APPLIED METHODS FOR ESTABLISHING RADON EXPOSURE IN UNDERGROUND SITES

Blagovesta Vladkova, Dimitar Dimitrov, Nadezhda Kostadinova, Zahari Dinchev, Diana Makedonska, Alexander Krilchev

University of Mining and Geology “St. Ivan Rilski”, 1700 Sofia; E-mail: blagovesta.vladkova@mgu.bg; ph001@mgu.bg; nadezhda.kostadinova@mgu.bg; dinchev@mgu.bg; diana.makedonska@mgu.bg; krilchev@mgu.bg
Corresponding author**:** *nadezhda.kostadinova@mgu.bg*

ABSTRACT: Radon is a member of the uranium-radium decay family, it is distributed everywhere on Earth – in soils, rocks, minerals, water and air. Part of the radon emitted in the volume of earth mass migrates through air pores and crevices, reaches its surface and is released (exhaled) into the surface air. Radon is the dominant factor for the Earth's population exposure from the natural radioactive sources. Irradiation in buildings is considerably greater than outdoor irradiation because it penetrates freely into them as earth gases through defects in the outer tiling and small cracks in the foundations; the deemanation of radon from water; exhalation from building materials with an increased content of 226Ra. The seepage of radon from the Earth's bowels can be observed in any closed ground spaces, tunnels, underground garages, basements. Radon entry into buildings depends on many factors, such as changes in atmospheric pressure, wind speed and precipitation, etc. Monitoring of radon concentration is relevant to human health if indoor radon concentration is high. The present study presents experimental measurements for radon content in four underground sites on the territory of the Sofia city, performed by means of two methods - numerical and analytical.

Key words: radon, thoron, exposure, safety, monitoring

ПРИЛОЖНИ МЕТОДИ ЗА УСТАНОВЯВАНЕ НА ЕКСПОЗИЦИЯ НА РАДОН В ПОДЗЕМНИ ОБЕКТИ

Благовеста Владкова, Димитър Димитров, Надежда Костадинова, Захари Динчев, Диана Македонска, Александър Крилчев

Минно-геоложки университет „Св. Иван Рилски“, 1700 София

РЕЗЮМЕ: Радонът е член на уран-радиевото семейство на разпад, той е разпространен навсякъде по Земята – в почви, скали, минерали, води, въздух. Част от радона, отделен в обема земна маса, мигрира през въздушните пори и цепнатини, достига до нейната повърхност и се освобождава (ексхалира) в приземния атмосферен въздух. Радонът е доминиращ фактор при облъчване на населението на Земята от естествените радиоактивни източници. Облъчването в затворени помещения (сгради) е значително по-голямо от облъчването на открито. В тях той прониква чрез почвения газ, проникващ през дефекти във външната обвивка и пукнатини в основите на сградата; дееманацията на радон от вода; ексхалация от строителни материали с повишено съдържание на 226Ra. Ексхалацията на радон от земните недра на практика може да се наблюдава във всякакви затворени приземни пространства, тунели, подземни гаражи, мазета. Навлизането на радон в сградите зависи от много фактори, като промени в атмосферното налягане, скоростта на вятъра и валежите и др. Мониторингът на концентрацията на радон е от значение за човешкото здраве, ако концентрацията на радон в помещенията е висока. В настоящото изследване са извършени експериментални измервания на нивата на радон в четири подземни обекти на територията на София, посредством два метода - цифров и аналитичен.

Ключови думи*:* радон, торон, експозиция, безопасност, мониторинг

Introduction

Radon is a radioactive gas discovered by the French chemist Friedrich Dorn in 1900. As early as the 16th century, the Swiss physician and naturalist Paracelsus mentioned in his book a “mysterious Schneeberg miner's disease”. This is considered one of the oldest written pieces of evidence for the existence of the so-called “radon problem”, which led to the deaths of miners in the Schneeberg mines of Saxony and Jáchymov, Czechia. This fact is also described in the remarkable mining book of that era, “De Re Metalica”, by Agricola (Dimitrov, 2020).

After the discovery of radon, it was listed as a probable cause of lung cancer. This opinion was reinforced after 1924, when high levels of radon-222 were first measured in the Schneeberg mines. In 1951, Bale found the real cause of lung cancer in miners, namely internal exposure from short-lived decay products of radon, also called “daughter products” of radon – these are 218Po, 214Pb, 214Bi and 214Po, (as 214Po is always in equilibrium with 214Bi and this fact is the reason why 214Po is not considered alone). The natural radiation background affects humans, and half of the effective dose received is due to radon.

Each year, around 1.8 million people worldwide develop lung cancer, making it one of the cancers with the worst prognosis – most patients die within a few years. According to the World Health Organisation (WHO) data from 2014, between 3% and 14% (about 230,000 people) of these cases are linked to radon. It is the second highest risk factor after smoking, and for non-smokers, it is the number one risk factor (WHO, 2009).

The only way to assess the levels of exposure due to various radon isotopes is through measurement. The majority of human exposure comes from radon decay products. Their measurement is directly related to the absorbed dose. Currently, measurements of radon alone can be conducted widely and over long durations, as recommended by WHO. Reference levels for buildings and workplaces in the European Union and in this country are given in terms of the annual average volumetric activities of 222Rn. For Bulgaria, the reference levels are 300 Bq/m^3 for buildings and workplaces (Directive 2013/59/Euratom; Ordinance on Radiation Protection 2018).

Variations of Radon

Radon is heavier than air and has no stable isotopes. It is an isotope from the uranium-radium series, originating from uranium-238 (238U) (Mezovska V. 2018). In the natural environment, there are three radioactive isotopes of radon that are part of the natural radioactive series: actinon (219Rn) (T1/2 = 3.96s) from the 235U series; thoron (220Rn) (T1/2 = 55.6s) from the 232Th series; and radon (222Rn) (T1/2 = 3.82d) from the 238U series (Dimitrov, 2020) (Fig. 1).

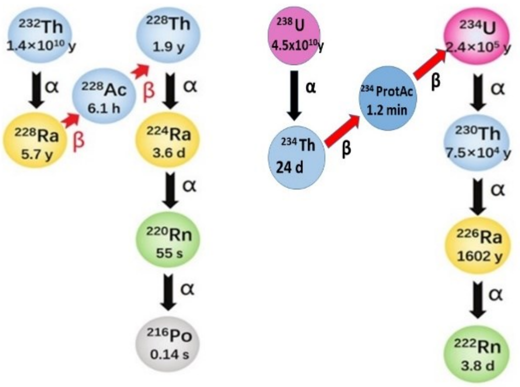

Fig. 1. Decay chains of the uranium-radium series

Spreading and impact

Inhaled radon reaches the lungs and emits α-particles, causing internal irradiation of the lungs. Radon inhaled into the body is further decomposed into hereditary nuclides, which then migrate from the lungs and oesophagus to the digestive organs along with body fluids, causing additional internal exposure.

The main sources of radon in closed spaces (buildings) (Fig. 2) are:

- Soil gas penetrating through the foundations of the building;

The demanation of radon from;

- Exhalation from building materials with an increased content of 226Ra;
- Intake through ambient air from the environment. This source is secondary, but it can become essential if there are sites and facilities, such as mining sites, tunnels for highway pipes, boreholes, etc., nearby. (Fig. 3).

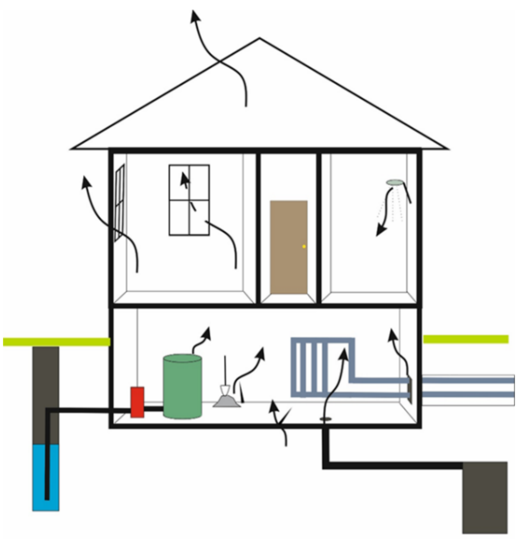

Fig. 2. The main sources of radon in closed spaces

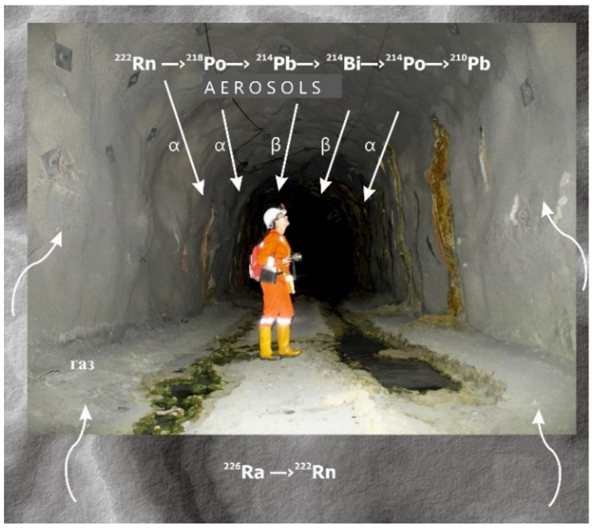

Fig. 3. Radon impact in underground mining sites

In underground mining sites, the concentration of radon may increase as a result of release from the rock massif during blasting operations or through groundwater (Shishkov and Stoycheva, 2021; Hristova et al., 2023).

Methodology

Selected Radon Measurement Methods

For the present study, experimental measurements have been carried out using two methods for measuring radon content in underground objects - digital and analytical. The aim is to monitor the processes of accumulation of hazardous gases in confined spaces, and accordingly to prepare models to ensure the health and safety of the working and living environment.

The analytical method for cumulative measurements of radon (222Rn) and thoron (220Rn): consists of placing CD/DVD plates for measuring radon/thoron in underground spaces and mine workings (mining galleries, caves, etc.). This includes specifying the influence of underground conditions on the readings of these detectors and comparing them with other methods (Dimitrov and Pressyanov, 2018).

In 2011, the capacity of the CD/DVD method was expanded (Pressyanov et al. 2014, 2015, 2018) with the possibility of differential measurements of thoron 220Rn, using a development of the CD-disk method. This also makes it possible to clarify the contribution of thoron to the irradiation of miners and over ground personnel.

The principle of the CD/DVD method: combines the high absorbency of the polycarbonate material of the discs with its track properties (Fig.4 and Fig. 5).

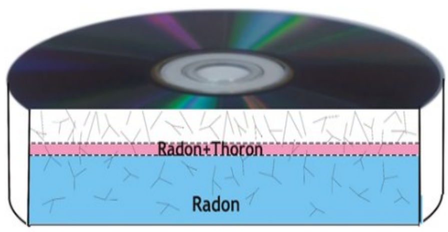

Fig. 4. The principle of the CD/DVD method for measuring radon and thoron. Signal formation.

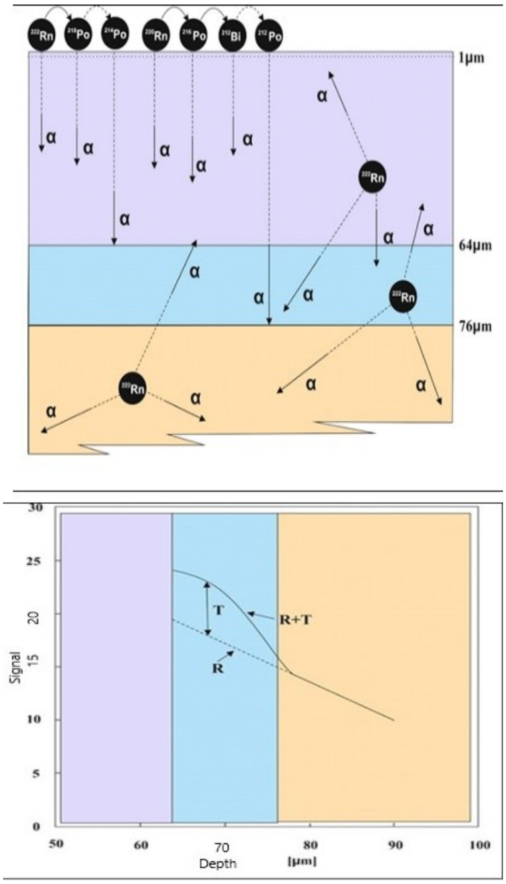

Fig. 5. Relationship between the density of the tracks at two depths below the surface of the polycarbonate and the time-integrated concentration of 222Rn (CF-calibration factor).

The calibration factor depends on the temperature at the time of irradiation. The temperature influence can be reported, incl. If it is not known, a posteriori correction can be applied. Other factors (pressure, dust, smoke, blast waves) do not affect the CD/DVD method. The CD/DVD method is sensitive and accurate enough to measure 222Rn and 220Rn in underground spaces and mines.

The digital method was applied using the *Radon Scout PLUS* radiometer (Fig. 6; Table 1), which carried out continuous monitoring of the concentration (volume activity) of radon in various underground sites (Gorbounov and Chen, 2019).

Fig. 6. The *Radon Scout PLUS* radiometer

Table 1. *Technical data of the Radon Scout PLUS radiometer*

Measurement range	0 – 10 MBq/m^3
Increased sensitivity	1,8 impulse/min @ 1000 Bq/ m^3
Built-in sensors for:	
- Relative humidity	(0 ... 100%)
- Temperature	(-20 ... 40°C)
- Pressure sensor	800 - 1200 mbar
2G Sensor	detecting movements/ hits
Measurement interval	1 hour or 3 hours can be adjusted
Measuring	Measuring chamber with HV collection and Si detector
Memory	672 Records
Display	3x16 Characters
Dimensions	175 x 135 x 55 mm
Weight	800g batteries incl.
Software included	Radon Vision

Other measurement methods

In addition to the methods chosen for this study, the most commonly used devices for determining the concentration of radon are: Alpha detectors, Activated carbon detectors, Electret ion chambers, Electronic sensors. Table 2 compares these methods.

Table 2. *Radon Measurement Methods*

Detector	Passive / Active	Uncer-tainty (%)	Duration of measure-ment	Price	Moisture resistance
Tracks	Passive	10-25	1-12 months	low	Depp. on application
Activated carbon	Passive	10-30	1-7 days	low	no
Electret ion chambers	Passive	8-15	5 days – 1 year	average	no
Electronic sensors	Active	~ 25	2 days – year (s)	average	no
Monitors for continuous measurements	Active	~ 10	2 days – year (s)	high	no
CD/DVD	Passive	10-20	year (s)	low	yes

Selection of underground sites for measurement

Four underground objects described in Table 3 were selected for the study. Figure 7 shows the location of the underground sites on the territory of the city of Sofia.

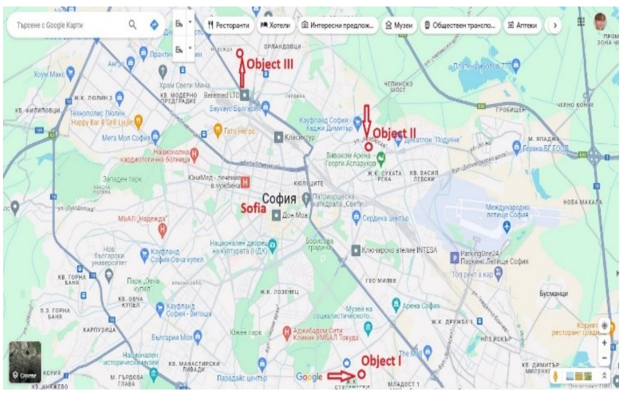

Fig. 7. Location of the sites on the territory of the city of Sofia.

Table 3. *Location and characteristics of the sites*

Object	Area	Type of location	Elevation	Period	Measurement duration
1	Sofia, Studentski grad	basement	-1,5 m	03.06. 23 - 13.11. 23	5 months – Analytical method; 7 days Radon Scout PLUS
2	Sofia, Hadzhi Dimitar res. area	Under-ground garage	-2 m, 20-23°C	03.06.2023 - 08.11.2023	5 months – Analytical method
3	Sofia, Nadezhda res. area	basement	- 2 m	03.06.2023 07.11.2023	5 months – Analytical method; 20 days Radon Scout PLUS
4	region Sofia	Under-ground mine	810, - 760	03.07.2023 08.11.2023	4 months – Analytical method; 20 days Radon Scout PLUS

OBJECT I – Sofia, Studentski grad –
Position 1 – Basement – elevation [– 1.5 m], Area 2.5 m^2

Fig. 8. Locations of the disks and radiometer at object I – position 1

Position 2 – Basement corridor

Fig. 9. Location of a disc in object I – pos. 2

The measurement data in the basement site Studentski Grad are summarised in Table 4. Figure 10 shows the report obtained after measuring with a *Radon Scout PLUS* device.

Table 4: *Reporting data from CD plates for object I:*

CD / No	Ca, Bq/m^3	δ_Ca, Bq/m^3	Object
7	45.95555	21.0%	basement
8	14.38977	19.7%	

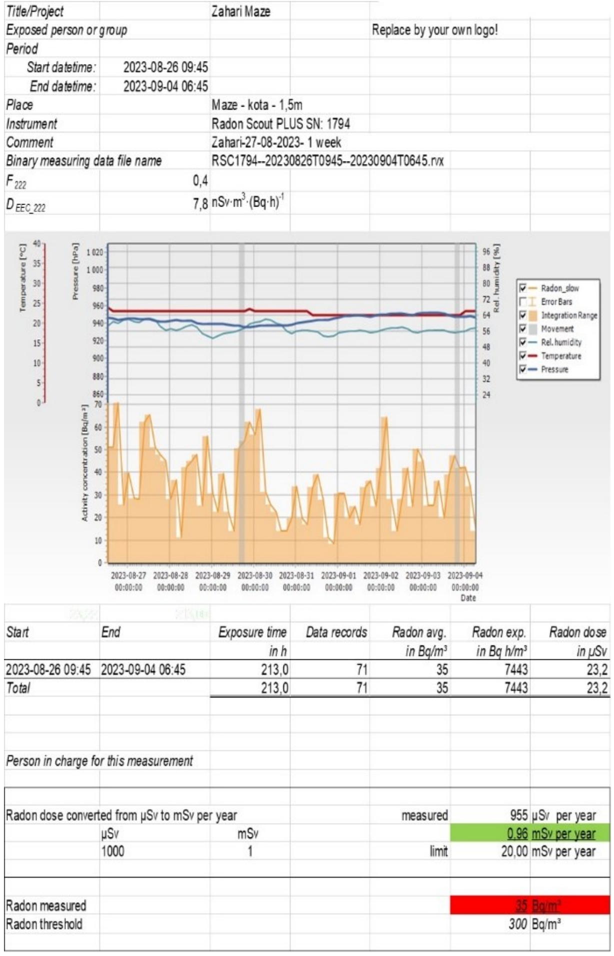

Fig. 10. Radon Scout PLUS measuring report for Object I

OBJECT II /Position 1 – Sofia, Hadzhi Dimitar res. area, Underground garage near the front door, elevation [– 2 m], Area 900m^2; Analytical method of measurements

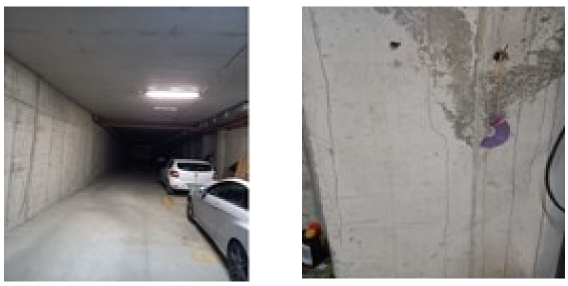

Fig. 11. Locations of the disks at object II – position 1

OBJECT II /Position 2 - Unventilated corner in an underground garage (Fig. 12)

Fig. 12. Location of a disc in object II – position 2

Due to lack of access control at object II, no measurement with a *Radon Scout Plus* radiometer was carried out in it. The results obtained from the measurement by the analytical method are summarised in Table 5.

Table 5: *Reporting data from CD plates for object II:*

CD / No	Ca, Bq/m³	δ_Ca, Bq/m³	Object
3	94.72281	14.3%	Underground garage
4	123.3058	11.5%	

OBJECT III – Sofia, Nadezhda res. area
Basement – elevation [– 2 m], area 3,2 m²
Position 1 – Basement (Fig. 13).

Fig. 13. Locations of the disks and radiometer at object III – position 1

Fig. 14. Location of a disc in object III – position 2

In object III, both measurement methods were applied. The results obtained by the analytical method are presented in Table 6, and Figure 15 visualises the measurement report with *Radon Scout Plus*.

Table 6: *Reporting data from CD plates for object III:*

CD / No	Ca, Bq/m³	δ_Ca, Bq/m³	Object
5	68.72841	13.9%	Basement
6	56.72616	12.1%	

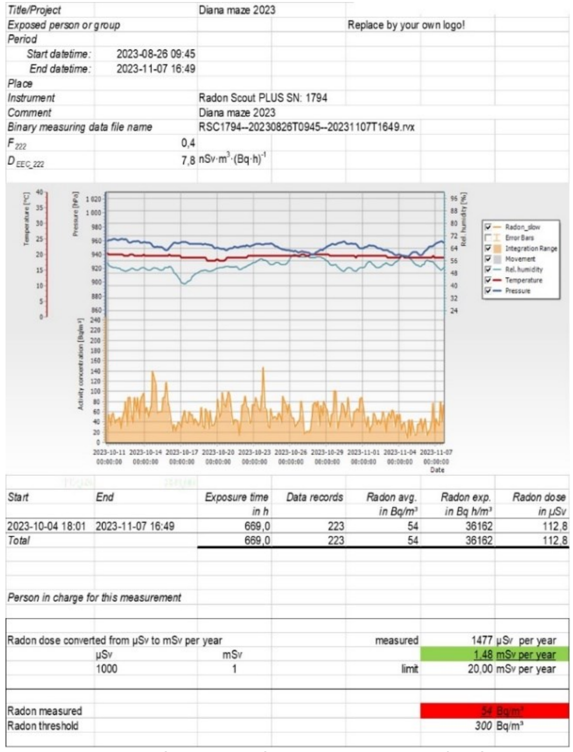

Fig. 15. ***Radon Scout PLUS*** **measuring report for Object III**

OBJECT IV – Underground mine – elevation [– 810; - 760 m], Area 25 m²

Fig. 16. Locations of the disks and radiometer at object IV - position 1

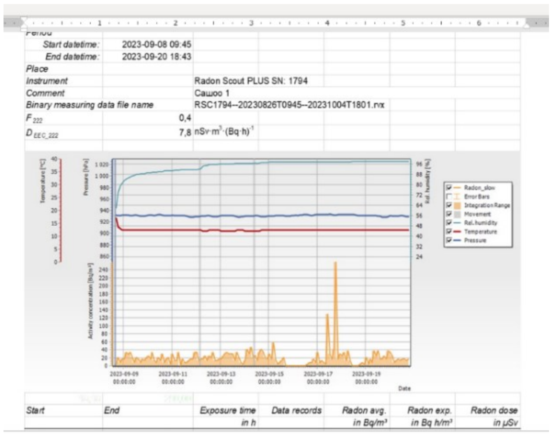

Fig. 17. ***Radon Scout PLUS*** **measuring report for Object IV**

Table 7: *Reporting data from CD plates for object IV:*

CD No	Ca, Bq/m³	δ_Ca, Bq/m³	Object
1	128.2615	13.2%	Underground mine
2	125.1702	18.5%	
9	**306.0969**	13.0%	Underground mine
10	25.74966	18.0%	
11	110	15.9%	
12	66.45911	15.1%	
13	69.12988	11.7%	
14	129.0014	15.9%	
15	72.13144	15.6%	
16	84	22.0%	
17	69.51581	15.7%	
18	28.56191	15.7%	
19	53.71669	9.8%	
20	56.97182	9.3%	
21	68.14635	16.1%	
22	113.9955	16.1%	
23	**245.0859**	18.6%	
24	121.0355	11.7%	
CD	96.79723	19.3%	

Result and analysis

The emanation of radon into buildings depends on many climatic factors, such as changes in barometric pressure, soil and air humidity, wind speed and direction, precipitation, etc. As a consequence of these influences, in addition to daily fluctuations, indoor radon concentrations show significant seasonal variations. Therefore, long-term (from three months to one year, according to WHO requirements) radon measurements in homes, educational, working and public buildings are needed. Monitoring radon concentrations is important for human health. Prolonged exposure to environments with high radon concentrations can lead to a significant increase in the risk of developing lung cancer (Fig. 18).

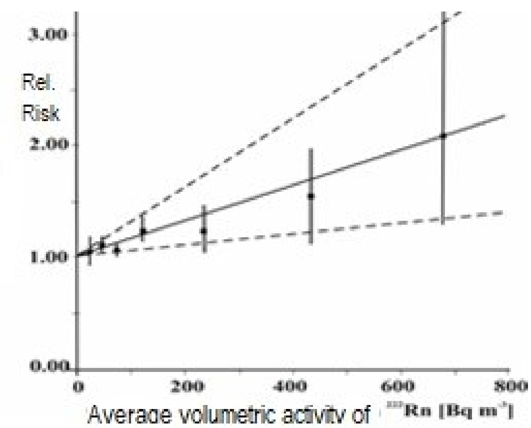

Fig. 18. Relative risk for lung cancer vs. the average residential radon concentration (WHO)

Specialised radon measurement is the only way to detect increased concentrations of radioactive gas in residential or public buildings. It is important to mention that during the winter months, there is an increase of about 4 times compared to the warmer ones. The concentration of radon is also influenced by the structure of the building and its ventilation. This also determines the complexity of forecasting.

It is important to note that within a day, variations in concentration are possible on the order of tens of times, depending on atmospheric changes. Therefore, the short-term measurement is not sufficiently representative.

Various underground objects have been selected for the study. The aim of the authors is to cover sites of different depth and purpose – residential buildings, industrial zones, and underground mines, where the expectations are for an increased radon emanation and different ventilation conditions. A continuous measurement was carried out using the passive method within 5 months. Using an active method (with an electronic device), the duration of the study is indicated for each object in Table 3. The challenge in these measurements was the low levels of radon and, as a consequence, the low density of the tracks. This low signal density results in a higher relative error (Table 8).

Table 8. *Comparison of data reported by CD-plates for all objects*

CD / No	Vol. Concentration: Ca, Bq/m3	Deviation: δ_Ca, Bq/m3	Object
1	128.2615	13.2%	Underground mine
2	125.1702	18.5%	
3	94.72281	14.3%	Underground garage
4	123.3058	11.5%	
5	68.72841	13.9%	Basement
6	56.72616	12.1%	
7	45.95555	21.0%	Basement
8	14.38977	19.7%	
9	306.0969	13.0%	Underground mine
10	25.74966	18.0%	
11	110	15.9%	
12	66.45911	15.1%	
13	69.12988	11.7%	
14	129.0014	15.9%	
15	72.13144	15.6%	
16	84	22.0%	
17	69.51581	15.7%	
18	28.56191	15.7%	
19	53.71669	9.8%	
20	56.97182	9.3%	
21	68.14635	16.1%	
22	113.9955	16.1%	
23	245.0859	18.6%	
24	121.0355	11.7%	
CD	96.79723	19.3%	

Conclusion

In recent decades, the attention of the economy and society has been increasingly turned to the future, with a certain amount of anxiety caused by the consequences of our current actions for future generations. Undoubtedly, the development of technology in all aspects of human life brings with it many positives. Unfortunately, rapid leaps in development are accompanied by harm, leaving a lasting imprint on human development and the environment. Improving the environment is also related to the creation of healthy and safe living and working conditions.

According to the Basic Standards of Radiation Protection included in National action plan (2018) and Strategy for Reducing the Risk of Radon Exposure (2018) recommended levels are accepted for the concentration of radon. If levels above the recommended ones are found, measures are taken to improve ventilation, reduce the entry of radon on the premises, etc.

According to the measured radon values in buildings, these are classified into three levels of risk – low, medium, and high. For each type, there are regulated specific measures that are evaluated at the design stage. In addition to the protection of new buildings, regulatory documents also describe in detail the technical requirements for radon protection in existing buildings.

Bulgaria has been present on the European map of natural radionuclides for several years. The purpose of the radon map is to outline the regions where high levels of radon are likely to be detected. The measurements carried out so far have covered some larger cities, cities with an increased incidence of lung cancer, as well as settlements influenced by the former uranium mining industry. The studies are not systematic and do not show the overall picture of exposure of the Bulgarian population.

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