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Faculty of Nuclear Sciences and Physical Engineering

National Radiation Protection Institute

BOOK OF ABSTRACTS

Contents

RADON2024 Conference sponsors

Intercomparisons of passive radon detectors at UKHSA

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Radon is a colourless, odourless radioactive gas which is the largest source of our annual radiation dose. It can only be measured using detectors, which can be passive or electronic.

Passive radon detectors are cheap and easy to manufacture or to buy, so companies can provide a radon measurement service for householders and employers. The accuracy of the detectors depends on various factors, such as how they have been stored before use, the sensitivity of the plastic detection medium, the design of the detector casing, the method used to etch the detector medium, how the exposed pits are counted, plus staff training, record-keeping and reporting of results.

In view of this, laboratories undergoing accreditation or renewing their accreditation should take part in recognised intercomparison exercises each year, where their detectors and those of other laboratories are exposed to a range of radon levels in a radon chamber. Their reported results are then compared against a reference instrument (e.g. ATMOS 12 DPX ionization chamber calibrated annually against a radon gas source from an accredited radon laboratory) to determine the performance classification. This can be useful for laboratories to confirm that their systems are working properly or to discover where they can make improvements.

UKHSA and its predecessor organisations have been carrying out the intercomparison every year, for over 40 years, typically for around 30 laboratories worldwide. All passive detectors are exposed side by side to 5 different exposures in our radon chamber, plus a transit group that is not exposed, which acts as a transit control. The detectors can be etched track, electret or (for UK laboratories only), charcoal.

Laboratories are ranked according to their performance (accuracy and precision). Anonymised results are shown from a recent intercomparison.

For those interested in taking part in future intercomparisons, or for more information, please contact radon.calibration@ukhsa.gov.uk.

Comparison and Application of Seasonal Radon Correction Factors in Slovakia

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The Council Directive 2013/59/EURATOM of the European Union mandates member states to implement national action plans to address long-term risks from radon exposure. The risk level posed by radon exposure can only be assessed based on its average activity indoors, derived from year round measurements. The activity of radon in houses varies over time, typically showing seasonal variations with a maximum in winter and a minimum in summer months. It is influenced by meteorological conditions (such as external temperature, air velocity, and pressure differences between the indoor and outdoor environments) as well as the activities of the house's occupants (such as ventilation and heating rates).

To address these seasonal variations, several models have been devised to calculate radon concentrations using seasonal correction factors. This method allows for determining the average annual radon concentration in buildings based on short-term measurements.

This study systematically compares the derivation of seasonal correction factors through various methodological approaches and evaluates their applicability. The derived and validated correction factors were applied to a series of 3-month radon measurements conducted in residential areas across Slovakia, providing insights into their efficacy in practical applications.

This work was supported by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and Slovak Academy of Science (VEGA Project No. 1/0019/22 and No. 1/0086/22) and the Slovak Research and Development Agency (project No. APVV21-0356).

New metrology research project RadonNET

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In frame of the research programme European Partnership on Metrology, new project ‘Radon metrology: Sensor networks for large buildings and future cities’ was accepted for funding. The project addresses the challenge of quantifying Rn-222 activity concentrations indoors, particularly in large buildings for future cities with a focus on connected, low-energy consumption buildings. The development of methods and sensors for detecting radon activity concentration as well as the creation of quality assured sensor network will enhance on-site Rn-222 metrology and provide support to the European radiation protection industry. This presentation is to introduce the project to the radon community.

Determination of the Radon Progenies Activity Size Distribution

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Knowledge of the activity size distribution of radon daughters is one of the main parameters for determining the effective dose from inhalation of short-term radon decay products. The presentation describes the laboratory validation of a method for determining the activity size distribution of radon decay products using the cascade impactor Dekati ELPI+ and the diffusion battery. Using nuclear track detectors placed on individual impaction plates of the cascade impactor, the equivalent equilibrium activity concentration of individual size classes can be determined in the ranges from 17 nm to 10 μm. For the determination of smaller particles in the area of unattached fraction, the diffusion battery is used. The presented method can further refine the knowledge of the activity size distribution of radon decay products in different types of workplace atmospheres. Workplaces with higher radon concentrations differ significantly in the size distribution of aerosol particles, radon activity concentration, and equilibrium equivalent activity concentration.

Factors influencing outdoor radon variability: A time series study in Bratislava, Slovakia

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This study investigates the temporal dynamics of outdoor radon activity concentration (RAC) in Bratislava, Slovakia, using a four-year dataset of continuous measurements. The fast Fourier Transform (FFT) analysis of the RAC data revealed the presence of periodicities at 24, 12, and 8 hours. A typical diurnal RAC cycle was observed, with peak concentrations occurring in the early morning and the lowest levels in the late afternoon. However, the diurnal RAC pattern exhibited distinct seasonal variations, being more pronounced during spring, summer, and autumn compared to winter. Seasonal variations in RAC were analyzed in the context of their daily minimum (background) and maximum values as well as their amplitudes. In order to gain insight into the underlying factors influencing RAC variability, we examined the relationships between RAC and a number of selected meteorological parameters, boundary layer height, and radon flux modelled based on uranium content and soil properties. The results of the correlation analysis indicated that the primary factors influencing the variation of background radon are wind direction, boundary layer height, and relative humidity. Wind direction was also the dominant factor affecting maximum daily RAC. The amplitude of RAC variation was strongly correlated with radon flux, temperature, and wind speed. The effect of other meteorological factors such as precipitation and atmospheric pressure on RAC was found to be statistically insignificant. Our results indicate that seasonal fluctuations in RAC are primarily influenced by changes in radon exhalation rate and atmospheric dispersion conditions caused by turbulence and thermal convection. These findings enhance our understanding of atmospheric radon dynamics.

This work was supported by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences (VEGA projects No. 1/0019/22 and 1/0086/22), the Slovak Research and Development Agency (project No. APVV-210356), and the excellent grant of Comenius University (No. UK/3056/2024).

Assessment and comparison of the long-term performance of Electronic Radon Integrating Monitors

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Many Electronic Radon Integrating Monitors (ERIMs) have been developed and retailed over the last decade. ERIMs are targeted to non-professional consumers, are smaller and lighter than an AlphaGUARD, and have a screen and/or mobile application for the display of radon levels. Many of them use a small diffusion chamber with a silicon photodiode for the detection of radon. Some ERIMs could allow a consumer to read their radon concentrations from the device daily or weekly. However, the UKHSA advice is to use it for at least 3 months to account for the diurnal and seasonal fluctuations of indoor radon. Some manufacturers also claim that their devices would not need calibration which is investigated here.

This study investigated the performance of a range of ERIMs (AlphaE, AER Plus, Canary, Corentium Pro, Radon Scout Home, Ramon and Wave) and the UKHSA passive radon detectors. The monitors were placed in a container flushed with nitrogen gas to determine their background readings for 10 days. Then all monitors and passive radon detectors were exposed for 3 months in 2019 and 2022, to 4781 Bq m-3 and 166 Bq m-3 in the UKHSA radon chamber and in a low radon exposure facility, respectively. The reference levels of radon were established with calibrated instruments traceable to a primary radon gas standard.

The performance of the ERIMs were evaluated with the UKHSA intercomparison classification based on the measurement error of the results. This allowed the grading to be based on both the accuracy and precision of the ERIMs. It was found that the performance of most ERIMs became worse when exposed to the radon levels below the UK radon Action Levels. The passive radon detectors were performing very well in both low and high radon levels, their measurement error was less than 10%.

The calibration factors of the ERIMs were measured at the beginning and the end of the experiment, to verify the claim of some manufacturers that ERIMs did not require calibration. The calibration factors were found to have greatly changed over 4 years, with percentage changes ranging from -46.3% to +63.3%.

Radon exhalation from soil and possible influence on high indoor radon concentrations

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In this paper the results of indoor radon surveys in three geologically different regions in Serbia were presented and analyzed according to the influence of nearby soil. The activity concentrations of natural radionuclides in the soil samples were determined by gamma spectrometry and indoor radon were measured applying the method of adsorption on activated charcoal. Possible correlations between radium content in building soil and indoor radon concentrations in houses were investigated for low, medium and high radon levels. Three distinguished regions of Serbia with different geological substrate were selected for this study: the agricultural region of Vojvodina, the region of Kosovska Mitrovica in industrial and mining complex of Trepča and the potential Radon Priority Area RPA – settlement Niška Banja. Very high concentrations of radium were observed in the soil near buildings with significantly elevated concentrations of radon around 10,000 Bq m-3. To explore surface exhalation rate of radon from the soil samples the method based on direct radon measurements in closed circulation of air from the exhalation chamber by active radon monitor RAD7 was used. The contribution of radon exhalation from the surface soil to the total indoor radon was estimated and discussed.

Analyses of 3 years of continual monitoring of ^{222}Rn and CO_2 concentrations in the soil and their exhalations in an area of FMPH CU in Bratislava

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Radon is a natural radioactive gas released from the soil as the result of ^{226}Ra decay. Although, together with its short-lived decay products, it is monitored mainly in a purpose of radiation protection, in research can apply as a potential tracer of various natural processes. Carbon dioxide, on the other hand is a stable gas, but classified as a greenhouse gas with a key role in a climate changes issue. Roughly 2000 PgC is stored in the soil with a total flux with the atmosphere around 2.6 PgC/y [1] which makes the soil the most important source of CO_2 on earth.

While the production of ^{222}Rn as such is constant and its concentrations in the soil with its exhalation depend only on the meteorological conditions, the storage –releasing process of CO_2 in the soil is influenced by the activity of vegetation which changes during a year even a day. As the result, the direct measurement of CO_2 exhalation can be distorted and burdened with a high uncertainty with no representative value for a given area.

Just a radon can be used as a tool to determine CO_2 exhalations from the soil by the method "Radon Tracer Method" though it requires to know the concentrations of ^{222}Rn and CO_2 in the soil and also the exhalation rate of ^{222}Rn [2,3]. For this reason, it is important to understand the variations of these gases in the soil, their mutual correlations as well as their dependence on meteorological conditions. For this purpose, we have focused on a comprehensive analysis of the concentrations of ^{222}Rn and CO_2 and their exhalations from the soil measured on the area of the campus of FMPH CU in Bratislava. These measurements took place continuously in the period from October 2020 to March 2024 during which we monitored the concentrations of these gases at a depth of 80 cm and their exhalation rate using an accumulation method, along with monitoring of meteorological parameters such a moisture, temperature, rainfall, etc. These long-term measurements provide us a comprehensive picture of the behaviour of ^{222}Rn and CO_2 in the soil, unaffected by soil characteristics (e.g. soil texture) and eliminating random fluctuations or possible abnormalities, while the results show interesting albeit complicated dependences.

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Assessment of indoor radon concentration and annual effective dose for workers' exposure in an arsenic concentrate warehouse

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The arsenic concentrate was used in the production of high-purity zinc (99.99%) according to hydrometallurgical process. This study analyzed arsenic concentrate from the former Lojane mine in North Macedonia, which was used in the chemical industry Zorka Šabac, Serbia. The activity concentrations of ^{226}Ra in 15 samples of arsenic concentrate, which were necessary for assessing indoor radon concentration, were determined using gamma spectrometry. The average value was around 200 Bq kg^{-1}. To assess indoor radon concentration for workers in the warehouse, the radon mass exhalation rate was measured, given that the material is powdery. The RAD7 device was used to determine radon mass exhalation. Based on the obtained values, indoor radon values to which workers were potentially exposed were estimated. Considering that the warehouse was well-ventilated, the contribution to the total indoor radon concentration from the arsenic concentrate was less than 5 Bq m^{-3}. This resulted in annual effective doses from radon exposure being below 20 μSv y^{-1}. The results indicate that workers were not excessively exposed to radon (drastically below 100 Bq m^{-3}) in the arsenic concentrate warehouse, despite the elevated ^{226}Ra concentration, due to the good ventilation rate of the warehouse.

Evaluation of Radon and Thoron Adsorption Efficiency on Zeolites

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The aim is to estimate the adsorption capacity of Radon and Thoron on zeolites in order to reduce their activity in indoor environments and/or to develop a new measurement method. From a chemical point of view, Radon (Rn-222) and Thoron (Rn-220) are equivalent, therefore the adsorption process is similar. In our experiment we used thoron from the decay chain of Th-232, which often plays an important role in indoor radon monitoring. Its half-life is very short, about 55.6 s. Its progeny sometimes contributes significantly to the radiation dose in residential buildings. Zeolites have a well-defined three-dimensional porous structure and good radiation resistance. The size and shape of the pores are crucial for the trapping of gas atoms. Various natural and synthetic zeolites are used and evaluated for their adsorption efficiency. The study then focused on the chabazite type and zeolite 4A. The experimental work was carried out in a thoron exposure chamber where the gas diffuses uniformly and is monitored by an α-spectrometry device based on the electrostatic collection of thoron progeny. γ spectrometry, based on a hyperpure germanium detector, was used to characterize the zeolite before and after thoron exposure in order to estimate its adsorption capacity. The results are encouraging and will certainly contribute to the development of better radon removal materials and the establishment of standardized measurement techniques for routine radon monitoring.

Development of the BfS-UR1 thoron progeny calibration chamber

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Rn-220 (thoron) can be found in indoor spaces in different concentrations when Th-232 is contained in the building materials. Because of its effects on human health, according to the Council directive 2013/59/EURATOM, thoron must be taken into consideration when determining the corresponding occupational and public exposure.

Nonetheless, thoron is often neglected in radiation assessment as compared to its sister Rn 222

(radon): because of its short half-life time (55.6 seconds) it cannot diffuse further than a few tens of centimetres away from the walls and the spatial distribution of the indoor concentration is strongly inhomogeneous. For this reason, it is difficult to consider the measurand "thoron activity concentration" as representative for the risk connected to a specific indoor space.

On the other side, thoron progeny has significantly longer half-life times and can diffuse in the indoor space in a more homogeneous way. Furthermore, the biggest contribution to the dose of thoron is given by the inhalation of its progeny, so it is more representative as well as accurate to measure directly the thoron progeny through the potential alpha energy concentration (PAEC).

To understand if and how much thoron and its progeny are of concern or not, it is necessary to perform metrologically traceable measurements with quality assured methods, but a metrological structure for these measurements is currently not available in Europe. Addressing this gap, the Radon Metrology department (UR1) of BfS initiated the design of a chamber to create standard atmospheres for thoron decay products with the aim of performing instrument calibrations for the measurand PAEC. The current status of the development of the chamber as well as difficulties and open questions regarding thoron progeny calibrations will be discussed.

Indoor radon measurements in kindergartens in southern Poland

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In 2024, indoor radon concentration measurements were conducted in 59 kindergartens situated in southern Poland. The objective of the measurements was to ascertain the extent of workers' exposure to radon and its progeny. The measurement method employed was that of track detectors. In each room in the basement or on the ground floor, which were classified as workplaces, three detectors were placed and exposed for a period of one month during the heating season. Furthermore, a radon survey was conducted in each kindergarten. The survey was developed in accordance with the guidelines set forth by the IAEA Safety Report Series no. 98 "Design and Conduct of Indoor Radon Surveys". Information was gathered pertaining to a number of factors, including the type and age of the building, the materials used in its construction, the presence of a basement, the heating and ventilation systems in place, and the type of soil surrounding the building. A comprehensive statistical analysis of the results of indoor radon concentration measurements, with particular attention to survey results, will be presented.

ACKNOWLEDGMENTS

The research has been carried out on the basis of the findings of the multi-annual study "Government Program for the Improvement of Safety and Working Conditions - 6th stage, implementation period: 2023-2025". It was financed in the field of scientific research and development work from the funds of The National Centre for Research and Development. The programme was coordinated by the Central Institute for Labour Protection - National Research Institute.

Didactic radon measurement method using CR-39 detector –comparison of visual image assessment and digital analysis

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Education of students about radon can rise awareness on this topic in lay public. Experience is the best teacher, therefore teaching about radon is best supplemented by radon measurement. Didactic radon measurement method based on analysis of digital CR-39 detector image has been used successfully in order to familiarize students with basic principles of SSNTD and radon. In the experiment, students measure radon concentration in their homes by track detector. After detector exposure and leaching, they determine track density by two methods. Firstly, by manually counting number of tracks in each 1 mm^2 grid cell and secondly, using ImageJ software. Calculation of radon concentration from track density is performed in standard way.

This contribution presents preliminary results of comparison measurements. Batch of standard CR39 detectors was exposed to radon in a radon chamber, with continuous monitoring of radon concentration by AlphaGuard analyser. CR-39 detectors were etched and analysed by standard certified method, radon concentration and track density were determined. Subsequently, detectors were scanned by digital microscope and composite detector images were produced. Image analysis was performed by visual image assessment and digital image analysis using ImageJ software. Acquired results of track density were compared with the results from standard certified method. Preliminary results show good agreement between results, therefore justifying the use of standard calibration factors provided by detector manufacturer for the purpose of didactic analysis. However, further research on the subject is needed.

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2023 NRPI Prague international comparison of measuring instruments in a mixed field of radon - thoron gas and their short-lived decay product

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In March-April 2023, an international comparison of instruments for measuring radon, thoron and their short-lived decay products in their mixed field was organized at the SURO Prague. Eight national institutions participated in the comparison provided both continuous monitors and passive integral detectors. After the introduction of measurement conditions and exposure facility, the key results will be presented.

RadoNorm comparison measurement of radon and radon progeny in field conditions

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In the framework of the RadoNorm WP 5.4 project, an international comparison of radon activity concentration, equilibrium equivalent activity concentration total and unattached fraction was held at the Historic Silver mine in the city of Tarnowskie Góry in Poland from 20th to 23rd of February, 2024.

Comparison measurement of continuous monitors in laboratory conditions in mixed fields of radon and thoron was carried out in SURO's radon chamber during spring 2023 and which will be presented by Karel Jilek and colleagues. During the evaluation period, laboratory conditions were kept stable and homogeneity of activity was ensured. In contrast to that, at workplaces (underground workplaces which are the subject of detailed studies of the WP5.4 are not exceptions), measurement conditions and radon/radon progeny concentration may appear to be on the far edges of operating ranges. The conditions during exposure vary, and these variations can significantly impact the response of the detectors. Multiple parameters are subject to change, each potentially influencing the detector response in a different manner. As a result, these effects can either amplify or negate each other.

The main goal of this comparison measurement was to compare the results of currently mostly used continuous monitors for radon activity concentration measurement and radon progeny measurement in the real conditions of an underground workplace.

Interaction of radon and smoking on lung cancer risk

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The aim of the presentation is an evaluation of interaction of effects of radon and smoking on lung cancer risk. In occupational studies among uranium mines, smoking has not been considered in all original studies in early presentations. This issue was investigated later by nested case-control studies. The present analysis is based on two Czech studies of uranium miners. One cohort study of Dr Josef Ševc of 10 000 miners with 1029 lung cancer cases and another cohort study of Dr Vladimír Řeřicha of 23 000 miners with 826 lung cancer cases. The effect from radon and smoking is considered in two models –(1) additive and (2) multiplicative. Alternatively, the evaluation is based on geometric mixture model using a mixture parameter θ between 0 for the additive and 1 for the multiplicative models. The interaction is closer to the additive interaction, particularly in the combined study with a higher statistical power to distinguish the two models.

Lung cancer mortality attributable to residential radon in Germany

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Radon is one of the most important risk factors for lung cancer after smoking. An illustrative way of describing the lung cancer risk of residential radon is to give the number of so-called population attributable lung cancer deaths caused by radon in homes, since this indicator can help policy makers and the public to understand the health impact of radon exposure. In 2006, it was calculated that around 1,900 lung cancer deaths per year are attributable to radon in homes in Germany. Some of the data used to calculate the number of attributable deaths have changed since then. Thus, the talk presents the population-attributable fraction (PAF) and the number of lung cancer deaths attributable to residential radon in Germany per year using updated data and an advanced method of calculation.

Data on lung cancer mortality (2018 - 2022), smoking behavior (2017), and the estimated distribution of radon concentrations in homes in Germany (based on a radon measurement survey from 2019 to 2021) are used. The considered risk model is derived from the pooled European residential radon study, the so-called Darby study, which indicates that the excess relative lung cancer risk is increased by 16% per 100 Becquerel per cubic meter long-term radon concentration. In contrast to the PAF approximation formula mostly used in the literature, which only takes into account the average radon exposure in a population, we applied an approach, which incorporates the entire distribution of radon exposure and leads to more accurate results.

Compared to the results from 2006, the current analyses give a slightly higher PAF (6% versus 5%) and a substantially higher number of radon-induced lung cancer deaths in Germany. The slightly higher PAF is mainly due to the improved knowledge about the residential radon distribution in Germany, which yielded higher radon values (63 versus 49 Bq/m³ mean value). The higher radon levels as well as the increase in annual number of lung cancer deaths over time in Germany lead to an increase in the calculated number of radon-attributable lung cancer deaths. Most of the radon-attributable lung cancer deaths are current smokers and ex-smokers. However, a considerable proportion is also found among never smokers.

The results confirm that radon in homes is a relevant risk factor for lung cancer and emphasize the importance of protection measures against radon in Germany for all population groups.

Impact of smoking on radon risk in residential areas

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Smoking and radiation are among the most important factors influencing the risk of lung cancer, but their interaction is not well understood yet. Without an understanding of their synergistic effect on lung cancer, it is not possible to properly assess the radon risk of the general population, including groups of smokers with different daily cigarette consumption. The interaction between radiation and smoking is therefore a subject of interest in current epidemiological and theoretical studies. To quantify radiation damage to lung epithelial cells, we developed a microdosimetric threshold energy model based on the assumption that an exposed cell is inactivated when the specific threshold energy is exceeded (otherwise it is sublethally damaged) [1]. Threshold energy is increased by the production of surviving, a protein that protects the cell from apoptosis, and its amount depends on the number of cigarettes smoked. Sublethally damaged cells represent a radiation response of lung tissue that is proportional to the increase in relative risk of lung cancer.

In addition to cell radiosensitivity, smoking also alters morphological and physiological parameters of the lung, depending on its intensity and duration. The degree of these changes is reflected in the bronchial dose and can be characterized by the obstructive factor [2].

After calibration of the microdosimetry model, the biological effect of the radon impulse was used to monitor the time course of smoking-induced lung changes. For the general population, the time since exposure effect was taken into account.

To assess the predictive ability of the model, we performed a number of calculations that were compared with epidemiological data. From the comparison of the results, it can be concluded that the proposed model satisfactorily explains the interaction between smoking and radiation. By extrapolating this interaction to the region of low long-term radon exposures, the model can contribute significantly to the assessment of radon risk of the general population in environments with different smoking habits. Moreover, the model has the potential to predict risk increases even in smokers who have quit smoking [3].

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Practical aspects of determining the effective dose from inhalation of radon decay products

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The concentration and size distribution of aerosol particles and ventilation conditions of the inner atmosphere of the different workplaces have a crucial effect on the ratio between the radon activity concentration and the potential alpha energy concentration. The presentation summarizes the main differences in determining the quantities mentioned above using grab sampling, continuous measurement, and integral personal monitoring. The main focus of the contribution is the possibility of distorted results in environments with a higher unattached fraction.

Should we re-evaluate radon risk?

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For some years there has been increasing doubt about the applicability of the Linear-No-Threshold model (LNT) of radiation risk, in particular of radon risk. This concerns exposure below about 100 Bq/m³ long term, for which current epidemiological data do not seem to allow proposing a robust risk model. For exposure caused by higher concentrations, a positive, essentially linear relation seems to be assured.

The matter is relevant because the majority of the population - about 75% of Europeans - are exposed to less than 100 Bq/m³. This means that for this large fraction of citizens there is no reliable model of radon risk.

On the other hand, estimated risk is one justification of radon policy. While it is unlikely that revision of the risk model would strongly affect delineation of Radon Priority Areas, minimization of low radon exposure and certain topics of Radon Action Plans may become questionable.

In this presentation literature is quoted which is sceptical about the LNT. A number of authors are in favour of sub-linear or even hormetic models for low exposure. In any case, even if no particular model is favoured, in the absence of a reliable model one can investigate scenarios: How would Rn risk be geographically distributed, relative to the one projected by the LNT, if a different model is applied?

The overall conclusion based on scattered evidence is that the matter deserves attention and should be further studied. Large scale case control or cohort epidemiological studies are expensive, but one may re-evaluate existing data including the large amount of indoor radon measurements - more than a million in Europe - which might be used in (less reliable) ecological studies.

Data driven up dates to Canada's National Radon Program to more effectively address rising radon exposure

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As part of its National Radon Program, Health Canada consistently reviews and updates national radon risk guidance and resources to address knowledge gaps and adapt to the evolving radon landscape in Canada. Health Canada actively seeks and gathers information to ensure its actions are evidence-based and effectively mitigate this health risk.

With emerging data indicating growing radon risks for Canadians, Health Canada has been promoting measures to reduce radon exposure and is updating key guidance elements. Due to the many factors affecting radon levels across Canada's varied geography and climate, identifying data that directly answer key questions about Canadians' radon exposure can be challenging. To address this, the National Radon Program conducts targeted studies to fill data gaps and gather the necessary evidence for informed decision-making.

Health Canada will present its recent progress in radon reduction strategies, highlighting the data and evidence driving these efforts. This notably includes research and studies supporting the strengthening of Canada's building codes and the modernization of radon testing guidance with the proliferation of electronic radon monitors. The presentation will also expand on the existing unknowns in the radon testing of Canadian homes, and explore Health Canada's efforts to answer these remaining questions. Ultimately, these efforts aim to more effectively protect Canadians from the hazards of radon exposure.

National Radon Database (NRD), especially focused on schools, fulfils goals of the Czech National Action Plan for control of public exposure to radon (RANAP)

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National Radon Database (NRD), especially focused on schools, fulfils goals of the Czech National Action Plan for control of public exposure to radon (RANAP)

RANAP –National Radon Action Plan is a binding document of the State Office for Nuclear Safety and the state administration bodies involved regulation of public exposure to radon.

One of the specific tasks of RANAP is the creation and management of the National Radon Database

(NRD), which collects measurement results of natural radionuclides and comprehensive information about the occurrence and volumetric activity of radon in residential buildings (schools and family houses) and workplaces. An important functionality of the NRD is its ability to analyze incoming data provided by so-called mandatory subjects. This provides us with the most important tool for identifying problematic buildings, including the radiation levels of specific individuals in specific workplaces (such as flight crews, radon and NORM workplaces) from the beginning of the Radon Program in the Czech Republic. The NRD application allows for timely and graduated planning and subsequent implementation of measures to reduce radon exposure.

Currently, significant attention in the NRD is focused on data measured in schools, where ensuring low radon levels is crucial for protecting the health of children and employees.

The establishment of the NRD and effective cooperation with mandatory subjects can already be characterized as a significant contribution to the safety and protection of public health from radon exposure in the Czech Republic.

Proposal for the creation of national radon activity monitoring networks based on the national pre-university school network. Information, Education, Research.

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The scientific environment has proven the carcinogenic effect of radon. The results convinced the politicians to pass laws in the interest of the citizens. All European Union countries have adopted specific national laws. However, implementation faces difficulties.

On the other hand, we all agree that we need as many measurements as possible, reaching the level of the number of homes and jobs. (ICRP-1995-PAG.19, PAR. 63)

Through our work we have demonstrated that this is possible through collaboration with the Local Authority and the pre-university school system.

Our method has so far made it possible to collaborate with 10 Local Authorities, 14 schools, 30 teachers, almost 1000 students and their parents in a geographical area with a high potential for radon activity and with cancers above the national average.

Through this collaboration, we obtained results with scientific value about radon activity and information about the houses in the locality, respectively the involvement in our activity of a wide spectrum of citizens. The paper is a synthesis of the results and experiences accumulated over the years and goes through the stages through which we managed to develop a working model that can be easily multiplied, obtaining results with scientific value and with a capacity to educate and inform citizens from genuine reliable sources. The model is informative, educational and scientific at the same time.

Long-term effectiveness of measures to prevent and mitigate radon in houses

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Techniques and procedures are known that can significantly reduce radon levels in houses, both preventive and remedial. One issue remains unclear, namely the durability of these measures. The long-term effectiveness of remedial measures should be considered when assessing actual risk reduction, for optimisation efforts and cost-effectiveness studies. They could be important also for the willingness of homeowners to initiate radon mitigation. This issue has been addressed in the RadoNorm project using datasets from Norway, Finland, Austria and France.

Data from the Czech Republic will be presented showing the sustainability of preventive and remedial measures after 30 years

Various aspects of measurement and exposure assessment at workplaces

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In most cases, radon is measured at workplaces to comply with Directive 2013/59/EURATOM's requirements through integrative long-term measurement done by solid-state nuclear track detectors. While integrative measurements are quite simple and relatively cheap, time-resolved measurements provide valuable information on the measured quantity's temporal variability. When the long-term average does not accurately reflect the radon concentration or radon progeny concentration during the worker's stay in the workplace, time-resolved measurements should be used as an auxiliary measurement or the only measurement. A typical example of such a situation is the spa with thermal water rich in radon; radon concentration in the workplace is higher when using the water during working time. On the other hand, when forced ventilation is turned on during office block occupancy, radon concentration is usually substantially lower than during nights and weekends, which are counted in the average radon concentration.

If a particular workplace exceeds the reference level, it is necessary to optimize workers' exposure. If it is not possible to lower the radon concentration below the reference level, it is necessary to calculate the effective dose. Due to their conditions, some workplaces may require determination of the PAEC, or the concentration of the attached and unattached fractions of radon decay products. Given the already described variability of workplace conditions, there will likely be a shift towards continuous monitoring of decay products or the implementation of personal dosimetry. The aim of the presentation is to show, using real examples, how much the measured data can influence the result of the exposure estimation.

Development of the system of radiation protection against radon and radon progenies with focus on dose assessment

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The system of radiation protection against radon and radon progenies has had a long development, mainly by the ICRP but with significant contributions from other international organizations, such as EC, HERCA, IAEA, UNSCEAR, and WHO.

Within this evolution the role of dose assessment has been important and often subject of discussion and debate, as regards both the scientific aspects and the practical implications.

A typical example is the discussion about the epidemiological and dosimetric approach to the dose assessment, which has often been misunderstood.

Moreover, due to the last (and no more recent) changes of the ICRP dose coefficients (ICRP-137, 2017), with an increase by a factor 2 or 4 compared with previous ones (ICRP-65, 1994), several discussion and initiatives regarding the practical implementation in some workplaces have been carried out and are also on going.

This presentation will try to shortly summarize the above mentioned evolution and to mention the main present issues. Finally, some personal comments will be reported.

Requirements for radon barriers - current status and future

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In countries where buildings are normally protected against soil moisture or underground water by continuous waterproofing, the waterproof course also provides basic protection against radon from the subsoil. There is currently no European or international standard that specifies how to design waterproof membranes as radon barriers. An overview of the requirements for radon barriers as they are applied in individual states is presented. In general, procedures are available prescribing either the maximum value of the radon diffusion coefficient, or the minimum thickness of the membrane, or the minimum value of the radon resistance. The applicability and reliability of all the design procedures is discussed in detail.

Current situation, when each individual state applies different requirements for the properties of radon barriers, is dysfunctional. It is especially a complication for manufacturers of waterproof products, which are mostly multinational companies, because they must demonstrate compliance with national requirements in each state individually. Therefore, a proposal for a unified approach is introduced. Unification is based on radon resistance because it is the only parameter that expresses the true barrier capability of a waterproof product. Radon resistance takes into account both the radon diffusion coefficient and the thickness of the product. The greater the radon resistance, the better the barrier capability of the given product. Individual European states should therefore incorporate the requirement for a minimum radon resistance value, which every waterproof product must meet, into their legislative or standard requirements for radon barriers. Possibilities of how to determine the minimum value of radon resistance with regard to national specifics such as building parameters, radon potential of foundation soils, etc. will be introduced.

Development of a new mathematical procedure for radon diffusion coefficient measurement; application to eco-friendly construction materials

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The use of supplementary cementitious materials (SCMs) is one of the most used ways to reduce CO2 emissions associated to the production of Portland cement. However, many of these SCMs are Naturally Occurring Radioactive Materials (NORM), which present naturally occurring radionuclides. Radon emission from these types of materials, together with radon infiltration from the ground through them, is one of the main sources of indoor radon. Radon transport through any material is regulated by its radon diffusion coefficient, D, hence playing an important role when trying to mitigate radon accumulation indoors. Current methodologies developed to determine D can be difficult to apply. ISO 11665-13 imposes restrictive conditions on the experimental system and requires the application of numerical methods. In this work, a new algorithm and its software were developed to complement the ISO. The algorithm solves for the physical governing equations and finds the value of D that best fits the data by minimising the differences between the predicted and experimental concentrations. Two sets of seven cement pastes, with different quantities of additives and cured for 2 and 28 days, respectively, were used to test the algorithm, resulting in a total of 14 samples. A validation procedure was developed for internal validation, and results were compared with the literature for external validation. The radon properties of the cement pastes were studied in function of the technical properties to determine their suitability as building and insulating materials against radon. The D of the pastes changed by an order of magnitude between those with a 2-day curing time and those with a 28-day curing time, the latter being less permeable to radon. In addition, there was a decrease in D as the percentage of superplasticiser admixture increased, due to the reduction in the porosity of the final pastes and the reduction in radon permeability. In conclusion, the methodology for radon diffusion coefficient measurement was tested and validated satisfactorily and, with his application, it was found that different characteristics of the cement paste production, which influence the final microstructure, can produce cements containing NORM material with radon permeabilities low enough to be used as a barrier against radon.

The first experimental apparatus to evaluate the actual effectiveness of facemasks to reduce the effective dose due to radon progeny

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The International Commission for Radiological Protection (ICRP) recommends to consider a dose coefficient of 20 mSv WLM^{-1} for workers in tourist caves instead of 10 mSv WLM^{-1} generally applicable to the majority of circumstances [1]. Furthermore, the radon concentration in touristic caves is generally higher than in the majority of workplaces and the remedial actions are typically very difficult to be implemented [2].

The effective dose due to the inhalation of radon progeny can be reduced by face masks. Some different works have recently investigated the effectiveness of different masks in filtering the radon progeny [3-5]. However, the reduction of the radon daughters inhaled has been measured by experimental apparatuses that only consider the filtering effectiveness throughout the tissue of the mask: i.e., the reduction in the filtration capability due to the morphology of the human face is always neglected.

A novel experimental apparatus has been developed at the Italian National Institute of Health to specifically investigate the overall filtering effectiveness of facial mask relative to the radon progeny. The objectives of the project as well as the design of the setup is described. The experimental evaluations to be performed by this novel apparatus will take place from September 2024 and the results for the first typologies of mask will be available by the end of 2024. The further development of the setup currently being studied are also presented.

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Preliminary investigations for the design of radon remediation works

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This report analyzes the main design criteria for achieving low indoor radon concentration levels both in new constructions and in existing buildings that are part of the historical heritage of our cities. Although achieving low indoor concentrations in new buildings is relatively straightforward with good foundation insulation and the avoidance of emitting materials in the construction envelope, remediation of existing buildings becomes much more challenging. Italian constructions, in fact, differ significantly from those in other European countries, and the techniques described in foreign design manuals can only be partially utilized. A rigorous technical approach is therefore absolutely necessary and desirable. In the historical centers of many Italian cities, the building envelope is made of lapideous or semi- lapideous materials from local quarries that are highly emitting, whose contribution cannot be underestimated; hence, a technique for evaluating the exhalation rates from construction materials widely used by the author in preliminary investigations for the design of radon remediation works is described. All these criteria must be considered in the initial phase of building design to meet the recommendations of the World Health Organization and the standards for implementing Directive 59/2013, which in Italy has been transposed by Legislative Decree 101/2020. For new constructions, we can identify three design criteria assuming the use of non-emitting materials in the construction of the building:

1. Establish a barrier to radon gas rising;
2. Depressurize the sub-foundation;
3. Dilute indoor air with external air using heat recovery systems.

These criteria will be used partially or in combination with each other depending on the area risk characteristics calculated based on Soil Radon and permeability

For existing buildings, in addition to the 3 criteria already mentioned, a 4th is added related to the evaluation of exhalation rates from the construction materials used to create the building envelope. When utilized, these criteria can prevent radon infiltration and lower the concentration of radon in indoor air. Radon can cause lung cancer, and it is not known if there is a safe lower limit for humans; therefore, it is important to reduce the indoor radon concentration as much as possible. Air rising from the ground is the main source of radon indoor, but the contribution of the materials making up the building envelope cannot be underestimated in the design of remediation works for existing homes.

Development and implementation of a monitoring network to real-time monitor the radon concentration levels in a large-scale Italian historical building

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In the context of a comprehensive remediation project for a large-scale, historic Italian building utilized as a governmental workplace and containing over 1500 rooms, an advanced monitoring system has been implemented with dual objectives: i) to assess the effectiveness of the remediation interventions, ii) to monitor radon concentrations in all the sections of the entire structure after the remediation interventions, including to promptly trigger alerts in the event of anomalous radon level measured.

The monitoring network contains about 100 probes of type TSRE1, manufactured by Tesla company (now manufactured by Piketronic company), that are connected to both a power supply, allowing to collect radon concentration continuously, and an ethernet network, enabling real-time data transmission. The probes are capable of measuring not only radon concentrations but also environmental parameters such as temperature and humidity.

Monitors have been distributed in all the 4 main levels of the building containing rooms, from the ground floor up to the third floor. The building's layout for these 4 levels is characterized by a configuration of seven corridors, with rooms at both sides of each corridor: a central corridor in a square shape, flanked by three additional corridors on both the left and right sides. A probe has been placed in 3 rooms of each corridor, for a total of about 80 probes.

Moreover, at the underground level where the remediation system, composed by several fan, is located, a probe has been placed in proximity to nearly each fan, for a total of about 20 probes. These probes have a crucial role because they allow to verify the proper functioning of the remediation system.

Data from each detector is collected by a double redundant system. The first system allows the downloading (both on site or by remote connection) from each probe of measurements performed and stored over time by an internal solid-state memory. The second system (backup system) consists of an ad-hoc software, developed in the R CRAN framework, to interrogate all probes every hour. This software allows to obtain, for each single premise, plots showing how the radon concentration varies over time, together with the mean radon concentration by last day, week and whole data collection period. In addition, the mean radon concentration values, grouped by floor and/or block, are calculated and plotted.

Radon diagnostics in historical buildings I

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Historical structures can have complex construction characteristics since they have been rebuilt multiple times, typically without precise blueprints accessible. The primary instruments for identifying at least some of the radon pathways are a determination of the average air exchange rate, grab sampling from suspicious places, and simultaneous continuous monitoring of the radon activity concentration.

Two case studies providing preliminary results and lessons learned of radon diagnostics will be presented.

Radon diagnostics in historical buildings II - the importance of determining air exchange rate

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Radon measurements in historical buildings are always very interesting, but in many cases require a special approach. Historical buildings are often measured prior to planned renovation at a time when they no longer serve their original purpose and are only minimally used. Therefore, meeting the requirements for occupancy or conservative conditions is often impracticable and simultaneous determination of the air exchange rate with radon activity concentration measurement is practically necessary.

A new high-resolution residential radon map for Germany using a machine learning based probabilistic model

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Radon is a carcinogenic, radioactive gas that can accumulate indoors. Therefore, accurate knowledge of indoor radon concentration is crucial for assessing radon-related health effects or identifying radon-prone areas.

Indoor radon concentration at the national scale is usually estimated on the basis of extensive measurement campaigns. However, characteristics of the sample often differ from the characteristics of the population due to the large number of relevant factors such as the availability of geogenic radon or floor level. Furthermore, the sample size usually does not allow estimation with high spatial resolution. We propose a model-based approach that allows a more realistic estimation of indoor radon distribution with a higher spatial resolution than a purely data-based approach.

A two-stage modelling approach was applied: 1) a quantile regression forest using environmental and building data as predictors was applied to estimate the probability distribution function of indoor radon for each floor level of each residential building in Germany; (2) a probabilistic Monte Carlo sampling technique enabled the combination and population weighting of floor-level predictions. In this way, the uncertainty of the individual predictions is effectively propagated into the estimate of variability at the aggregated level.

The results show an approximate lognormal distribution with an arithmetic mean of 63 Bq/m³, a geometric mean of 41 Bq/m³ and a 95 %ile of 180 Bq/m³. The exceedance probability for 100 Bq/m³ and 300 Bq/m³ are 12.5 % (10.5 million people) and 2.2 % (1.9 million people), respectively. In large cities, individual indoor radon concentration is generally lower than in rural areas, which is a due to the different distribution of the population on floor levels.

The advantages of this approach are 1) an accurate estimation of indoor radon concentration even if the survey was not fully representative with respect to the main controlling factors, and 2) an estimate of the indoor radon distribution with a much higher spatial resolution than basic descriptive statistics.

Measurement of radon exhalation from clay bricks obtained by recycling waste phosphogypsum and fly ash

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In Serbia, during the production of electricity and burning of lignite, about 6.5 million tons of waste fly ash are produced annually. During the production of phosphoric acid, about 810 thousand tons of waste phosphogypsum are generated. Available data indicate that about 5% of waste fly ash is recycled in cement production, while phosphogypsum is piled up in landfills. Both wastes contain an increased concentration of ^{226}Ra activity, compared to the raw materials used for brick production. This paper deals with the investigation of the possibility of recycling these two wastes in the production of clay bricks in a radiologically acceptable manner. A total of 8 systems of brick samples were produced with a proportion of phosphogypsum in the range of 0-35% and fly ash in the range of 0-17.5%. The proportion of phosphogypsum in each investigated system was twice as high as the fly ash content. The gamma spectrometry method was used to determine the concentrations of ^{226}Ra activity in raw materials and all brick samples. The measured concentrations of ^{226}Ra activity are 536±20 Bq kg^{-1}, 182±10 Bq kg^{-1}, for phosphogypsum and fly ash, respectively. Measurement of radon exhalation was carried out using the RAD7 device. The values of surface exhalation rate and indoor radon concentration for a room of standard dimensions were estimated, after which the annual effective dose from radon inhalation was determined. Estimated values of indoor radon concentrations are acceptable and below 100 Bq/m^3, which gave an annual effective dose of less than 1 mSv y^{-1}. Bearing in mind that building material is not a dominant source of radon in ground rooms, this way of recycling the analyzed waste materials is acceptable with a lower proportion of phosphogypsum and fly ash. The higher content of these wastes in the brick also contributes to the higher content of ^{226}Ra, which gives a significantly higher contribution to the total indoor radon concentration.

Preliminary results of RadoNorm project activities on in-situ measurements of radon exhalation rate from building structures

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Council Directive 2013/51/Euratom requires to consider any source of radon including the building materials. Assessing the radon activity that exhales from building structures is crucial to identify the best strategies to prevent radon from entering a building or reducing its concentration in the inhabited spaces. According to the current state of knowledge and technology, the radon surface exhalation rate from building structures may be estimated through i) the modelling of the radon transport inside the structure [1], ii) the theoretical correlation with the radon exhalation rate measured on a sample of the same building material [2], or iii) the direct measurement performed on the manufact [3].

Among the three approaches, only the third one is suitable to consider the influences of the environmental parameters and the installation conditions, i.e., the width and geometry of the slab, how units are laid in and bound together, the presence of binding elements and covering layers. In the framework of the European project RadoNorm, a study has been designed to investigate the possible correlation existing between the radon exhalation rate measured in closed containers on a building material sample [4] and the actual radon exhalation rate from a building manufact (a wall) made of the same material. The radon exhalation rate measurements on the wall have been performed through an experimental apparatus developed at the Italian National Institute of Health.

The design and objectives of the study are presented as well as the preliminary results obtained with some high-exhaling building materials. These results include the comparison between the radon exhalation rate obtained from the material sample and the exhalation rate measured directly on two walls having different sizes. The influence of the superficial treatment on the resulting radon exhalation rate is discussed as well.

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Tests on the effectiveness of air purifiers as a method to reduce radon exposure

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The study presents tests on the effectiveness of using air purifiers as a method of reducing radon exposure. Five commercially available air purifier models with different filter sets were tested. To ensure the credibility of our results, each air purifier was tested under similar conditions in terms of radon concentration in the air and duration of the experiment.

During each measurement, the radon activity concentration, the potential alpha energy concentration, the equilibrium factor and the environmental conditions (pressure, relative humidity and temperature) were monitored.

This approach allowed a comprehensive evaluation of the effectiveness of the air purifier in filtering both radon and its progeny.

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The first experimental apparatus to measure the radon exhalation rate on-site from existing building manufacts

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Exposure of the population to indoor radon is one of the leading causes of lung cancer [1]. Building materials are a recognized source of indoor radon [2], and current national and international regulations [e.g., 3] require consideration of the specific contribution of building materials to indoor radon concentration. This contribution is generally quantified by means of the exhalation rate, i.e., the radon activity that escapes from the surface of a building element (e.g., a wall) per unit of surface area and time. The exhalation rate can be evaluated analytically or measured experimentally.

The first approach involves applying case-specific solutions of the general transport equation for radon in porous media [4]. The main limitation of this approach is the need for a large set of parameters—often very difficult to determine—to accurately characterize the emitting artifact. The second method, on the other hand, involves measuring the radon exhalation rate on a representative sample of the building material [5] and subsequently correlating it theoretically with the actual exhalation rate from the existing artifact [6, 7]. The main criticalities in this case are represented by (i) the difficulty of obtaining a representative sample of the building material due to its often unknown composition, and by the impossibility of considering (ii) the advective contribution to radon transport through the artifact and (iii) the influence on the exhalation rate of installation conditions (e.g., the bonding and covering materials used in the artifact [8]) and environmental conditions (i.e., temperature and humidity [9]).

The limitations of the two currently employed approaches are overcome if the measurement of the radon exhalation rate is carried out directly on the surface of the existing building element (e.g., a wall) using, for example, the method reported in the ISO 11665-7 standard. The main problem related to this technique—and which has most hindered its use—is that of guaranteeing the tightness of the system, especially at the interface between the accumulation chamber and the surface of the exhaling material [10].

An innovative device, called SIREN, was specifically developed, at the Laboratory of Radioactivity of the Italian National Institute of Health, to measure in-situ the radon exhalation rate from the internal surfaces of walls. The equipment has been designed and developed to overcome all the main limitations that have discouraged the use of this approach in the evaluation of the contribution of building materials to indoor radon concentration.

The apparatus has been subjected to commissioning, experimentally evaluating its tightness and repeatability of measurements. The device's sealing system, based on a complex of pressing springs that exploit friction with the underlying surface to exert pressure on the accumulation chamber, has been studied, showing that the results do not differ statistically significantly from destructive accumulation systems based on mechanical clamping techniques (e.g., anchors and expansion screws). The repeatability of the measurements, evaluated for two levels of the measurand, was found to be below 10%. A measurement and data analysis protocol has been specifically developed to guarantee and control the accuracy of the measurement with respect to the main interfering phenomena during measurements.

The developed apparatus is portable and allows for rapid and non-destructive measurements of the effective contribution of building materials to indoor radon concentration, considering both atoms generated by the materials and those produced elsewhere and transported through the building element. The results of in-situ measurements conducted using SIREN can provide a decisive contribution to improving the specificity, and therefore the effectiveness, of remediation interventions to reduce indoor radon concentration.

The project is completely open source to promote the dissemination of the test method and contribute to its standardization: 3D printing models and algorithms will be soon made available online.

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Thoron interference on radon exhalation measurements on building materials samples

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Council Directive 2013/51/Euratom [1] requires considering any source of radon including the building materials. Measuring the radon exhalation rate from building materials samples is a useful "screening tool" to compare the likely contribution of building materials to the indoor radon. According to the current state of knowledge and technology, reliable values of radon exhalation rate from building materials sample are mainly achieved through the "dynamic method", described by the IAEA Technical Report 474 [2]. The sample is enclosed in an accumulation chamber and radon concentration growth is monitored through a continuous radon monitor (CRM).

Most of the detectors used are not capable of distinguishing pulses produced by the interaction of alpha particles from radon and thoron progenies. The thoron interference may consequently lead to overestimate the radon exhalation rate.

Several measurements of radon exhalation rate have been carried out on samples of Italian tuffs characterized by high radium-226 and thorium-232 activity concentrations. The measurements have been performed with different experimental setups by varying the CRM, the ventilation inside the accumulation chamber, the position of the CRM and the radon-bearing air flow-rate inside the circulating loop.

The results will be presented focusing on the magnitude of the thoron interference on the estimation of the radon exhalation rate. Furthermore, the different experimental setups will be compared in terms of assessment accuracy and precision, time consumption, technical and economic feasibility.

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Long term radon monitoring in the Bozkov dolomite caves in the context of the geological situation

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These caves are situated in a Lugian region, in the area geologically called the Krkonoše-Jizera crystalline unit. Carbonate rocks occur in discontinuous streaks and lenses in this area. The lens in which the Bozkov caves were formed is 300 m in length and has a maximum width of about 150 m. The cave is permeated by calcareous and siliceous dolomite lenses from the Silurian age, surrounded by phyletic shales. The bedrock below the underground areas is the major source of radon. The environment of caves is typically characterized by 100% humidity, and the number of aerosol particles is around 100 times lower than outside (but the number of free ions is higher). The concentration of radon in the Bozkov dolomite caves may reach levels tens of thousands Bq/m^3. The methodology for effective dose from radon estimation for cave guides is based on integral radon activity concentration measurement cV,Rn (integral RAMARN detectors) and evidence of working hours spent in the underground. Continuous radon measurement has been taking place here since 2003, and the measured concentrations form a complete set of data that was processed for the purpose of estimating and predicting movements in the earth's crust.

Monitoring by integral monitors at basic communication (ventilation) nodes in the cave can also show how in-outside temperature changes affect air mass movements in a given cave, if we have a cave model available. 2 years ago, the continuous measurement was extended to a total of 7 positions in the cave system, and the measurement results allow a better understanding of the cave ventilation. The presented contribution introduces 3D cave system visualization (LiDAR technology), embedded in a geological environment following the results of in situ gamma spectrometry (surface above the cave) and continuous radon activity concentration measured by a set of TSR probes.

Seasonal variation of radon and effective dose estimation in the Demänovská Cave of Liberty, Slovakia

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Show caves are special workplaces with increased health risk from radon exposure. Demänovská Cave of Liberty is one of the most visited show caves in Slovakia, situated at the northern side of the Low Tatras Mts. It is formed in the Middle Triassic Ramsau Dolomite and in carbonate rocks of Gutenstein Formation with Gutenstein limestone and dolomite, Annaberg limestone and organodetritic 'Demänová' limestone, along the tectonic faults by the ancient ponor flow of Demänovka stream and its side hanging ponor tributaries. Radon activity concentration (RAC) in the cave was monitored from May 2021 to December 2023, using Ramarn track detectors (National Institute of Nuclear, Chemical and Biological Protection, Milín, Czech Republic), changed after one month exposure. Six monitoring stations were established in the cave, where RAC values varied in different intervals: Těsnohlídkovo Lake (190 –1310 Bq/m^3), Crossroad (650 –6100 Bq/m^3), Deep Dome (250 – 2500 Bq/m^3), Tricolour Lake (270 –3310 Bq/m^3), Cemetery (190 –2900 Bq/m^3) and Pink Hall (1900 –5400 Bq/m^3). The lowest annual average of RAC was found in the Cemetery station (730 Bq/m^3) situated close to the cave exit, the highest in the Pink Hall, equal to 3200 Bq/m^3.

Seasonal variation was observed at each station, with two maxima. The first appeared in the spring months and the second in autumn in each monitoring site. Spring maximum exceeded autumn maximum, or their levels were comparable (Tricolour Lake, Pink Hall). With exception of Těsnohlídkovo Lake, all stations were situated on or close to the tourist route. Effective dose for cave guides and visitors was estimated. Cave guides were exposed to annual effective dose in the range 1.1 –3.5 mSv, depending to the number of their entries to the cave per month during the year and RAC in that month. Visitors who completed a short circuit (without Pink Hall) received 0.004 –0.013 mSv per visit, who completed a long circuit received 0.009 –0.024 mSv per visit, depending on different RAC in month of their visit.

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Radon concentrations in Veternica cave - Croatia

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This study focuses on the measurement of radon concentrations in Veternica Cave, a karst cave system located at Medvednica Mountain, in the city of Zagreb –Croatia. This is the first time radon concentrations are being measured in Veternica Cave. Up to now the total of 6000 m of the cave has been explored, however only 380 m is available for visitors. These measurements involved systematic sampling of radon levels within visitor part of the cave. Passive radon detectors (SSNTD produced by Radosys) were used at 16 locations (exposure of 36 days). The average radon activity concentration (RAC) was 7394 ± 104 Bqm^3, and ranged 7254 to 7542 Bqm^3, with the highest RAC measured at the "Concert hall" location. The estimated effective dose for workers, taking into account the maximum possible time spent during visitors' tours (300 h/year), was 15 mSv/year. The results indicate that detailed investigation, including seasonal variations is necessary to better estimate the radon fluctuation within the cave. The findings underscore the importance of continuous radon monitoring in underground environments, particularly those frequented by tourists, to mitigate potential health risks.

Application of ground surface temperature measurements for indirect estimation of airflow in uranium waste rock dumps

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Uranium waste rock dumps contain residual uranium mineralization and, as a result, the entire uranium decay chain, notably the radioactive gas radon. Due to their high air permeability and large thermal capacity, these dumps naturally facilitate airflow through the stack effect. This thermally induced airflow leads to both spatial and temporal variations in radon gas exhalation at uranium waste rock dumps.

The airflow in these dumps is driven by temperature differences, primarily between the dump's inner structure and the atmosphere. This behaviour can be simplified into two main regimes: winter—gas flows upwards, and summer—gas flows downwards.

To obtain long-term observation of this phenomenon, our study utilizes thermometers placed just below the surface of the waste rock dump. These thermometers are advantageous due to their resistance to harsh environments, inconspicuous nature and small size that allows easier placement between large rocks. The ground surface temperature should follow atmospheric temperature at a location of gas intake and mirrors the internal temperature during at a location of gas outflow. We propose that these measurements can identify the temperature at which gas flow inversion occurs (the change in the flow regime).

We will present results from an in-situ pilot campaign as well as preliminary findings from a long-term in-situ study.

Waste rock dumps as remnants of uranium ore mining can be strong sources of radon –introduction to the Brod village case study - I

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One of the remnants in the areas of uranium ore mining, which are a potential source of radon, are waste rock dumps. Most of them are historically revitalized by natural means or targeted remediation carried out professionally. The aim of the remediation was and still is to prevent the spread of radon to the surrounding settlements, which is in fact very complicated due to the gaseous nature of radon. In the areas of uranium mining in the Czech Republic, the material of some dumps was (or still is) sorted based on the U content and used as a base material for roads or railways construction, the remaining U rich ore content was processed into yellow cake.

Many of the waste rock dumps, containing large volumes of excavated material, cannot be remediated naturally due to the high tilt of the slopes. Artificial overlay cannot be placed without demanding technical adjustments involving claims for additional land. As sources of radiation for a representative person, these objects are, in accordance with the legislation in the Czech Republic, monitored year-round as part of the monitoring program by the company DIAMO s.e.

Their impact on the environment and residents is assessed every year. Since the annual effective doses for a representative person in the village of Brod approach the value of 1 mSv, a number of other measurements and analyses of radon concentrations and meteorological parameters were carried out in the vicinity of the largest of them (dump № 15) with the aim of understanding the behaviour of the dump under various external conditions and associated variations in radon concentrations and its further spread to surrounding municipalities.

On the basis of more detailed long-term measurements, which covered both the area of the dump and its immediate surroundings, it is possible to estimate and assess the health impact of such slightly radioactive but huge piles of stones. DIAMO, s.p., SURO, v.v.i., SUJCHBO v.v.i. and FNSPE CTU jointly participated in the research works, including, in addition to measuring radon outside and inside the waste rock dump, also measuring gamma spectrometry in situ, aerial monitoring using unmanned devices and simultaneous measurements outside and inside buildings in the village of Brod.

The impact of uranium waste rock dumps on the outdoor atmosphere

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Based on collaboration between the staff of the SÚJCHBO, v.v.i., DIAMO s.p., SÚRO, v.v.i. and FJFI ČVUT measurement campaigns were conducted in the vicinity of the uranium waste rock dumps in the Příbram region. These measurements confirmed high radon activity concentrations in the ambient air at levels exceeding several kBq.m^{-3}. The measurements also verified annual and daily variations of radon in the outdoor atmosphere and its emanation from the waste rock dumps body. Based on these measurements, different approaches were developed to describe the distribution of radon into the external atmosphere and its impact on the surrounding environment.

Possible influence of an external source of radon on indoor radon concentration

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Radon from soil gas is generally recognised as the main cause of increased radon concentration in buildings. It is also widely understood that underground water or building material might be the secondary cause of radon problems indoors. Putting those well-known sources aside, we focused on a rather non-traditional source of indoor radon. We investigated the possibility that radon concentrations in houses (and around them) could be impacted by a large-volume nearby source of material with a higher radium concentration (such as a waste rock dump or rock bodies). If such a correlation is found, it is reasonable to assume that it will strongly depend on climate conditions, house construction, and the daily routine of the residents.

The presentation aims to provide some preliminary results of monitoring indoor radon concentration in such houses.

Estimation of the effect of an external radon source on the irradiation inside buildings –village of Brod case study II

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The main internal source of radon (not only in living spaces) is the geological subsoil; it can also be building material or water. These sources are already relatively well captured and legislative mechanisms have been established to monitor and evaluate their health impact over the long term, and eliminate them in case of exceeding the guideline or reference values. However, it is a question of what part of the representative person exposure inside the buildings can be caused by external sources. In our case study the source represent the material of the waste rock dump after uranium ore mining. The impact assessment was developed for the village of Brod, which is about 200 m away from the waste dump shaft № 15 bottom.

The effort to answer this question led the authors to perform an analysis of the previously known results of available measurements of radon concentrations in this area. At the same time, a number of long-term data such as wind direction, external temperature, etc., i.e. parameters that have a fundamental influence on the behavior of radon gas, were analyzed. At the same time as these analyses, series of measurements were carried out to provide a comprehensive picture of the situation and to describe how radon spreads from the dump to the village, where it passes and how the concentration level changes during its spread. Simultaneous measurements of radon concentrations and meteorological parameters outside and inside selected buildings in the village of Brod enabled to make a first estimation of the influence of an external source of radon on the exposure inside selected buildings from external radon. The facts found may have an impact on local village planning.

The measurements were carried out in cooperation with DIAMO, s.e., SURO, v.v.i., SUJCHBO v.v.i. and FNSPE CTU. The finalization of the summary analysis was supported by the Ministry of Industry and Trade of the Czech Republic.