizing basements.

Epidemiological studies have shown a clear connection between inhaling high concentrations of radon and the development of lung cancer. Radon is a pollutant affecting indoor air quality around the world. According to the US Environmental Protection Agency (EPA), radon is the second most important factor, after tobacco smoke, in the development of lung cancer. Unlike radon gas, the "daughter" elements of radon are solids that can adhere to surfaces, such as dust in the air, and when inhaled can contribute to the development of lung cancer.

Radon is a gas, so it can move in and out of solid materials. As a result, people can inhale radon and be exposed to radiation. Radon has four daughter decay products (Po-218, Pb-214, Bi-214 and Po-214) that have short lifetimes. Therefore, after inhaling radon, its activity quadruples after three hours due to the emission of alpha, beta and gamma radiation when the atoms decay, which can be harmful to the lungs.

The radioactive decay of radon eventually transforms the atoms into stable atoms. The number of radioactive atoms in a given material decreases over time. The time it takes for the activity to halve is called the "half-life".

Thus the activity decreases to one quarter after two half-lives and to one eighth after three half-lives (this is about 12.5 per cent) of the initial value (figure 9). In other words, the activity rate of radioactive decay reduces the level of radioactivity to one thousandth after ten half-lives.

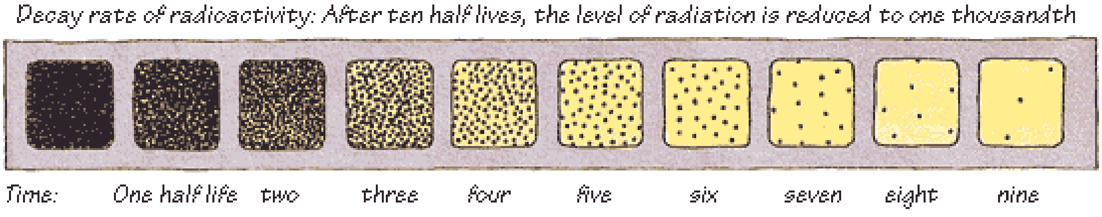

Figure 9: Decay rate of radioactive substance after ten half-lives

The half-life of a radioactive isotope is a fixed and precisely known characteristic. For different radioactive isotopes this value can vary from fractions of a second to several billion years. For example, the half-life of uranium-238 is 4.47 billion years, lead-210 is 22.3 years, radon-222 is 3.823 days and polonium-214 is 0.000164 seconds.

In Figure 10, it is possible to visualise the decay periods of the different elements and the radiation that occurs when doing so.

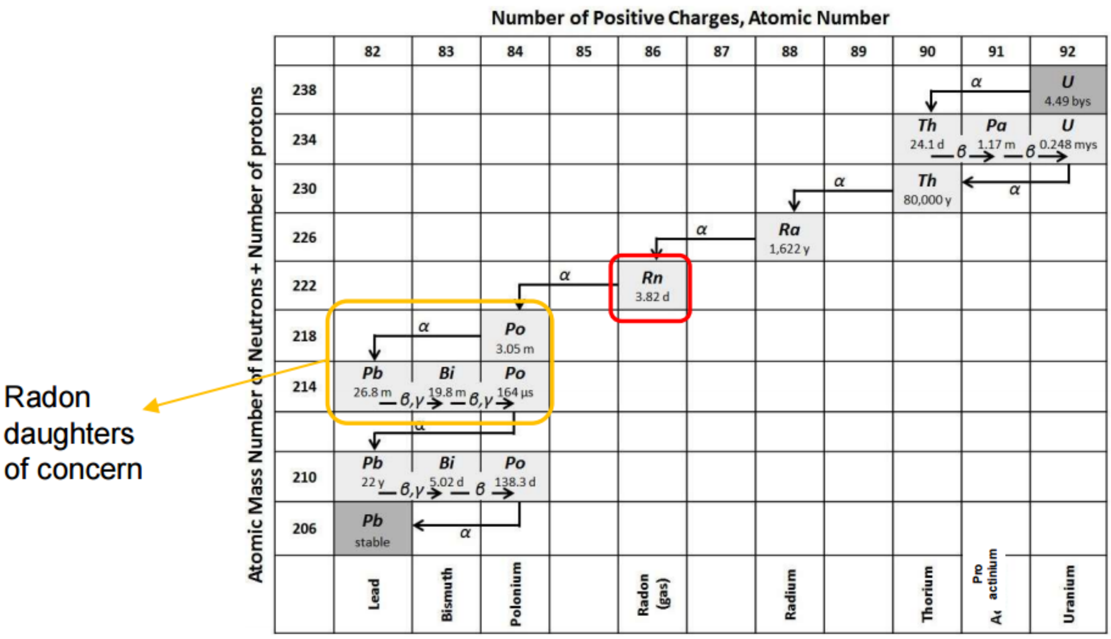

Figure 10: Decay scheme of substances from uranium to lead

1.4 Units and measuring instruments

The following units of measurement are used in radioactivity:

– Potential alpha energy (PAE) in megaelectron volts (MeV), which is contained in isotopes.

– Potential alpha energy concentration (MeV/m³ or J/m³), which expresses the concentration of PAE in air.

– Potential alpha energy exposure (J*h/m³), which is the amount of exposure after inhaling a radioactive substance for a specified time.

– Effective dose (millisieverts), which estimates the probability of harm to the human body given the potential energy contained [2].

The number of nuclear decays occurring per unit time in a substance is called the "activity". The unit of activity is the becquerel (Bq), where 1 becquerel equals one nuclear decay per second.

Specific activity refers to the ratio between the activity of a radionuclide and its mass and is measured in becquerels per gram (Bq/g).

In practice, activity is related to other quantities such as:

- Area ("local activity") in becquerels per square metre (Bq/m^2).
- Volume in becquerels per cubic metre (Bq/m^3).
- Mass in becquerels per gram (Bq/g).

Radiation control is regulated and normalized by indexes such as: exposure dose rate (EDR) of gamma radiation and annual average equilibrium volume activity (EROA) of radon [3].

Exposure dose rate (EDR) of gamma radiation has the following limitations:

- When a land plot is allocated, the exposure dose rate must not exceed 30 micro-roentgens per hour.
- When commissioning a new building and in existing buildings, the open area gamma radiation dose rate must not exceed 30 micro-roentgens per hour.
- The annual average equivalent equilibrium volume activity (EROA) of radon also has a limit:
- In buildings being commissioned, radon EROA levels should not exceed 100 becquerels per cubic metre.

Radiation monitoring indicators are usually determined during the pre-construction survey phase for the selected construction site. Under current legislation, local authorities must conduct radiation monitoring on land that is given to a citizen for individual housing construction. If the established sanitary standards and radiation limits are followed, the citizen will be allowed to use the plot [4].

It is important to remember that not every type of radiation can be measured with the same instrument. Accurate data requires the use of optical, electrical or thermal effects. Most instruments measure pulses. In combination with a certain flow of pumped air the pulses per volume are calculated. The result is given in Bq/m^3. The difficulty that can be encountered is that different isotopes have different energies. Doses can only be calculated if it is known which isotope with which energy decays. For radon in full equilibrium, doses can be calculated analytically. If air is vented to a free atmosphere before equilibrium is reached, the equilibrium factor F must be estimated or calculated from other measurements.

Two ways of obtaining readings for radon and its decay products are presented below:

Measurement of radon and radon decay products

Recent value of radiation

Dosimeter

(worker carries a chip which will be analyzed after some months)

It is important to note that there are two types of radiation measurement devices:

- active (they measure radon and can calculate the effective dose after entering the equilibrium factor);
- passive (measure radon decay products).

In Russia, different instruments with their own spectrum of functions are used to obtain measurements of the hazardous gas, which are listed in Table 2 [5].

№	Device	Characteristics
1	"Alpharad Plus" is a complex measuring device designed to monitor radon, thoron and their daughter products. 	• express measurements and continuous monitoring of equivalent volumetric activity (EVA) and volumetric activity (VA) of radon-222 and radon-220 (thoron) in air; • radon-222 content in water samples, soil air; • radon flux density (RFD) from soil surface.
2	Radioactive aerosol radiometers "RAMON-02" 	• Radon and thoron ERA in residential and industrial air, in atmospheric air; • value of "hidden" energy of radon and thoron; • volume activity of radon daughters in air.

3	Alpha radiometer RAA-20P2 	• equivalent equilibrium volume activity of radon and thoron daughter decay products in air; • Radon volumetric activity in air, "equilibrium factor", room air exchange ratio; • ambient gamma radiation external dose equivalent power
4	Radon monitoring measurement complex "CAMERA-01" 	• 1-6 day average volumetric activity (VA) of radon in indoor air • volume activity of radon in air samples • average radon flux density (RFD) from the surface of earth and building structures in 1-10 hours • volume activity of radon and radium in water samples • emanating power of samples of construction materials and rocks.

Table 2: Radiation measurement instruments in Russia

Examples of passive devices are ion tracks in polymers or photographic films, which require further analysis in the laboratory, whereas active devices are, for example, DOSEman or Radon Scout, which produce values almost instantaneously.

1.5 The impact of radiation on human health

In regions where granite, gravel, phosphorite and other similar materials are located close to the surface, high-risk zones arise. The population of these areas, as well as people living near industrial plants for mining and processing of minerals, metallurgical plants and thermal power plants, are exposed to relatively high doses of radiation.

As already mentioned, radon enters the atmosphere from the soil, and if a building is located in such an area, radon may accumulate indoors. If there is no or insufficient ventilation, the concentration of radon indoors can be tens of times higher than outdoors.

Construction materials are another possible source of radon in rooms. If raw materials containing radon have been used in their manufacture, radon will enter the inside of the building irrespective of the number of floors.

Numerous studies show that radon is emitted from the earth's crust everywhere, but its concentration in the air varies widely in different parts of the planet. Most human exposure to radon occurs in closed, unventilated rooms. In temperate climates, the average indoor radon concentration is about 8 times higher than outdoors.

Radon enters rooms through cracks in foundations and floors, gaps in floor and wall joints, technological openings around pipes or wiring that go through floors, pores in walls made of hollow concrete blocks, and is also released from building materials. Radon concentrations in residential air can vary considerably, sometimes reaching occupational exposure levels, as in uranium mines [6].

The concentration of the gas and its daughter products in the air of residential and industrial facilities depends not only on the radon content in the soil under the building, the specific construction and building materials, but also on geodynamic factors (pressure, humidity, air temperature, precipitation, etc.), but also on the lifestyle, habits, cultural and social level of the residents. For example, due to the tendency of radon daughter products to attach to dust and other particles in the air, higher concentrations of radon are observed in dusty and smoky rooms. Concentrations of radon in different rooms may vary considerably depending on the above factors. Therefore, the results obtained for one building cannot be simply transferred to other buildings, and the radon concentration in each room can only be identified through mass measurements.

The geological space under buildings is the main source of radon entering the air. Building materials such as wood, bricks and concrete emit small amounts of radon. However, granite and pumice, which are widely used in construction, especially in Russia, have higher radioactivity.

Radon isotopes are adsorbed by solids. Coal is a particularly effective adsorbent, so coal mines require increased government attention. This also applies to industries that use coal as a fuel.

Sorbed radon atoms are very mobile and move from the surface layers of solids to deeper layers. This applies to organic and inorganic colloids as well as to biological tissues, which greatly increases the radon hazard. The sorption properties of substances depend on various parameters such as temperature, humidity and others. These properties should be taken into account when developing anti-radon remedies [7].

Short-lived daughter products of radon penetrate lung walls and affect unprotected cells through the release of alpha particles that collide with cells. This interaction leads to damage to the DNA within the cells, which disrupts their repair mechanism. As a result, the cell begins to encode the wrong information, which can lead to the development of lung cancer associated with the daughter products of radon.

1.6 Causes of radon

Radon and its decay products in the air come from a variety of sources, including rocks, soil, water and natural gas. Radon concentrations vary greatly from one area of the Earth to another.

Tectonic faults can influence the distribution of radon in the ground and its occurrence in buildings because cracks and pores in rocks can form in zones of tectonic activity. These cracks and pores can serve as pathways for radon to move to the ground surface where it can enter buildings and accumulate in enclosed spaces.

Radon in the Earth's interior is a source of radioactive radiation and comes from rocks such as granites, syenites, clays and shales that contain uranium and its radioactive products, including radium-226. Radon is released from rocks and building materials by two main mechanisms: diffusion and recoil.

In diffusion, radon atoms migrate through a layer of solid material that contains radium before entering the gaseous environment. This process requires overcoming the crystal lattice and is slow. "Radon" layer, in which radon is released, is usually very thin and is millimetres, but in porous or fractured materials it can be up to a metre thick.

Another mechanism of radon release is recoil, in which the radon atom acquires a significant momentum upon formation and instantly traverses a thin layer of material. The thickness of this layer is very small and the recoil process does not depend on time or temperature. Once released into the pore space of soil or rock, radon quickly migrates and reaches the surface. The release of radon in this way creates vast areas of the earth's surface with high concentrations of radon, which coincide with areas where the specified rocks are close to the surface.

In addition, radon can be locally released in tectonically active areas that mark faults, karst channels, and other structures that facilitate radon movement. In such "hot spots", radon concentration can significantly exceed background values by hundreds and thousands times, reaching values of tens of kilobecquerels per cubic meter.

Moreover, tectonic faults can affect geological processes associated with the formation of rocks containing uranium and thorium, which are sources of radon. In areas of tectonic activity there may be upwelling or downwelling of ground layers, which may affect the distribution of rocks containing radioactive elements.

Rocks release radon at different concentrations depending on the specific surface area. Those areas where rocks contain high concentrations of uranium (such as granites, carbonaceous-siliceous shales, phosphorites, and others) usually have high radon-emitting activity.

The presence of radiogeochemical anomalies in the geological environment is associated with the peculiarities of the geological structure of the territory. A classification has been developed that takes into account radon levels in soil air (high, normal or low), uranium and radium content in rocks and soils, soil permeability and moisture, and gas emanation volume.

The areas of highest risk are associated with areas dominated by impermeable gravelly-sandy materials of glacial deposits (e.g. oases and terminal moraines), as well as areas where radioactive granitoids are distributed.

The concentration of radon in micropores of rocks, such as ordinary granites and basalts, exceeds that in the surface atmosphere by several million times and can reach 0.5-5.0 Bq/m3. The activity of radon is measured by the number of decays of radon in 1 m3 of air - 1 Becquerel (Bq) corresponds to one decay per second. Magnetostrictive compression-expansion in a high-frequency geomagnetic disturbance field causes radon to be released from rock micropores. The magnetostriction amplitude depends on the magnetite content in the rock and the frequency of geomagnetic variations. The effect of radon displacement is due to high perturbation frequency and high gas concentration, although the amplitude of magnetostrictive compression of rocks in the geomagnetic perturbation field is very small [8].

Soil analysis usually reveals a typical value of radium concentration of 41 Becquerel per kilogram of soil. The emanation factor, which reflects the rate at which radon is released from the soil into a gaseous state, is 0.35 and the soil porosity factor is 0.4. Based on these data, it is estimated that the radon concentration in soil gas is approximately 37 kBquerels per cubic metre. The radium content in soil varies according to the soil type, and the presence of radon in the soil is determined by the porosity, humidity and uranium content of the material from which the soil is formed. Radon is transported indoors by diffusion processes and pressure differences.

In water normally used for everyday purposes, radon concentrations are extremely low. However, some water sources, especially deep wells or artesian wells, may contain high levels of radon. The maximum recorded activity of radon in water supply systems is 100 Mega Becquerels per cubic metre.

The radioactivity in the water is maintained by the presence of radon and its decay products. Short-lived decay products of radon-222 can have twice the activity of radon itself.

Formation waters in oil fields containing radium (e.g. Ukhta region and others) may also have increased concentrations of radon which leads to abnormal accumulation (300-600 Becquerels per cubic metre) indoors.

It can be concluded that significant concentrations of radon may be present in surface water bodies. This is probably due to intensive leakage of radon-containing waters through cracks, which maintains stable radon content in surface water bodies.

In groundwater, radon concentrations vary widely and reach maximum values in granites. Usually the highest levels of radon are observed in individual wells, and radon concentration decreases with increasing number of users. The contribution of water radon to the domestic atmosphere is 37 Becquerels per cubic metre with radon content of 370 kBecquerels per cubic metre in water.

When boiling water or cooking hot food radon evaporates significantly, so it is mostly raw water that enters the body. Even so, radon is rapidly removed from the body. A greater danger is inhaling fumes with high radon content in the bathroom [9].

Natural gas is the main source of atmospheric radon, which diffuses from surface soils. In addition, some small sources of radon include volcanoes, groundwater, natural gas and ventilated mine air.

Radon also penetrates natural gas underground. During gas pre-treatment and storage before delivery to the consumer, a large proportion of radon escapes. However, indoor radon concentrations can increase significantly if gas cookers, heating systems and other gas appliances where gas is burned are not equipped with extraction systems. If there is extraction connected to outside air, however, the use of gas has practically no effect on the radon concentration in the room.

A significant amount of radon that has escaped from natural gas during the pretreatment process goes into the liquefied gas, which is a by-product of this process. In general, significantly more radioactive material enters homes through natural gas (by a factor of 10-100) compared to the more radioactive liquefied gas, as the consumption of natural gas is much higher.

The level of radon in natural gas is 1,850 Becquerels per cubic metre. High concentrations of radioactive gas occur in poorly ventilated mine workings and basements [10].

Table 3 shows the radiation doses and the possible consequences following exposure.

0,05 mSv/yr	A very small fraction of natural background radiation, is the design target for maximum radiation at the perimeter fence of a nuclear electricity generating station. In practice the actual dose is less.
0,3 - 0,6 mSv/yr	Typical range of dose rates from artificial sources of radiation, mostly medical.
1,5 mSv/yr	The minimum dose received by all humans anywhere on Earth.
3 mSv/yr	This is the (approx.) typical background radiation from natural sources in North America, including an average of almost 2 mSv/yr from radon in air.
3 - 5 mSv/yr	Typical dose rate (above background) received by uranium miners in Australia and Canada.
10 mSv/yr	Maximum actual dose rate received by any Australian uranium miner.
20 mSv/yr	Averaged over 5 years is the limit for radiological personnel such as employees in the nuclear industry, uranium or mineral sands miners and hospital workers (who are all closely monitored).
50 mSv	Conservatively, the lowest dose at which there is any evidence of cancer being caused in adults. It is also the highest dose which is allowed by regulation in any one year of occupational exposure. Dose rates greater than 50 mSv/yr arise from natural background levels in several parts of the world but do not cause any discernible harm to local populations.
>100 mSv	The probability of cancer (rather than the severity of illness) increases with dose.
250 mSv	As short-term dose was maximum allowable for workers controlling the Fukushima accident.

1 Sv	In a short-term dose is about the threshold for causing immediate radiation sickness in a person of average physical attributes but would be unlikely to cause death. The estimated risk of fatal cancer is 5 of every 100 persons exposed to a dose of 1000 mSv (i.e. if the normal incidence of fatal cancer were 25%, a 1000 mSv dose would increase it to 30%).
>1 Sv	Over a long period they are unlikely to have health effects but they may create some risk that cancer will develop many years later.
2 - 10 Sv	In a short-term dose would cause severe radiation sickness with increasing likelihood that this would be fatal.
10 Sv	As a short-term and whole-body dose would cause immediate illness, such as nausea and decreased white blood cell count, and subsequent death within a few weeks [11].

Table 3: Radiation levels and their effects

1.7 Radon applications

In nature, every substance has its own value, and in addition to important research in chemistry and physics, radon is used in many areas of human life. In medicine it is used to create "radon baths", in agriculture to activate pet food, in metallurgy as an indicator of the speed of gas flows in blast furnaces and gas pipelines. Geologists find deposits of uranium and thorium using radon, and seismologists, by analysing radon emissions from soil, can predict strong earthquakes and volcanic eruptions.

Small doses of radiation, acting as a mild stressor, stimulate cell protection and the immunity of the body as a whole, hence the use of radon "baths". Treatment with radon "baths" is used for arthrosis, arthritis, hypertension, rheumatism, osteochondrosis, bronchial asthma, eczema and other diseases. However, such procedures must be carried out under the strict supervision of specialists, since the therapeutic doses of radon in radon baths are much lower than the maximum allowable norms. [12].

Around the world there are efforts to solve the problem of earthquake prediction, but despite this, research is often confronted with unexpected seismic events caused by forces of nature hidden in the Earth's interior. Therefore, new indicators for earthquake precursors are being sought. Recent research [13] led to the idea of using the process of radon release (exhalation) from rocks to predict seismic events. Analysis of these data leads to return to Gilbert-Reid (1911) elastic recoil theory, according to which energy is accumulated in rock mass before earthquake and released during earthquake itself in areas, where these rocks experience elastic deformation.

Changes in radon content before an earthquake were first observed in the Soviet Union, where a decade-long increase in radon dissolved in water from deep wells was followed by a sharp drop before the 1966 Tashkent earthquake (magnitude 5.3) [14].

A method of earthquake prediction consisting in carrying out of routine observations of changes in radon concentration in the massif of rocks is characterized by drilling of ventilation observation holes, the depth of which is less than the depth of ground water level and in each of the holes the dynamics of radon release from the massif of rocks and the total amount of seismic energy received in each observation hole is recorded uninterruptedly. Based on a series of observations, zones with successive decrease or increase of radon emission taking into account the seismic energy received are marked in time, the mentioned zones are mapped in the investigated area and the position of the epicenter and magnitude of the expected earthquake are judged by the area of dynamic decrease of radon emission, while the dynamics of radon emission and/or increase in observation wells is used to judge about the time of the expected seismic event [15].

2 Study of radon emanation in residential buildings and comparative analysis of the data obtained

2.1 Research on radon emanation in the Russian Federation

There is currently a need in the Russian Federation to protect and preserve the well-being of the environment. Russian legislation in the field of environmental safety and environmental protection is constantly evolving, and environmental compliance regulations are being refined [16]. When constructing buildings and structures, it is important to comply with the following documents:

1. Федеральный закон от 9 января 1996 г. N 3-ФЗ "О радиационной безопасности населения". Federal Law of January 9, 1996 N 3-FZ "On Radiation Safety of the Population".
2. СанПиН 2.6.1.2523-09 (вместе с "НРБ-99/2009). "Санитарные правила и нормативы. Нормы радиационной безопасности". Hygienic standards and requirements for ensuring safety and (or) harmlessness to humans from environmental factors. SanPiN 2.6.1.2523-09 (together with NRB-99/2009). "Sanitary Rules and Norms. Radiation safety standards".
3. СанПиН 2.6.1.2800-10 "Гигиенические требования по ограничению облучения населения за счет источников ионизирующего излучения". SanPiN 2.6.1.2800-10 "Hygienic Requirements for Limiting Exposure of the Population to Ionizing Radiation Sources".
4. СП 2.6.1.2612-10 "Основные санитарные правила обеспечения радиационной безопасности (ОСПОРБ-99/2010)". SP 2.6.1.2612-10 "Basic sanitary rules for radiation safety (OSPORB-99/2010)".
5. "МУ 2.6.1.2398-08. 2.6.1. Ионизирующее излучение, радиационная безопасность. Радиационный контроль и санитарно-эпидемиологическая оценка земельных участков под строительство жилых домов, зданий и сооружений общественного и производственного назначения в части обеспечения радиационной безопасности. Методические указания". "MU 2.6.1.2398-08. 2.6.1.1. ionizing radiation, radiation safety. Radiation monitoring and sanitary and epidemiological assessment of land plots for construction of

dwelling houses, buildings and facilities of public and industrial use in terms of ensuring radiation safety. Methodical instructions".

6. МУ 2.6.1.12-01 "Определение индивидуальных эффективных доз облучения персонала от короткоживущих дочерних продуктов изотопов радона". MU 2.6.1.12-01 "Determination of individual effective radiation doses of personnel from short-lived radon isotope daughter products".
7. "МУ 2.6.1.2838-11. 2.6.1. Ионизирующее излучение, радиационная безопасность. Радиационный контроль и санитарно-эпидемиологическая оценка жилых, общественных и производственных зданий и сооружений после окончания их строительства, капитального ремонта, реконструкции по показателям радиационной безопасности. "MU 2.6.1.2838-11. 2.6.1 Ionising radiation, radiation safety. Radiation monitoring and sanitary and epidemiological assessment of residential, public and industrial buildings and facilities after completion of their construction, major repair, reconstruction according to radiation safety indicators.
8. "МР 2.6.1.0172-20. 2.6.1. Гигиена. Радиационная гигиена. Ионизирующее излучение, радиационная безопасность. Оценка радиационного риска для здоровья населения за счет внутреннего облучения радоном и его дочерними продуктами распада. Методические рекомендации". "MR 2.6.1.0172-20. 2.6.1. hygiene. Radiation Hygiene. Ionizing radiation, radiation safety. Estimation of radiation risk for public health due to internal exposure to radon and its decay products. Methodical Recommendations".
9. "МУ 2.6.1.037-2015. 2.6.1. Ионизирующее излучение, радиационная безопасность. Определение среднегодовых значений ЭРОА изотопов радона в воздухе помещений по результатам измерений разной длительности. "MU 2.6.1.037-2015. 2.6.1. ionizing radiation, radiation safety. Determination of annual average values of radon isotopes EROA in indoor air based on measurements of different durations.
10. Пособие к МГСН 2.02-97 "Проектирование противорадонной защиты жилых и общественных зданий". Manual to MGSN 2.02-97 'Design of Radon Protection of Residential and Public Buildings'.

The following basic hygienic standards (permissible dose limits) of exposure on the territory of the Russian Federation related to the use of ionizing radiation sources are in force:

- For the population, the average annual effective dose should not exceed 0.001 Sievert, and the effective dose over a period of life (70 years) should not exceed 0.07 Sievert. In certain years, higher values of effective dose may be allowed, provided that the annual average effective dose calculated over the last five years does not exceed 0.001 Sievert.
- For workers, the annual average effective dose should not exceed 0.02 Sievert and the effective dose over a period of employment (50 years) should not exceed 1 Sievert. Exposure with an effective dose of up to 0.05 Sievert per year is allowed, provided that the average annual effective dose calculated over the last five years does not exceed 0.02 Sievert.

Legislatively established values of radiation dose limits do not include doses associated with natural background radiation and man-made altered background radiation, as well as doses received by citizens (patients) during medical radiological procedures and treatment. The specified values of radiation dose limits serve as the starting point for establishing permissible levels of exposure for humans and their organs.

In case of radiation accidents, it is temporarily allowed to exceed the established basic hygienic standards (permissible dose limits) within the limits and for the duration defined by sanitary norms and rules.

Uranium is known to be a source of radon. The content of uranium in the earth's rocks varies from region to region. Some areas have relatively high concentrations of uranium in the soil (and therefore elevated levels of radon in the air), while other areas have less uranium. Typically, radon concentrations are higher in areas where crustal formation processes have taken place or are taking place, such as mountainous areas. High levels of radon are also associated with geological plates close to the surface because they contain more uranium [17]. Many regions of the Russian Federation have such geological features. For a complete picture of radon throughout Russia, one can refer to the corresponding map (Figure 11).

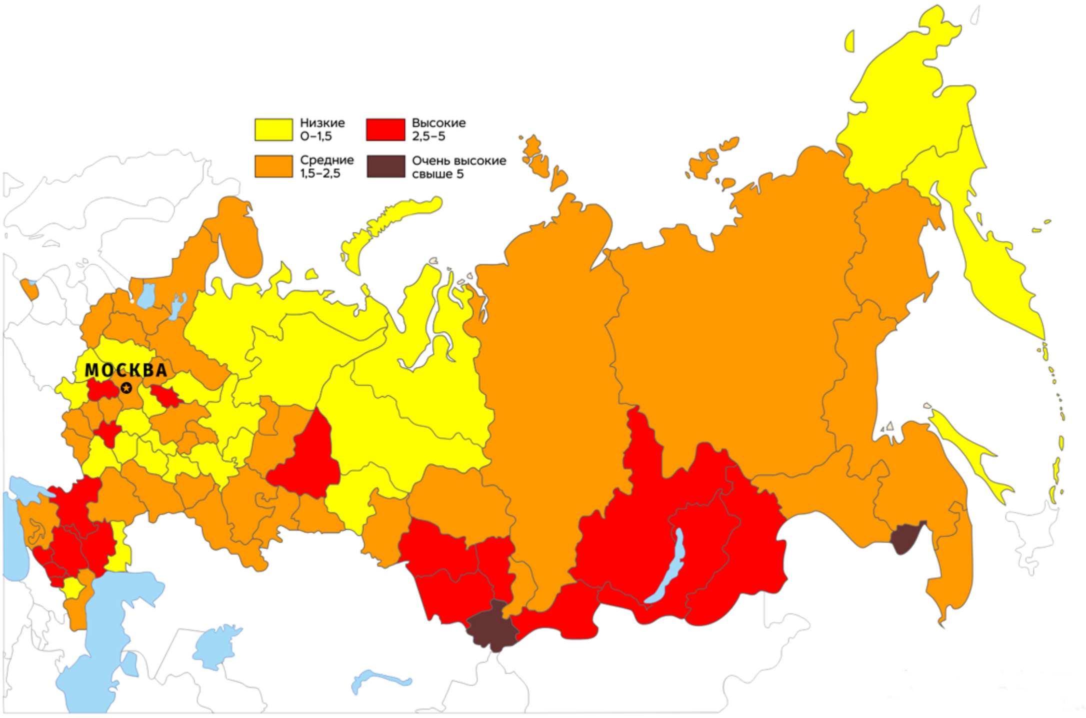

Figure 11: Radon distribution in the Russian Federation

In 10 regions of the Russian Federation (Republics of Tyva, Khakasia, Sakha (Yakutia) and Chuvash Republic; Amur, Belgorod, Ivanovo, Kemerovo, Murmansk, Tambov regions) exceeding of hygienic standards for residential and public buildings under construction was noted in relation to average annual equivalent equilibrium volume activity (EROA) of radon exceeding 100 Bq/m3.

In 20 regions of the Russian Federation (Republics of Altai, Bashkortostan, Tyva and Sakha (Yakutia), Amur, Belgorod, Ivanovo, Irkutsk, Kirov, Kemerovo, Leningrad, Magadan, Novgorod, Sverdlovsk, Tula, Orenburg regions; Stavropol and Zabaikalsky territories; Jewish Autonomous Region, Moscow. Moscow) excesses of hygienic norms for exploited residential and public buildings with average annual radon ERA exceeding 200 Bq/m3 have been registered [18].

Radon concentration norms in indoor air are established by regulatory documentation. The Ministry of Construction of Russia carries out an expert review of each project for sufficiency of radon protection characteristics of the building's underground containment.

Building standards and regulations require that measures be taken to protect buildings from radon intrusion from the ground beneath them. Figure 12 shows a map of Russia showing areas with the highest probability of radon reaching the

Earth's surface. These areas represent a potential hazard regarding radon for people [19].

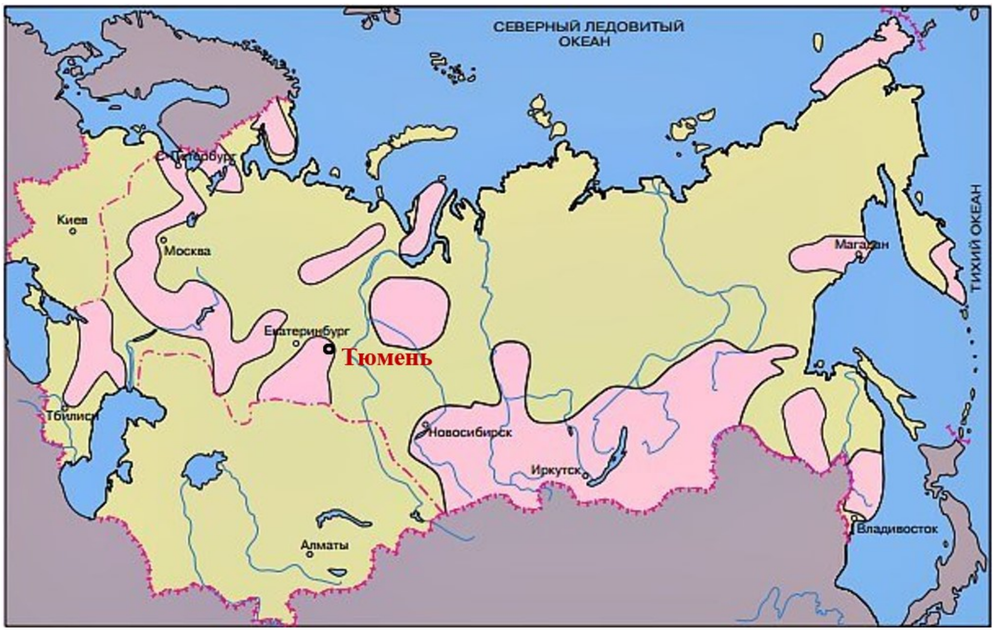

Figure 12: ` Radon emanation map of Russia

The map marked in colour pink shows areas with increased radon emission. This is not a widespread phenomenon in all these areas, but rather represents focus points of varying intensities and sizes. In other areas there may also be individual point-like hotspots with intense radon emission.

According to geological studies there was an earthquake in the area of modern Tyumen from VIII to XII centuries that resulted in geological faults on the surface and changes in the riverbed of the Tura. As a result of these tectonic processes, the earth's crust has fractured in several places, forming geopathogenic zones. The inert gas Radon is actively released from these fractures, soil and groundwater accumulations in depressions and on the site of former swamps, which may spread through cracks in the environment and get into residential buildings through foundations and basements where it accumulates in the absence of proper ventilation [20]. This theory is represented graphically in Figure 13.

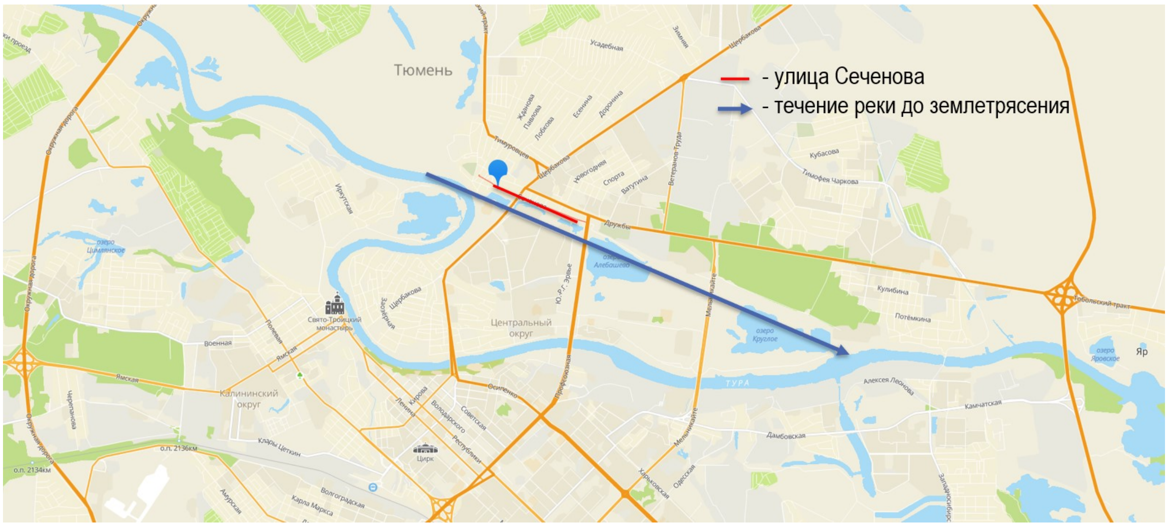

Figure 13: Geological fault theory

The Zarechny district, also known as Zarechny-2, is located in a particular block bounded by Gazovikov Street, Shcherbakov Street, Solnechny Proyezd and Zarechny Proyezd.

The Zarechny district in Tyumen city is a large and young residential area located on the right bank of the Tura river. Its construction began in the 1970s, and the area is now home to many apartment buildings, most of which were built using bricks and panels between the 1980s and 2000s. The area is also home to various retail outlets, educational institutions, kindergartens, schools, pharmacies, hospitals, cafes and restaurants [21].

The Zarechny district offers parks and recreational areas, and is bordering a large lake area of Tyumen. In addition, large shopping centres, supermarkets and cinemas can be found here. Infrastructure and public transportation in the Zarechny district is well-developed, providing residents with convenience and comfort. The area is in close proximity to the city centre, which makes it even more attractive to live in.

Most of the buildings in the area are well soundproofed and thermally insulated, providing comfortable living conditions throughout the year. Many are equipped with elevators, rubbish chutes and entrance doors with security systems.

All conditions have been created in the neighbourhood for comfortable living. The buildings of different heights are surrounded by landscaped courtyards, special driveways, pavements and pedestrian paths. In accordance with the development plan, there are also children's playgrounds, cosy rest areas and enough parking spaces for cars. The street lighting is well organized, and lawns, shrubs and trees have been planted.

Most of the buildings in the Zarechny district are built from environmentally safe natural materials that meet modern requirements of reliability and quality [22].

To obtain initial data, measurements were taken at five low-rise houses in the Zarechny housing estate on Sechenova Street (Figure 14), located at different distances from each other. This data was taken and analysed in 2022 during the warm season.

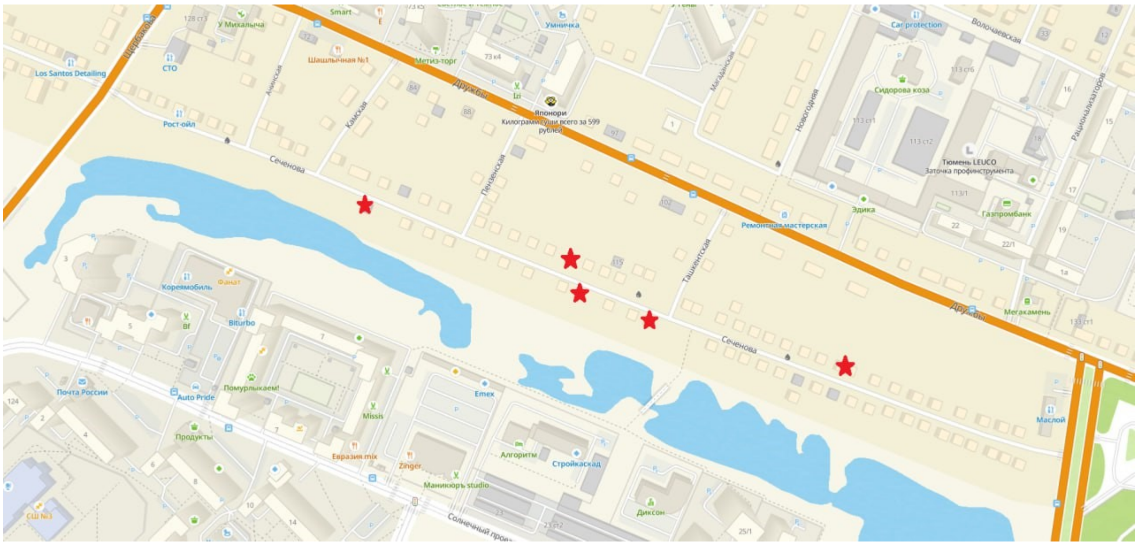

Figure 14: Map, Sechenova Street, Tyumen

At houses No 76, No 94, No 100, No 109 and No 141 in Sechenov Street, measurements were taken in the basement, on the 1st and 2nd floors. Basic characteristics of the houses are presented in Table 4.

Actual address	Sechenova str. 76	Sechenova str. 94	Sechenova str. 100	Sechenova str. 109	Sechenova str. 141
Year of construction	1960	1963	1998	1969	1999
Type of foundation	earthy floors	earthy floors	piled	belt	piled
Type of slabs	wooden	wooden	wooden	wooden	reinforced concrete
Wall material	timber	timber	timber	timber	brick
Ventilation	natural	natural	air duct	natural	air duct
Water supply	missing	missing	central	borehole	central

Table 4: Characteristics of houses, Tyumen city

The resulting data in houses in Tyumen city is shown in Figure 15.

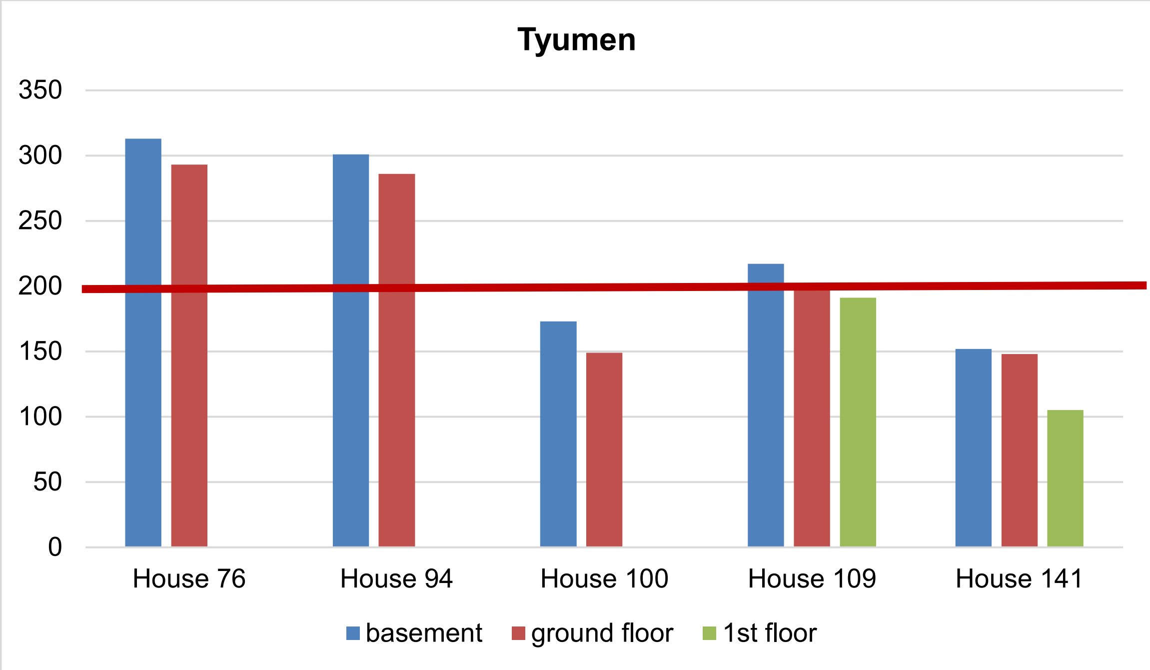

Figure 15: Radon concentrations in low-rise houses in the Russian Federation

The results of measurements show that in most basements of houses in the private residential sector of the Zarechny district, located on Sechenova Street, radon content exceeds the norm by 1-1.5 times. In some of these houses an excess of radon content was found even on the ground floor, which indicates a violation of construction standards and rules for the ventilation of these buildings and creates an environmentally unsafe situation.

2.2 Research on radon emanation in the Austria

In Austria, building regulations are set on the level of the federal states, so that building legislation and regulations apply in each individual federal state [23].

Below is a list of documents that regulate the interaction with radon hazard zones:

1. Radon Protection Act (Radonvorsorgegesetz). This act establishes requirements for the protection of the public against radon and its daughter products and specifies measures to prevent radon from entering buildings and requirements for controlling radon levels in rooms and workplaces as of 1 January 2019.
2. Radon Recommendations (Radonleitfaden), which have been developed for organisations and businesses that work with radioactive substances and radiation sources. They contain recommendations for radiation protection and

radiation safety as well as for monitoring radon levels in rooms and workplaces from 2019

3. The Guidelines for Radon Control in Indoor Areas (Richtlinie zur Messung der Radonkonzentration in Innenräumen), which define the requirements for monitoring radon levels in rooms and workplaces and contain recommendations for measurement methods and the assessment of the results from 2019
4. Radon Technical Guidelines (Technische Richtlinie Radon, TRS 421): these guidelines define the requirements for protection against radon in buildings, including structural and ventilation requirements from 2014
5. Ordinance of the Federal Minister for Climate Protection, Environment, Energy, Mobility, Innovation and Technology on Measures for the Protection of Persons against Radon Hazards (Radon Protection Ordinance - RnV)
6. Federal Act on measures to protect against the dangers arising from ionising radiation (Radiation Protection Act 2020 – StrSchG 2020)
7. ÖNORM S 5280-2. Radon - Part 2: Structural precautions for buildings
8. ÖNORM S 5280-3 Radon - Remediation measures for buildings.
9. 2013/59/Euratom - protection against ionizing radiation
10. The reference annual average radon concentration in common areas of residential buildings is 300 Bq/m3.

The reference values for the annual average concentration of radon in workplaces are 300 Bq/m3 for general workplaces and 1 000 Bq/m3 for certain workplaces.

The effective radiation dose is 6 mSv/year [24].

The effective dose limit for occupational exposure should be set at 20 mSv/year. However, if the dose reaches 50 mSv during a year, it may be allowed provided that the average annual dose does not exceed 20 mSv during five years in a row, including the years when the limit was exceeded.

If the effective dose to an employee exceeds 20 mSv during a year, the responsible person should immediately inform the relevant authority and provide a written explanation of the reasons for the exceedance and describe the measures taken to ensure compliance with the limits for that employee [25].

According to the Radiation Protection Act (StrSchG) 2020, sections 84 and 100, the determination of radon concentrations in workplaces and the assessment of radiation doses for workers employed in these workplaces must be carried out by "authorised control agencies". The Federal Minister for Climate, Environment, Energy, Mobility, Innovation and Technology shall issue the necessary authorisation according to § 131 StrSchG 2020 on the basis of an application. The determination of radon concentrations in residential buildings is voluntary and optional, but if conducted to confirm compliance with control values, it must be performed by an authorised monitoring body in order to ensure standardised procedures and legal certainty.

Radon protection zones and radon precaution zones have been defined on the basis of Austrian-wide radon measurements in buildings. This ensures effective and sustainable health protection from radon. The radon map (Figure 16), based on around 50,000 measurements, makes it easy to identify which zone a particular municipality is in [26].

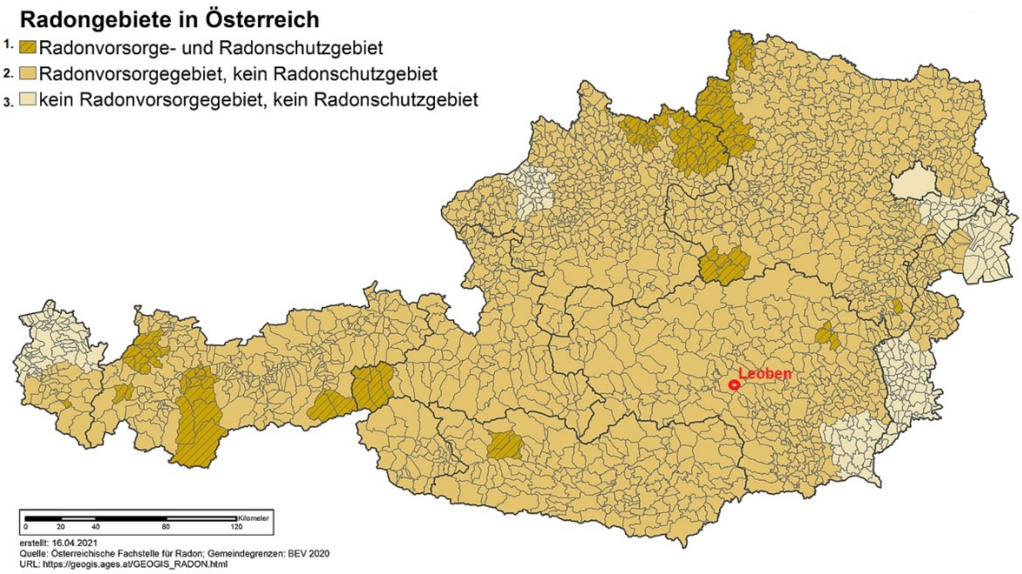

Figure 16: Radon zones in Austria

An extensive indoor radon concentration measurement campaign covering the whole of Austria was carried out to take health issues into account. In addition to the measurements, the campaign also collected structural information about the buildings by means of a questionnaire. Unlike the previous ÖNRAP project, the measurements were made on a geographical basis with a systematic approach to site selection. In this new campaign, some 50,000 measurements were carried out all over Austria. Using the measurement results and the data collected, radon protection zones and radon prevention zones were defined using scientific methods.

Various devices are available to measure radon levels indoors in Austria, including radon dosimeters and radon monitors. A radon dosimeter is a device that is used to measure radon levels in a room over a period of months or even years. It consists of a small plastic container with a sensor for measuring radon and its decay products. When the measurements are completed, the dosimeter is sent to a laboratory to analyse the results.

A radon monitor, a more advanced device, allows continuous real-time monitoring of radon levels in a room. The monitor is usually installed over several days or weeks and automatically records the level of radon and its decay products. The results of the monitoring can be read on the device screen or downloaded to a computer for later analysis.

In Austria, radon dosimeters and radon monitors are available from specialist shops and online shops. There are also certified laboratories that conduct professional monitoring of radon levels in premises using specialised instruments and equipment [27].

In 1996, on behalf of the Federal Ministry of Health, Sports and Consumer Protection, extensive radon measurements were carried out by the Styria (Figure 17). The value indicated on the radon potential map for each municipality helps determine the need for radon tests and measures to address possible problems [28].

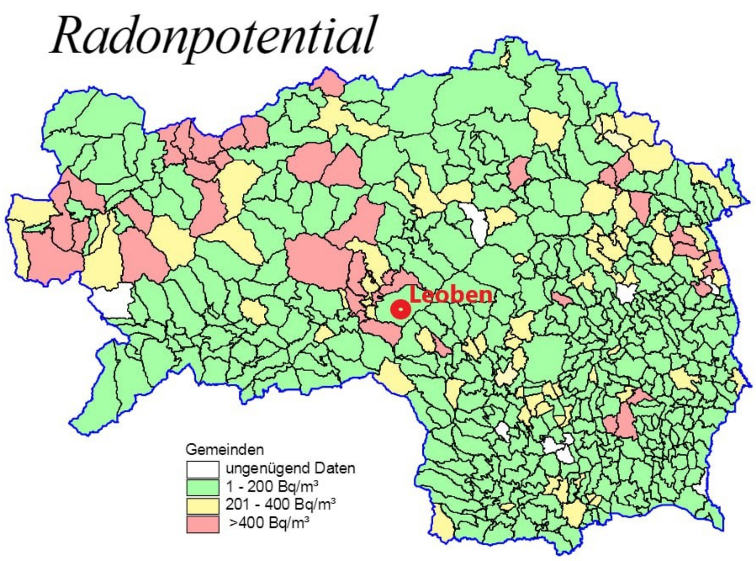

Figure 17: Map of the Institute for Isotope and Nuclear Physics Research at the University of Vienna, Styria

The radon potential map of Austria is based on measurements of radon in residential buildings and provides information on locations in the country where radon levels in buildings are likely to be elevated.

This study will look at the city of Leoben, located in Styria. Minerals are mined in this region, including:

Iron ore: Leoben is located in one of the largest ore regions in Europe, and iron ore mining is an important industry in this region.

Hard coal: Styria has large hard coal reserves, which are mined in several locations close to Leoben.

Copper: The region produces copper ore, which is widely used in the steel industry.

Graphite: the area around Leoben is also rich in graphite, which is used in the manufacture of pencils, electrodes and other products.

Silicon: Silicon is also mined in this region and is used in the production of glass, electronics and other products.

Overall, Leoben and its surroundings have considerable industrial potential due to the presence of large mineral reserves.

Table 5 below shows the characteristics of residential houses in Leoben.

Actual address	Hans-Kloepfer-Gasse 2	Alois-Edlinger-Gasse 2	Alois-Edlinger-Gasse 2	Rechenhofgasse 9	Ottokar-Kernstock-Gasse 1
Year of construction	1990	1991	1991	1998	1999
Type of foundation	slab	belt	slab	piles	slab
Type of slabs	hollow core slabs	hollow core slabs	hollow core slabs	prefabricated monolithic	prefabricated monolithic
Wall material	gas blocks-brick	brick	brick	brick	gas blocks-brick
Ventilation	natural	natural	natural	natural	natural
Water supply	available	available	available	available	available

Table 5: Characteristics of houses, Leoben City

The resulting data in houses in Leoben is shown in Figure 18.

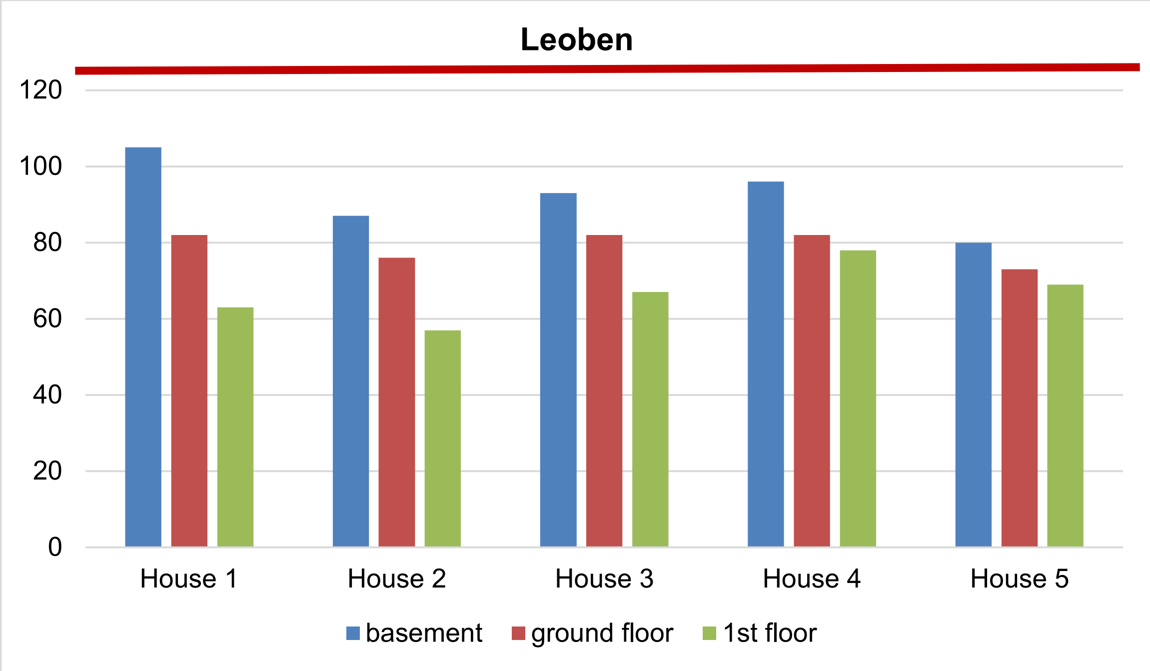

Figure 18: Radon concentrations in low-rise buildings in Austria

According to a report by the Austrian Environment Agency (Umweltbundesamt), the average radon level in buildings in Austria is about 50 Bq/m³ (Becquerelles per cubic metre). However, this level can vary greatly depending on the specific location and type of building.

The technical requirements for measuring radon concentrations in the common areas of residential buildings in Austria are as follows:

- Radon concentrations must be measured in the two most used rooms of the residence.
- The duration of the measurements must be at least six months, including the recording of daily and seasonal fluctuations in the radon concentration in the house.
- At least half of the measurements must be made between 15 October and 15 April (heating period).
- Measurements are taken using two radon detectors placed in the two most used living rooms. The devices must remain in the same room for the whole period of measurements, provided that the rooms are normally used [29].
- The result is the radon concentration in the rest room, which is the average value over the whole measurement period.

- To verify compliance with the reference value, the arithmetic mean value of radon concentrations in two rest rooms must be compared with the reference value without regard to measurement uncertainty.

Radon detectors should be placed out of reach of children and animals. When choosing a location for the detectors the following must be taken into account:

- Avoid placing detectors directly next to windows or doors to avoid air flows.
- Avoid placing detectors in locations that are exposed to sunlight or heating.
- The distance between the detector and the wall or floor should be at least 10 cm.
- It is important to note that detectors must be in the same room for the entire measurement period.

Radon protection is regulated by building regulations in all federal states [30].

2.3 Research on radon emanation in the Germany

In Germany, radon is regulated in accordance with legal acts of the European Union and national legislation. There are regulations that regulate radon [31]. These documents include:

1. The Radiation Protection Act (Strahlenschutzgesetz - StrlSchG), which contains regulations relating to the protection of the public from radiation dated 27 January 2018
2. General administrative regulations on radiation protection (Allgemeine Verwaltungsvorschrift zum Strahlenschutz - AVV Strl), which contains recommendations and requirements for radiation protection dated 15 June 2018
3. Guidelines for Radon in Buildings (Leitfaden zum Schutz vor Radon in Gebäuden), which contain recommendations for protection against radon in buildings then 30 April 2020
4. Technical regulations on protection against radon radiation (Technische Regeln zum Schutz gegen Röntgenstrahlung und radioaktive Stoffe - Strahlenschutz - TROS), which contain requirements for protection against radon radiation in the workplace dated 20 July 2018
5. Radon standards (Radonvorsorge) set by the German states, which establish permitted levels of radon concentrations inside buildings

In Germany, there are limits for the permissible concentration of radon in rooms. The standards differ depending on whether the premises are residential or non-residential, and on the level of radon in the environment.

In Germany, the permissible radon concentration for residential areas is 300 Bq/m³ (Becquerelles per cubic metre). This value meets the requirements set by the European Commission and is the recommended level in many countries [32].

In the case of non-residential premises such as offices and public buildings, the acceptable radon concentration can be higher but must not exceed 1 000 Bq/m³.

When measuring radon concentrations in premises in Germany, other factors are also taken into account, including the radon level in the environment, the type of ground on which the building is located, and other factors that may influence the radon concentration inside the building [33].

In Germany, there are regulations concerning radon levels that are set by the federal states and regional authorities. These regulations may vary slightly from region to region in Germany. Below is an overview of the recommended levels of radon concentration in indoor air as set out in various regulations:

- According to the guidelines for protection against radon in buildings (Leitfaden zum Schutz vor Radon in Gebäuden) published by the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz), the permitted level of indoor radon concentration is 300 Bq/m³.
- In the regional regulations set by the German federal states, the permissible indoor radon concentration can vary from 100 Bq/m³ to 300 Bq/m³.
- According to the protection against harmful effects of ionising radiation law (Strahlenschutzgesetz - StrlSchG), which includes standards for radon, the German states must develop their own standards for radon in accordance with the recommendations of the Federal Office for Radiation Protection [34].

The aim is to maintain an acceptable level of radon concentration indoors, which should not exceed 300 Bq/m³. In Germany, it is recommended to regularly measure radon concentrations indoors, especially in buildings where there is an increased risk of radon accumulation. This may be due to the building being located in radon zones or having special characteristics that contribute to radon accumulation, such as cellars or poor ventilation.

According to the Guidelines for Radon Protection in Buildings (Leitfaden zum Schutz vor Radon in Gebäuden), measurements of radon concentrations in residential areas are recommended at least once every five years. However, if work has been carried out in the building to improve ventilation, insulation or other measures to reduce radon concentrations, the next measurement must be carried out one year after the work has been completed.

In non-residential premises such as offices and public buildings, it is recommended that radon concentrations be measured at least once every three years.

In addition, if renovation or construction work has taken place in the room that may affect the radon concentration, measurements at shorter intervals are recommended in order to ensure that the radon concentration does not exceed the permitted limit.

An illustration showing the distribution of radon in Germany can be seen in the attached Figure 19.

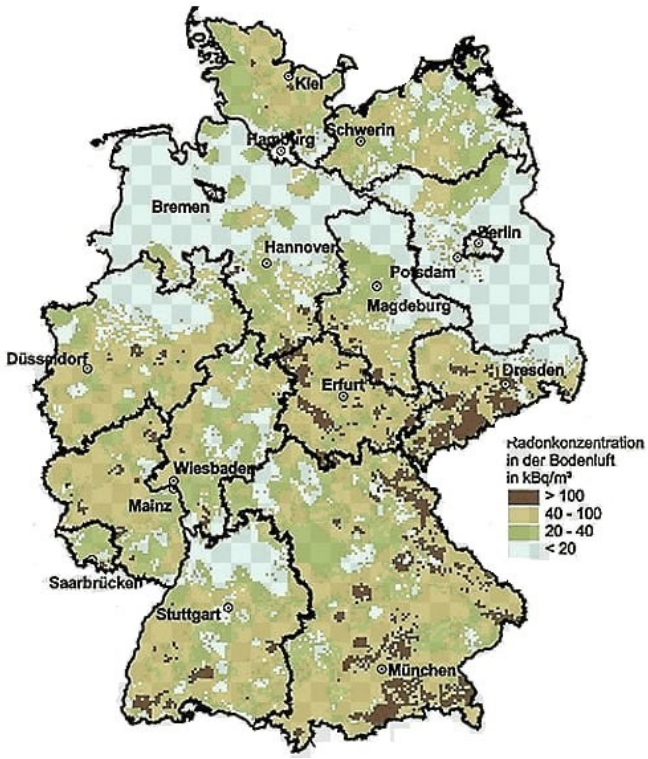

Figure 19: Distribution of radon in Germany

In Germany, there are regional differences in the radon content of soil, air and buildings. The North German Plain generally has low radon concentrations, whereas most low mountain ranges, the Alpine foothills and regions dominated by moraine rocks from the last ice age have relatively high radon concentrations.

The level of indoor radon concentration depends on several factors, including the amount of radon generated in the subsoil, the permeability of the subsoil to radon transfer and the construction of the building. On average, the annual indoor radon concentration is about 50 Bq/m^3. However, the actual levels of radon concentrations in rooms can only be determined by measurements [35].

The map is based on data obtained from measurements at 6,239 geological points, which are representative of Germany. These measurements were carried out between 1992 and 2020 and include data from the measurement programmes of the BfS (Federal Office for Radiation Protection) and the federal states. Predictions for mapping radon concentrations in soil were made using machine learning and artificial intelligence methods that enable patterns and dependencies to be detected in datasets. To create the map, measurement data from around 6,000 points were used, which were linked to characteristics of the natural environment, such as geology, soil properties and climate. These data were updated in 2020.

The map presented (Figure 20) shows a prediction of the radon concentration in soil air for the whole of Germany, with a grid resolution of 1 x 1 km.

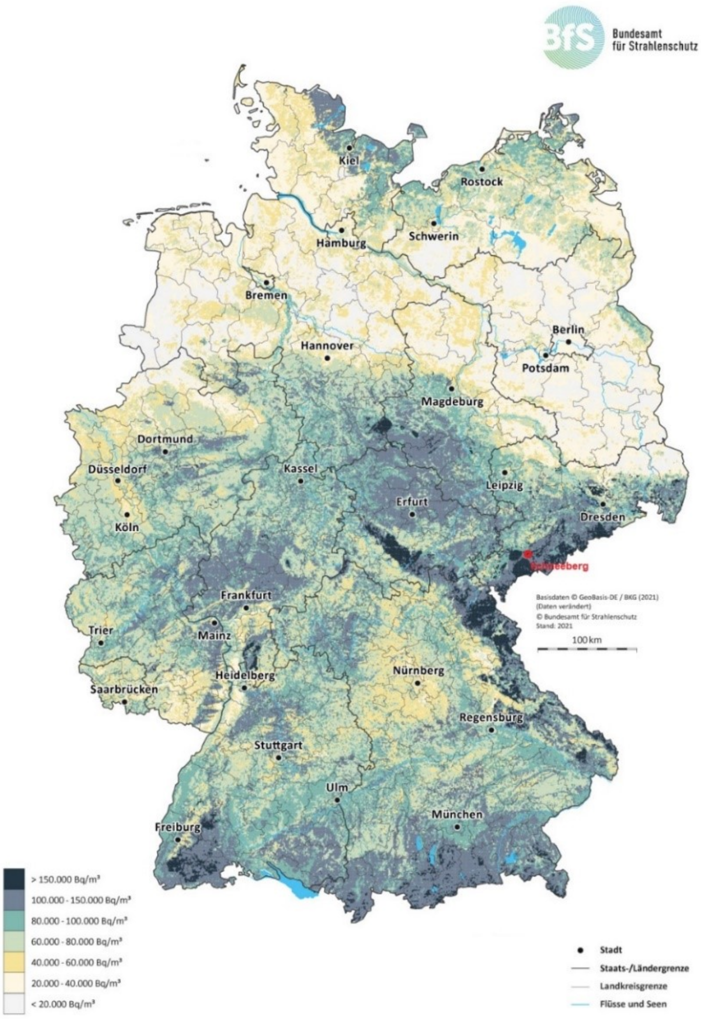

Figure 20: Radon in soil, estimating radon activity concentration in soil air on a 1x1 km grid

The half-life of radium, which produces radon in soil, is about 1,600 years. Due to this long half-life, the radon concentration in the soil air remains stable for a long time. If the radon level at a site is known, further measurements are only sensible if significant underground work is carried out [36].

Schneeberg is located in the state of Saxony in the south of the region, close to the Czech border. It has a rich history of mining silver and other precious metals that dates back to the Middle Ages. Nowadays Schneeberg is a popular excursion destination for tourists with its historical sights and beautiful natural landscape.

Schneeberg in Saxony has a rich history of mining various minerals, including silver, copper, lead and zinc. A particularly important resource was silver, which has been mined here since the 13th century and contributed to the development of the town and the region as a whole. The mining of silver and other metals flourished in Schneeberg until the 19th century, when supplies began to run out.

Schneeberg is situated in a mountainous area where extensive metal mining took place in the past. This led to high concentrations of uranium and thorium in the rocks and soil in the area, which in turn led to high concentrations of radon in the groundwater and rocks.

According to the German Institute for Radiation Protection (Bundesamt für Strahlenschutz), radon concentrations in Schneeberg and its surroundings can reach several tens or even several hundred becquerels per cubic metre of air.

The million-euro project at Schneeberg aims to reduce the population's exposure to radon. The project will rehabilitate ventilation shafts in old mine workings and build new ones at a cost of around 26.5 million euros, according to the Mines Authority. Underground works and the construction of surface ventilation systems are expected to take about ten years. Operation of the ventilation will cost about €100,000 per year [37].

Table 6 below summarises the characteristics of the houses in Schneeberg.

Actual address	Hans-Kloepfer-Gasse 2	Alois-Edlinger-Gasse 2	Alois-Edlinger-Gasse 2	Rechenhofgasse 9	Ottokar-Kernstock-Gasse 1
Year of construction	1990	1991	1991	1998	1999
Type of foundation	slab	belt	slab	piles	slab
Type of slabs	hollow core slabs	hollow core slabs	hollow core slabs	prefabricated monolithic	prefabricated monolithic
Wall material	gas blocks-brick	brick	brick	brick	gas blocks-brick
Ventilation	natural	natural	natural	natural	natural
Water supply	available	available	available	available	available

Table 6: Characteristics of houses, city of Schneeberg

The measurement chart for houses in Schneeberg, Germany is shown in figure 21.

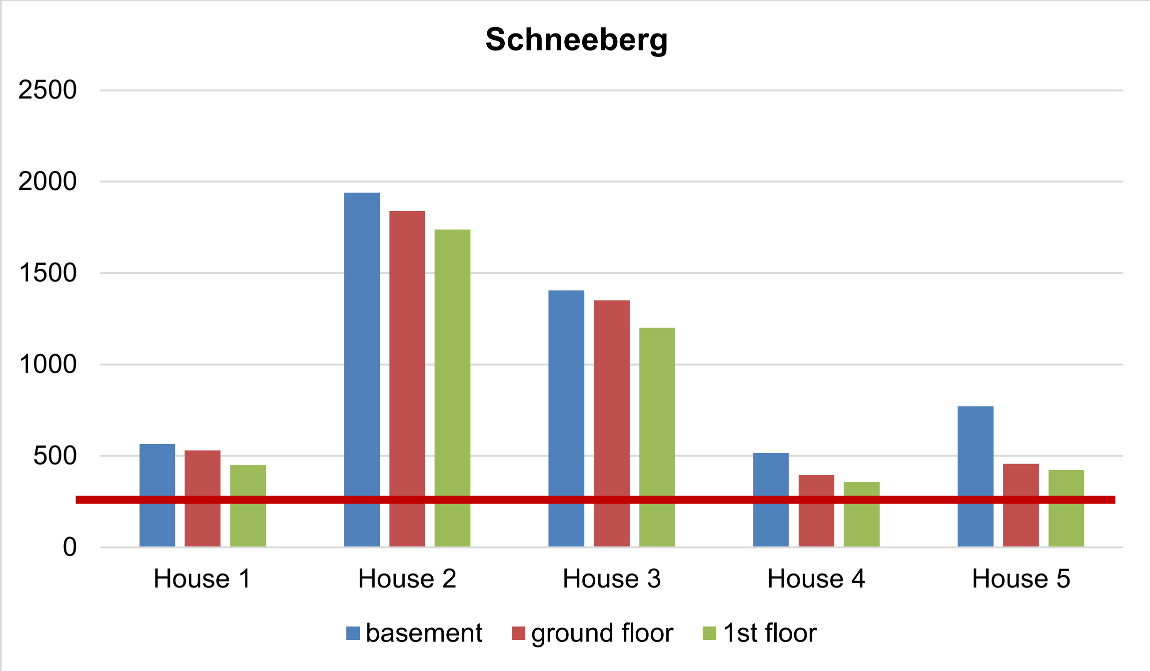

Figure 21: Radon concentrations in low-rise buildings in Germany

In Germany, there are different types of instruments that are used to measure radon concentrations in rooms [38]. These include:

- Electronic radon detectors: These are the most common instruments for measuring radon concentration indoors. They are designed for long-term measurements lasting several months. Detectors can be installed in a room for a certain period of time and then removed to analyse the data obtained.
- Alpha spectrometers: These are more sophisticated instruments that provide more precise measurements of radon concentration. They are able to detect not only the concentration of radon but also its decay products. Alpha spectrometers can be used for both short-term and long-term measurements.
- Contimeters: These instruments are designed for continuous monitoring of radon concentrations indoors. They can be permanently installed indoors and provide real-time radon concentration data.
- Active Radon Collectors: Special instruments used to collect indoor air samples. They can be installed in a room for a certain period of time and then withdrawn for subsequent data analysis in a laboratory.

In general, it is recommended to use instruments that are certified according to the requirements and standards established in Germany and the European Union for the measurement of radon concentrations indoors [39].

2.4 Calculation of radon concentration as a function of floor height and air exchange rate

The following specific graphs and dependencies were created using Microsoft Excel:

- A dot plot illustrating the relationship between radon concentration and floor height.
- Trend line presented as a polynomial relationship. These graphs show the general trend of radon concentration as a function of floor height.

There are also data reflecting the dependence of radon concentration on countries, which are presented in the corresponding Figures 22, 23 and 24 concerning measurements for three countries.

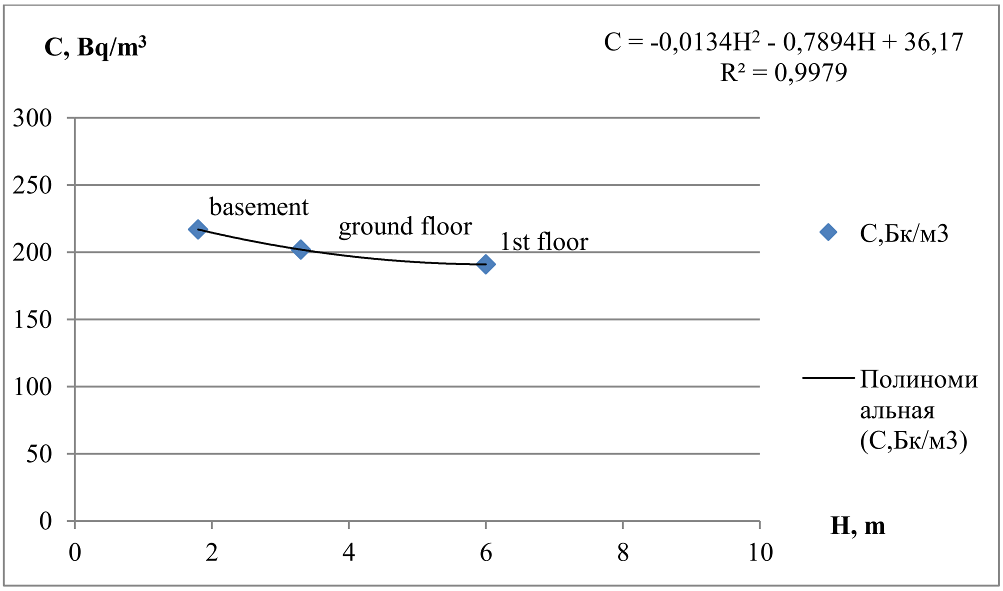

Figure 22: Dependence of radon concentration on floor height Tyumen, Russian Federation

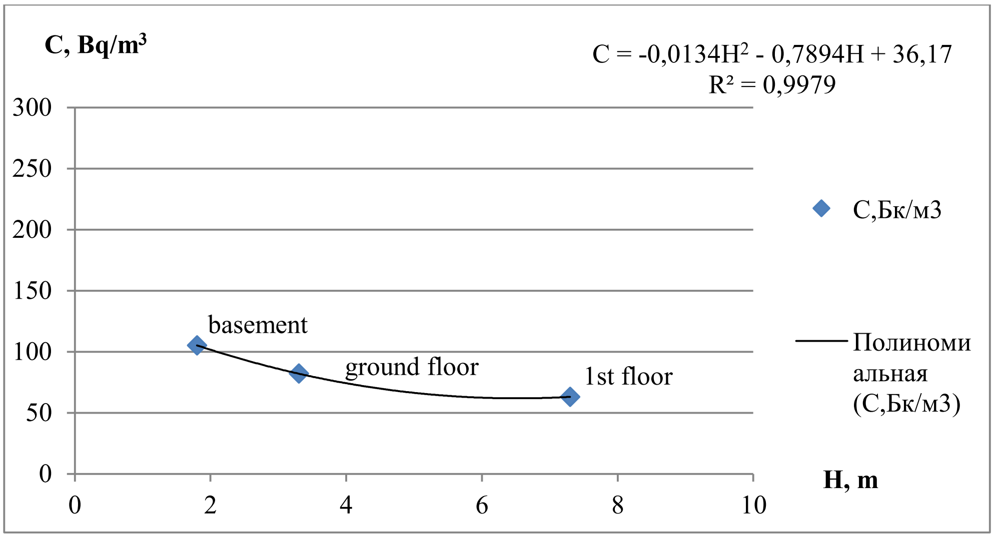

Figure 23: **Dependence of radon concentration on floor height Leoben, Austria**

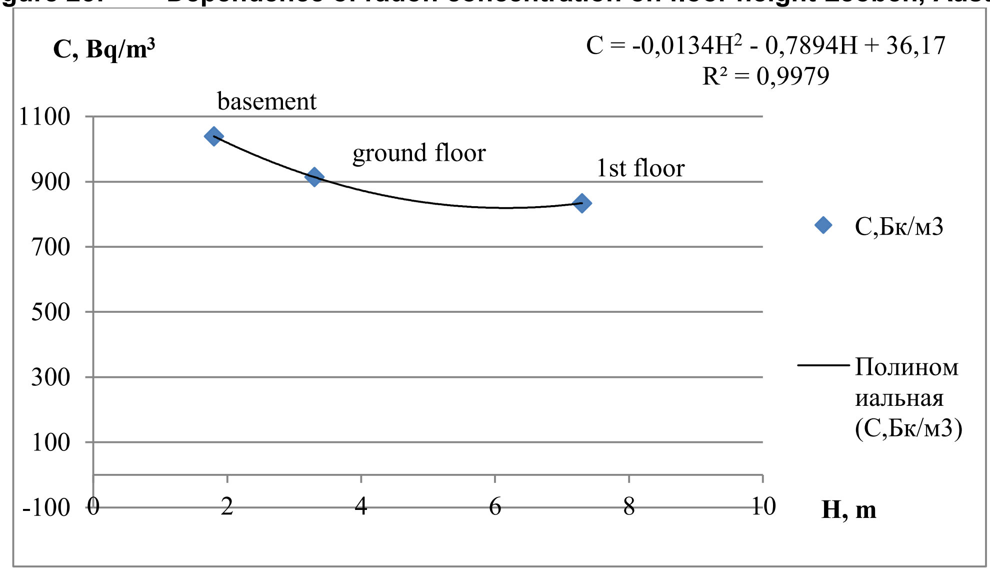

Figure 24: **Dependence of radon concentration on floor height Schneeberg, Germany**

Using this program, equation (2.1) has been automatically formulated to calculate the concentration of hazardous gas at any height. This equation becomes a useful tool when designing a ventilation system because it allows the determination of the required air exchange volume for efficient ventilation.

$$C = -0{,}0134H^2 - 0{,}7894H + 36{,}17 \qquad (2.1)$$

C – radon concentration, Bq/m^3;

H – floor height from the foundation at which the air exchange rate is measured, m.

Using Microsoft Excel, the approximation reliability coefficient R^2 was also calculated, which was 0.9979. Taking into account that the approximation reliability coefficient value is close to 1, we can conclude that equation (2.1) describes accurately the spread of experimental data [40].

In order to obtain dependence of radon concentration on air exchange rate we have to calculate it by the formula:

$$Q = \upsilon * S, \tag{2.2}$$

где Q – air exchange rate, m3/h;

υ – air renewal rate, m/s;

S – ventilation opening area, cm2.

Dimensions of the ventilation opening: a = 13 cm, b = 16 cm.

Ventilation opening area: S=208cm2.

Air exchange rate (υ) was measured with an anemometer TESTO 425.

In order to create a graph it is necessary to have data on radon concentration depending on the floor, on which the measurement was made, as well as data on dependence of gas concentration on ventilation rate [41]. After obtaining all necessary data, diagrams of radon concentration dependence on air exchange rate can be plotted using Microsoft Excel (Figures 25, 26, 27).

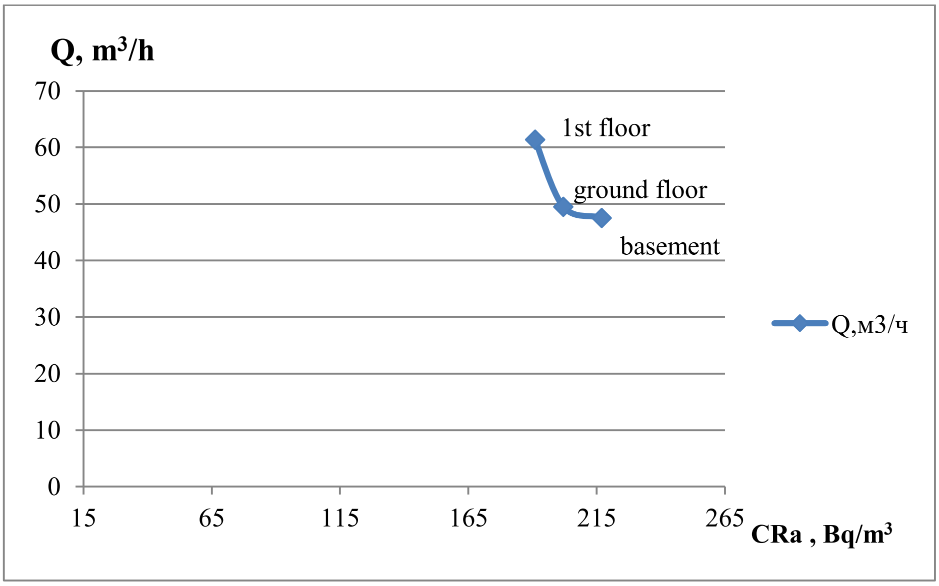

Figure 25: Dependence of radon concentration on air exchange rate Tyumen, Russian Federation

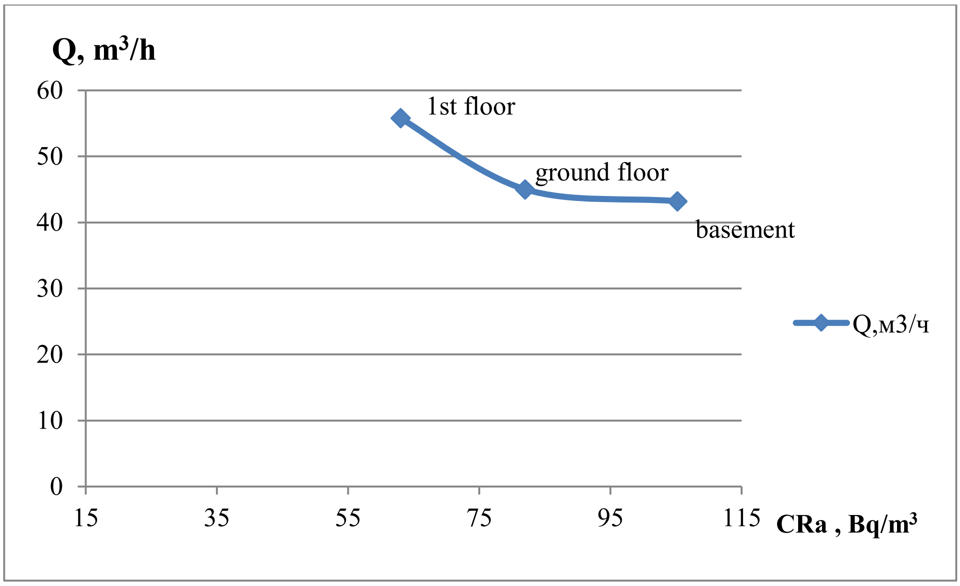

Figure 26 Dependence of radon concentration on air exchange rate Leoben, Austria

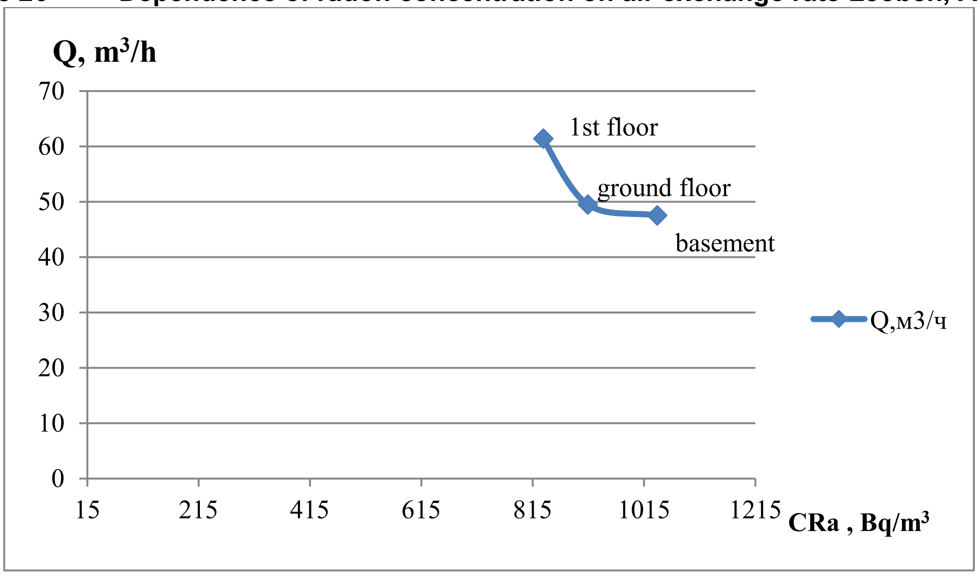

Figure 27: Dependence of radon concentration on air exchange rate Schneeberg, Germany

It is important to note that with increasing the rate of air exchange, the radon concentration decreases. This allows us to conclude that the ventilation system in the housing complex was designed and constructed with due consideration of the required speed and rate of air exchange. As a result of such measures, the radon concentration in the premises of this complex does not exceed permissible limits and the air in the dwellings is safe.

3 Calculation results and recommendations for protecting residential buildings from radon

3.1 Main methods of radiation protection in the Russian Federation

The accumulation of radon indoors depends on various factors, with the energy efficiency class of the building not being the most important one. The characteristics of the ground and the design of the underground building shell are important. Radon levels can also vary depending on the condition of the ground-atmosphere-building system. However, about 90% of radon enters the building from the ground, so if the building base has a sealed monolithic slab, the source of radon will be negligible. Even if there are defects in the underground containment, this gas will accumulate predominantly on the lower floors. Radon emitted from walls cannot accumulate in significant quantities indoors because of its short half-life.

Radon levels in private homes are usually higher than in high-rise buildings because this gas leaks into the air from the ground. However, a homogeneous concrete foundation can protect the occupants of a private home. Higher levels of radon do appear in basements and ground floors, but this problem can be solved by regular ventilation. Houses are naturally ventilated when people open windows or doors from time to time. Radon is a highly volatile gas, so it evaporates easily and quickly.

Weather conditions also influence the concentration of radon in the soil. For example, as a result of rain, snow or frost, pores in the soil may fill with water or freeze, making it difficult for radon air to escape. As a result, the concentration of radon in the upper layers of the soil increases. In addition, when atmospheric pressure rises, air from the atmosphere additionally penetrates into soil pores and rocks, which also increases the radon concentration in the soil. When atmospheric pressure drops, more radon is released [42].

Stable radon concentrations are usually found only in deeper soil layers. The permeability of the soil to the gas is important as it determines the influence of weather conditions and the higher the permeability, the deeper a stable radon concentration can be detected.

The transfer of radon from depth affects its concentration at the surface and is determined by the gas permeability of the soil and local flow routes. The presence of cracks and fractures in the ground facilitates the transfer of radon. In some places, the concentration of radon in the soil air can be much higher than normal levels for a given region. For example, cracks in the ground may serve as pathways for radon to travel. Water that dissolves radon produced by uranium decay can deposit radon at the edges of cracks, where it is released during radioactive decay. Also, at rock subsidence, which is usually more loosened, gas permeability for radon-bearing soil air is higher. In addition, more uranium may be deposited at the boundary between the different rock types, resulting in higher concentrations of radon as a result of its decay.

If necessary, developers and architects can obtain information on the radon situation in a building site by carrying out a subsurface assessment based on measurements and properties of the natural area.

The amount of radon emitted from the ground under a building also depends on various factors including the amount of radioactive elements in the ground, the structure of the earth's crust, gas permeability and water saturation of the upper soil layers, climatic conditions, the construction of the building and others [43].

In winter, the highest concentrations of radon in residential air are observed. Choosing a building with a gas permeable floor can increase the flow of radon escaping from the ground beneath the building by up to 10 times compared to an open area. The increased flux is caused by a pressure differential between the ground and the building's rooms, which averages about 5 Pa. This is due to two reasons: the effect of wind load on the building (which causes a depression at the boundary of the gas jet) and the difference in temperature between the indoor air and the air at the boundary of the ground (known as the chimney effect).

3.2 Main methods of radiation protection in Austria

The Austrian standard (ÖNORM S 5280-2 "Radon - technical precautions for buildings") specifies various building measures for protection against radon. The basic principle is that the tighter the building envelope is adjacent to the ground, the lower the radon risk. Preventive measures prove to be simpler, cheaper and more effective than upgrading. When the work is finished, a control measurement is recommended to confirm the effectiveness of the measures taken.

The Austrian Radon Action Plan is the basic guideline for radon protection. Its goal is to reduce the population's exposure to radon in Austria and to reduce the occurrence of lung cancer. The Action Plan provides an assessment of the radon risk, identifies areas requiring action and develops strategies for implementing new or improving existing radon protection measures. The plan serves as a guide for decision-makers in the legal, scientific and practical spheres.

The Radon Action Plan includes eight topics for which action needs to be taken:

1. Radon risk assessment for the Austrian population.
2. Radon protection in new buildings.
3. Radon protection in existing residential buildings.
4. Radon protection in workplaces and public buildings.
5. Radon protection in education and training.
6. Raising awareness about radon.
7. Linking radon protection with other topics.
8. Assessment and adaptation of legislation and standards.

Each of these themes is assigned a goal, shows the current status, indicates the necessary actions, identifies responsibilities and proposes possible strategies to achieve the objectives. Some of these strategies are already in the implementation phase [44].

The Radon Action Plan is developed in accordance with Section 93 of the Radiation Protection Act 2020 and takes into account the requirements set out in Annex XVIII of Directive 2013/59/Euratom. The main remediation measures can be divided into two groups. Firstly, the reduction of radon concentrations in rooms is achieved by air dilution (e.g. mechanical ventilation, cross ventilation, shock ventilation). Second, reduction of radon intrusion from soil into the building is achieved by sealing building elements that have contact with soil, as well as by sealing between the basement and living spaces, installing a basement exhaust system, and ventilating the basement space.

Simple radon remediation measures can be carried out for as little as a few hundred euros, while more complex remediation measures can cost between 1,000 and

10,000 euros. Some regions, including Upper Austria, Styria and Tyrol, allocate funds for structural radon remediation measures in cases of high concentrations.

In the planning of new buildings, it is important to ensure that the annual average radon concentration in dwellings is well below 300 Bq/m³. In order to achieve this it is necessary to use designs of building elements, connections and passageways in contact with the ground that have convection impermeability. In most cases, high indoor radon concentrations can be avoided by properly sealing the building to the ground. In certain areas, additional simple measures such as the installation of a radon drainage system may be necessary, especially if convection-tight construction of building elements cannot be ensured or if the building site is located in a radon-proof zone [45].

The amount of radon protection measures depends on the zoning on the radon map, the type of building (construction of the elements in contact with the ground or the basement) and its purpose.

In accordance with ÖNORM S 5280-2, buildings that are airtight against non-penetrating water and have convection-tight joints and openings usually also provide sufficient sealing against radon convection.

In addition, the following constructions are sufficiently sealed against radon convection:

A solid foundation slab with a thickness of at least 20 cm combined with convection-tight passageways for pipes and lines (e.g. sewer pipes, electrical lines). If the foundation slab is connected to vertical or horizontal concrete elements that have contact with the ground, permanent convection-tightness must be ensured by means of sealing tape or equivalent measures.

If it is not possible to create a convection-tight structure for elements in contact with the ground or if the building is located in a radon-protected zone, the installation of a radon drainage system with passive air extraction is recommended. If such a system is already provided for during construction, additional costs usually range from EUR 500 to EUR 2,000.

Simple measures to seal existing areas in contact with the ground (e.g. cellars and basements) are also recommended. If the building has a basement but is not intended to contain living spaces, sealing measures between the basement and the ground floor can prevent radon from spreading into the building. These measures include sealing ducts and shafts as well as all passageways through the basement ceiling. It is also recommended to install a self-closing door in the basement that prevents radon from convecting into the living area. These measures can be useful as additional radon protection measures for optimisation purposes. A control measurement of radon concentrations is recommended after the building is completed [46].

In any case, precautionary measures are simpler, more effective and cheaper to implement than potential radon remediation measures that may be needed later. Soil gas surveys at the construction site are not recommended as they are time-consuming and costly and do not exclude the possibility of classifying the area as a radon hazard zone, even if the measured values are low.

If the indoor radon norms are exceeded (more than 300 Bq/m3), the initial measure may be regular cross-ventilation and the use of exhaust ventilation in the living area, as well as possible room modifications.

There are also significant temporal and spatial variations in radon concentrations. Daily and seasonal fluctuations are due to differences in indoor and outdoor air temperatures (chimney effect). These fluctuations can be amplified depending on habits and lifestyles (ventilation and heating). In addition, differences in the use of rooms, the location of radon penetration points and the level of air exchange result in different levels of radon concentration in rooms. Generally, radon concentrations are lower on higher floors.

It is possible to install a supply and exhaust ventilation system with heated outdoor air (recuperation system). This makes it possible to regulate the ventilation of indoor air [47].

Projects aimed at reducing radon exposure and protecting the population from radon include various measures, including:

1. Radon level monitoring: Radon level monitoring projects are carried out to assess the radiation situation in areas with high radon levels. The purpose of such projects is to identify locations with elevated radon levels, determine the causes of the phenomenon and take appropriate measures to reduce it.

2. Building isolation: Building isolation projects include the installation of special materials that prevent radon from entering buildings. This reduces the level of radon inside buildings and prevents its negative impact on human health.
3. Educational programmes: Educational programmes about radon are designed to increase public awareness about radon and its health effects. These programmes help people to take appropriate measures to protect themselves from radon and reduce their risk of adverse health effects.
4. Development of Regulations and Standards: Various countries are developing regulations and standards that specify acceptable levels of radon indoors and outdoors. These standards assist in monitoring radon levels and in responding to exceeding regulatory limits.
5. Research: Research on radon and its health impacts helps improve understanding of radon's health impacts and the development of better mitigation practices.

These initiatives aim to reduce the risk of negative health impacts of radon and to create safer urban environments.

3.3 Main methods of radiation protection in Germany

To solve the problem of radon pollution in the city of Schneeberg or anywhere else in Germany, the following steps can be applied:

1. Measuring radon levels: Radon levels in buildings, especially in basements and ground floors, are measured to determine the degree of contamination.
2. Development of an action plan: Based on the measurement results, an action plan is developed, including the identification of priority areas with high radon levels and the definition of necessary measures.
3. Repair and sealing of buildings: Work shall be carried out to seal buildings to prevent radon from penetrating from the ground. This may include filling cracks and gaps, replacing defective windows, and installing appropriate ventilation systems.
4. Improvement of ventilation: Renovation or installation of efficient ventilation systems that promote efficient air exchange and reduce radon concentrations inside buildings.

5. Education and awareness: Local authorities conduct educational programmes and provide information about radon risks and radon mitigation measures.
6. Legislative measures: In some cases, depending on detected radon levels, legislative measures may be applied, such as requiring mandatory inspection and elimination of radon problems when selling or renting property.

It is important to note that specific measures and approaches may vary depending on regional legislation and environmental policies [48].

3.4 General measures to reduce radon

To ensure effective ventilation in rooms with high radon content, two basic principles must be observed:

- Creation of a small overpressure inside the rooms compared to the atmospheric air pressure outside the building. This condition prevents radon from penetrating from the atmosphere through windows and other possible passageways.
- Arrangement of fresh outside air flow along the floor of the room [49]. This principle takes into account the fact that radon, as a heavy gas, accumulates in the lower part of the room.

One of the most efficient methods of ventilation in such rooms is removal of radon from under floors of the ground floor. Special ventilation ducts are used to remove air from underneath the ceilings outside the building. The layout of pipelines and ducts may differ depending on the construction of the building.

Gas isolation or sealing of building structures is used to reduce the penetration of radon into the living floors [50]. Gas insulation is often combined with damp-proofing of basement and ground parts of buildings since the materials used for damp-proofing also have gas barrier properties.

The vapour barrier layer can also act as a barrier to radon. It is important to note that plastic foils - particularly polyethylene foils - let radon through. Therefore, polymer-bitumen roll materials and mastics are recommended for gas and waterproofing the basement of a building [51].

To achieve a good gas and water barrier, a method of bonding the structure with special waterproofing materials can be used. The joints of the rolled gas and water barrier materials, which are laid dry, must be sealed with adhesive tape. The insulation of horizontal surfaces must be tightly connected to the same covering of vertical structures. Particular attention must be given to careful sealing where communication pipes pass through ceilings and walls [52]. Such a barrier may not be sufficient and therefore a ventilation system or radondraining is used:

Drainage pipes with a diameter of at least 80 mm are laid under the concrete or foundation slab. Usually, when laid in gravel or rubble, the pipe system is laid, for example in a star or serpentine pattern, with a pipe spacing of up to 8 m and joined together to form a drainage pipe (solid wall pipe) of at least 125 mm diameter - preferably 150 mm - and must be laid inside the building above the roof (for example in the installation room) (figure 28). If the continuous wall pipe passes through an unheated attic, it must be insulated. Condensation on the outside of the pipe must be prevented by appropriate measures [53].

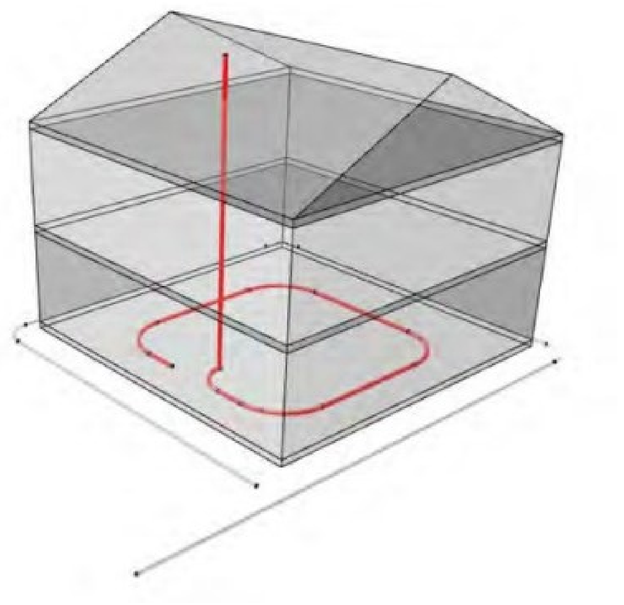

Figure 28: General scheme of radon extraction

It is very important to make a convection-tight construction of the building elements using the following materials (figure 29):

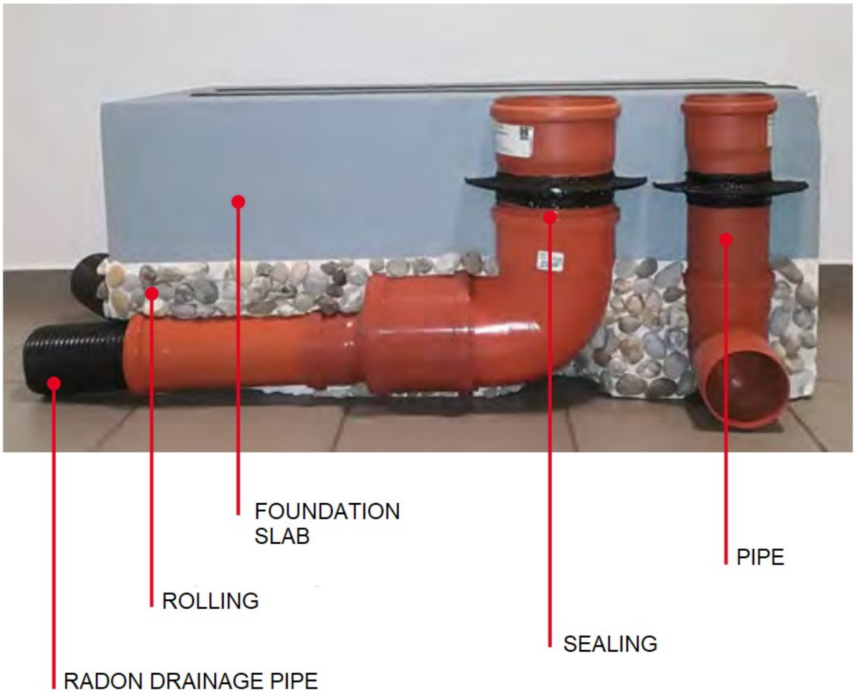

Figure 29: Example of using materials

The measure itself would look as follows (Figure 30):

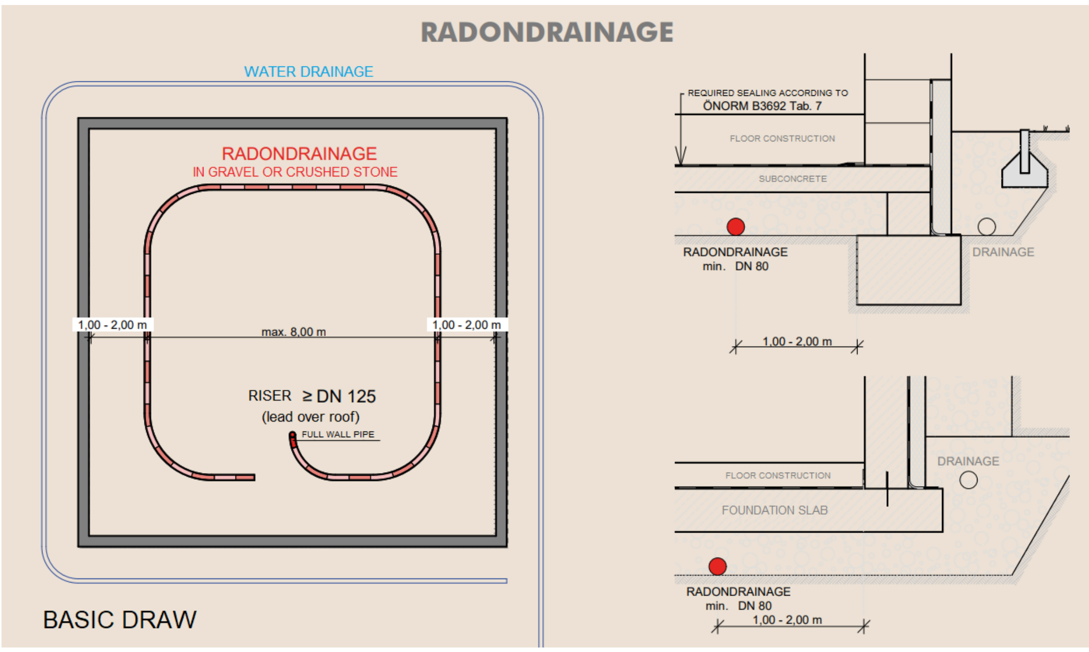

Figure 30: Layout of radon drainage in a building

Guidelines:

- Mechanical ventilation: The ventilation system must not cause negative pressure in the building. Fresh air intake at least 80 cm above the floor and at a sufficient distance (at least 100 cm) from basement vents.

- Earth sensing: Sealed pipe construction through components in contact with the ground (e.g. RDS).
- Air-to-ground heat exchangers: Use sealed pipes. Check regularly by measuring radon.
- Air wells: Limit the filling to gravel with a permanent impermeable layer (e.g. clay, foil).
- Regular inspection with radon measurements.
- Drains: Closed drains with siphonic drainage [54].

4 Conclusion

It has been scientifically proven that radioactive radiation poses a serious threat to everyone's health. The easiest way to be exposed to radiation is to inhale air that may contain radon, a substance that can either be a harmless compound or cause dangerous diseases.

Detecting radon and identifying areas with dangerous concentrations can be done quite easily and at low cost. Radon testing in residential areas is relatively inexpensive and quick. In order to reduce the risk of diseases, it is important to use the right materials in buildings and facilities, to pass water through filters and to ventilate the rooms more frequently.

In this thesis, low-rise residential buildings in the Russian Federation, Austria and Germany were investigated. The results showed elevated levels of radon in residential buildings in Tyumen (1-1.5 times the maximum permissible concentration) and Schneeberg (3 times the maximum permissible concentration). The values in Leoben were within the established maximum permissible concentration (MPC). Thus, the following is recommended for houses in the Russian Federation and Germany:

1. Conduct a survey of the premises to identify dangerous levels of radon concentrations in the air.
2. Install cleaning systems and filters for water and air.
3. Take measures to limit radon intrusion from the soil.
4. Eliminate sources of radiation, if necessary.
5. Consider recommendations in design solutions, such as ventilation of rooms, impregnation, coverings, use of membranes and barriers, radon collectors, depression of the subsoil, sealing of joints, seams and openings.

Today a lot of experience has been accumulated all over the world on repair and ventilation measures aimed at reducing radon concentration in indoor air. Moreover, the study of radon content can be included in engineering and environmental studies during the construction of residential facilities to immediately identify and mitigate adverse effects on human health.

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6 List of Figures

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