Radiation and Environmental Biophysics
https://doi.org/10.1007/s00411-025-01167-7

RESEARCH

Radon diagnostics using low-cost continuous monitors and air exchange rate measurement – a case study in a residential building

Katerina Navratilova Rovenska[1] · Miroslav Vanek[2] · Radim Moznar[1] · Martin Kaschner[3] · Elena Castaño Casco[4] · Shahed Khan[5] · Esther Osei Akuo-ko[6] · Ilaria Rocchetti[7] · Ondrej Parizek[1] · Jan Lenk[1] · Marcela Adamova[8] · Oana Elena Peneoasu[9] · Lukas Mareda[10]

Received: 15 August 2025 / Accepted: 3 November 2025

Abstract
Reliable and accurate radon diagnostics in buildings with elevated radon levels are crucial for selecting the most effective mitigation strategies. Traditionally, such diagnostics relied on passive integrating detectors paired with continuous radon monitors (CRMs), which offer time-resolved and detailed insights into radon fluctuations. However, the historically high cost of CRMs significantly limited widespread deployment. Recent advancements in digital electronics have made various low-cost CRMs such as Corentium Pro and Radonye + 2-broadly available. Although recent scientific studies have thoroughly assessed the performance of these detectors under controlled conditions, their effectiveness in real-world radon diagnostics is not yet well documented. The study aimed to evaluate the applicability of two types of low-cost CRMs – Corentium Pro and RadonEye + 2 – for radon diagnostic evaluation of a residential building. Radon levels were monitored in designated areas of the home across three separate measurement campaigns. To support comprehensive analysis, additional data were collected, including air exchange rates measured via tracer gas techniques, grab samples from indoors leaks and soil gas, and concurrent monitoring of meteorological conditions. Radon concentration measurements obtained from the different methods were in good agreement. Time-series analyses revealed a strong correlation between indoor radon levels and the temperature difference between the indoor and outdoor environments. Furthermore, measurements of air-exchange rates were instrumental in pinpointing the primary radon entry pathways, enabling the design of more effective remediation strategies.

Keywords Radon diagnostics · Continuous radon monitors · Air exchange rate measurement · Radon mitigation · Low cost

Introduction

There are three main sources of radon (^{222}Rn) in closed environments – soil gas, building material and underground water, while the soil gas is usually the one that contributes the most to the indoor radon activity concentration (RAC) (World Health Organisation 2009; International Atomic Energy Agency 2015). Radon enters enclosed environments via infiltration from the underlying soil and rocks beneath buildings through cracks in the building substructure, around improperly sealed piping and other penetrations. Several factors influence radon concentrations that include: geological composition, soil permeability, meteorological conditions, construction materials, ventilation systems, structural integrity (e.g., cracks and pipe inlets), and occupant behavior (International Commission on Radiation Units and Measurements 2012; Silva et al. 2022; Jiránek et al. 2024; Turtiainen et al. 2025).

Radon itself poses relatively minimal health risk compared to its short-lived decay products—particularly polonium-218 (^{218}Po) and polonium-214 (^{214}Po)—which contribute the majority of the radiation dose to the lungs upon inhalation (National Research Council (US) Committee on Health Risks of Exposure to Radon (BEIR VI) 1999; Darby et al. 2006; World Health Organization 2009; International Commission on Radiological Protection 2014;

Extended author information available on the last page of the article

Published online: 22 November 2025

Kelly-Reif et al. 2023). Although measuring radon progeny is complex, radon gas concentrations serve as a practical proxy due to the ease and reliability of gas-phase monitoring (International Commission on Radiation Units and Measurements 2012).

Given that individuals spend a significant proportion of their time indoors – whether at work or at home – and because inhalation of radon and its decay products accounts for approximately half of the total annual effective dose of ionizing radiation received by an average individual (UNSCEAR 2010, 2020), and since indoor radon concentrations can, in many cases, be effectively reduced through technical measures, exposure to radon and its decay products is regulated both at the international level by the International Basic Safety Standards (BSS) published by the IAEA (International Atomic Energy Agency 2014) and within the European framework by the EU BSS Directive 2013/59/EURATOM (European Parliament 2014). Among others, the EU BSS directive requires the Member States to establish a reference level for radon concentration in both dwellings and workplaces, recommending a maximum of 300 Bq/m³. EU member states shall establish national action plans covering strategies for radon measurement, mitigation, and public awareness. Overview of the status of establishment and implementation of radon action plans among EU Member States is presented in the report from the EU-RAP study (European Commission et al. 2023).

Due to the geological conditions, the Czech Republic has elevated radon levels, affecting over 4.5% of its housing stock. Czech National Action Plan for Control of Public Exposure to Radon (RANAP) was established in 2019 in accordance with the requirements of the EU BSS and their implementation by the Czech Atomic Act (European Parliament 2014; State Office for Nuclear Safety 2025) and entered in force on 1 st of January 2020. RANAP builds on previous Radon Programmes, which were implemented on the basis of the Government Resolution between 2000 and 2009 and between 2010 and 2019.

The plan sets three long-term objectives (State Office for Nuclear Safety 2019): public and professional awareness; preventive measures in construction and reconstruction of buildings; and control of existing exposure. RANAP mandates cooperation among state authorities, including ministries and regional offices, under the coordination of the State Office for Nuclear Safety (SÚJB). RANAP is reviewed every five years and updated based on new data and stakeholder input. Reference level applied to both housing stock and workplaces is 300 Bq/m³. The individual exposure of 3,000 Bq/m^3 (annual average of radon activity concentration in a building with residential rooms or rooms to be occupied by persons) is considered unacceptable and the owner is obliged to take measures to reduce the radon concentration. Existing exposure is addressed through standardized measurements of radon concentration in indoor environment of residential buildings and workplaces, measurement of content of natural radionuclides in building materials and drinking water supplied for public use, with conditional subsidies for justified mitigation, and implementation of technical measures.

Radon measurements in residential environments are typically performed as either short-term or long-term assessments. Short-term testing offers an initial snapshot of radon concentration, while long-term monitoring—often spanning two months to one year—provides a more accurate average exposure that accounts for seasonal variations, occupancy habits, and ventilation patterns (World Health Organisation 2009; International Commission on Radiation Units and Measurements 2012; International Atomic Energy Agency 2015). Radon measurement is not only vital for identifying high-risk environments but also for validating the effectiveness of mitigation interventions (Jiranek et al. 2008; World Health Organisation 2009; Jiranek 2014; International Atomic Energy Agency 2015; Kouroukla et al. 2024).

Radon measurement in buildings have traditionally relied on methods such as solid-state nuclear track detectors (SSNTDs) and electret ion chambers (EICs), which are widely used across Europe, and charcoal adsorption canisters, commonly employed in the United States (George 1996). While SSNTDs are used for long-term measurement (of the order of months), EICs and charcoal canisters are used for short-term measurements spanning from days in case of charcoal canisters to weeks in case of EICs. All these provide single average value for the measurement period. While for standard decision making process, e.g. compliance with the reference level, long-term average RAC is usually sufficient, for identification of radon pathways and analysis of temporal radon behaviour it is not. For such purpose, only electronic continuous radon monitors (CRMs) should be used. Radon diagnostic measurement is a set of measurement procedures, among which the use of continuous radon monitors is vital, aiming at the aforementioned analysis of radon pathways. Froňka et al. (Froňka et al. 2008; Froňka and Jílek 2014) suggested and tested a complex set of diagnostic methods, including continuous radon monitoring in building and subsoil air, blower – door test and infrared imaging to identify soil-gas pathways into the building and tracer gas method for ventilation rate analysis. Such detailed analyses provide comprehensive data, but for a considerable cost. Results of a radon diagnostic can, among other benefits, help guide the design of effective radon mitigation measures.

For years, electronic continuous radon monitors – typically expensive and research-grade – were reserved for scientific applications. However, recent advances in sensor miniaturisation and digital electronics have enabled the production of affordable, low-cost CRMs. Since radon diagnostics requires the use of multiple continuous monitors simultaneously, lower-cost devices would enable more frequent use in practice. At the same time, however, the quality and reliability of the data obtained should not be neglected.

This paper summarizes experience collected from a radon diagnostic in a single family home carried out following standard procedures for radon diagnostic applied at SURO, utilizing several CRMs from the low- and medium-cost category.

Materials and methods

Training course

Trained experts in the fields of radon measurement, preventive measures, and design and implementation of remedial measures are essential for successful management of radon indoors risk (World Health Organisation 2009; European Commission et al. 2023). The RadoNorm training course "From radon measurement to optimized mitigation" attempted to contribute to capacity building in this field. The course jointly organized by the National Radiation Protection Institute (SURO) and Faculty of Civil Engineering of the Czech Technical University in Prague provided participants with series of lectures on measurement techniques and diagnostic procedures for buildings. It also presented the principles of radon control technologies and described in detail the various preventive and remedial measures with particular emphasis on their design and implementation. To complement the theoretical component, participants carried out a practical demonstration of radon diagnostics in a single-family home previously identified as having potentially elevated radon concentrations. This diagnostics work was followed by further measurements, and present paper summarizes all results in the form of a case study.

The training course was supported by Work Package 7 of the RadoNorm project, which focused on recruiting and supporting early-career researchers, enhancing their skill through exchange visits, and providing targeted training in radiation protection research.

Description of the measurement site

The house is perched atop a rocky incline, with a small stream flowing at its base. The vertical drop from the house to the stream is around 10 m. Czech Geological Survey provides geological maps in scale 1:50 000. According to the map of the area where the house is built the rock composition is as follows: proterozoic graywacke, siltstone with possible layers of shale (upper part of the site) and alluvial sediment (lower part of the site) (Czech Geological Survey and State Office for Nuclear Safety 2023). The soil cover, especially in the area around the house, consists of fill soil that has been repeatedly modified for small-scale gardening purposes.

The building, originally approved for use as a recreational house, was constructed in 1939. It consists of two above-ground floors, a cellar located partially beneath the kitchen and living room, and two storage rooms situated under the hallway area, accessible only from the outside. In the middle of the cellar, there is a recess that was formerly used for coal storage. The cellar has two small single-glazed hopper windows. The upper floor is accessible from ground floor via an internal staircase. Access to the cellar is permitted only from the hallway area inside the house through wooden hatch in the floor. According to information provided by the owner, part of the cellar foundations was dug into the rock. The building has undergone two major reconstructions. The first around 1970 during which the hallway and entrance (veranda) were added as an extension of the old existing house. The second was carried out between 2010 and 2014. During this second reconstruction, original windows have been replaced with PVC/plastic windows, with good airtightness and the entire house, including the roof was thermally retrofitted.

The perimeter and interior walls of the ground floor are bricks, typical for the period when the building was built. Interior walls of the first floor are made of plasterboard, added during the second major reconstruction. The ground-floor slabs are primarily made of concrete and covered with a simple bituminous waterproofing insulation layer. No barrier or mitigation system is in place to prevent radon from entering from the ground. Water is supplied from the public water system. The central heating system is electric, with a boiler, and no underfloor heating is installed.

The house is not occupied permanently, it serves as a weekend and summer house.

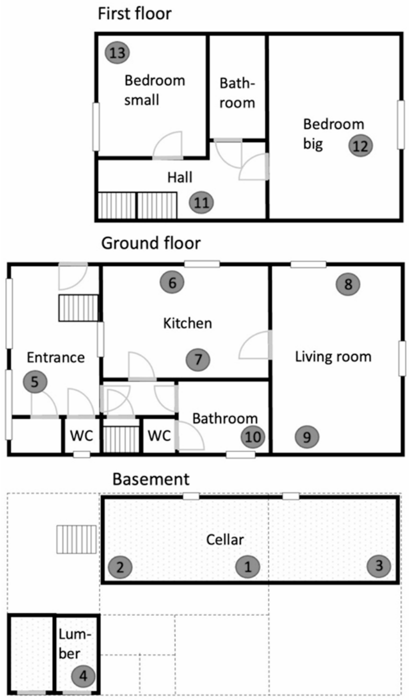
Floorplan of the house is shown on Fig. 1.

Instrumentation and applied methods

Radon activity concentration measurement

Grab sampling

The RM-2 measuring system (RADON.eu 2023) was used to determine radon activity concentrations (RAC) in air samples collected from structural leaks within the building. The system has Type Approval and was metrologically



Legend

Room	Point	Measurement T1		Measurement T2	
		Device	Type	Device	Type
Cellar	1	CP24	CP	CP17	CP
	2	CP14	CP	CP11	CP
	3	CP23	CP	-	-
Lumber room	4	-	-	CP5	CP
Entrance	5	CP11	CP	D20	RnE
		J45	RnE		
Kitchen	6	CP5	CP	D15	RnE
		K60	RE		
	7	-	-	J37	RnE
Living room	8	CP19	CP	C50	RnE
		H25	RnE		
	9	CP3	CP	-	-
		J43	RnE		
Bathroom	10	CP6	CP	J49	RnE
		H14	RnE		
Hall	11	CP1	CP	-	-
		J34	RnE		
Bedroom big	12	CP20	CP	D18	RnE
		D18	RnE		
Bedroom small	13	CP22	CP	C51	RnE
		J39	RnE		

Fig. 1 Floorplan of the house. Measurement points highlighted with grey circle and number. CP refers to Corentium Pro, RnE refers to RadonEye+2

verified in accordance with the requirements of the Czech legal framework.

Grab samples were taken on the ground floor of the building from leaks and suspected radon inflow points. Samples of 150 ml were collected using a large-volume flush syringe (JANETTE) fitted with a puncture needle. The samples were then transferred to an IK-250 ionization chamber of the RM-2 system, and the RAC was measured after a time delay of 15 min following sampling. Measurement in each chamber took 120 s. This setup enables on-site result acquisition and allows for additional sampling if needed.

A second set of grab samples was collected from probes for soil-gas RAC measurement. The probes consisted of small-diameter hollow steel rods with a free sharpened tip, driven to a standard depth of 80 cm at seven different locations in the vicinity of the house (a more detailed description of the sampling procedure is available in Neznal et al. 2004). By retracting the sharpened tip a few centimetres using a long wire, a cavity was created from which soil gas could be sampled with a syringe. The same RM-2 measurement system was used as for the building leak samples.

Continuous radon monitoring

A total of three measurement campaigns using continuous radon monitors were conducted in the house. All continuous monitors—Radim3AT (Tesla a.s.), RadonEye+2 (FTlab, South Korea), and Corentium Pro (Airthings, Norway)—had Type Approval and were metrologically verified.

The initial measurement campaign was carried out from May to June 2021 and lasted two weeks. RadonEye+2 monitors were deployed in habitable rooms on the ground floor (kitchen and living room), in the entrance, and in the large bedroom on the first floor. A Radim3AT monitor was deployed in the cellar. For most of this period, the building was occupied by at least two adults and two children.

The second measurement campaign was conducted within the framework of the RadoNorm training course and lasted one week. Several RadonEye+2 and Corentium Pro monitors were deployed in the house. With the exception of the cellar, both monitor types were placed side by side at each measurement point. During this campaign, the building was unoccupied.

The third measurement campaign was performed in May–June 2025, using a setup similar to that of the second campaign.

For clarity, the first campaign (May–June 2021) is hereafter referred to as T0, the second campaign (training course) as T1, and the third campaign (May–June 2025) as T2. The locations of measurement points (MPs) are shown in Fig. 1.

Average radon activity concentration measurement

During the second measurement campaign (T1), electret ion chambers were used to obtain average radon concentration. The electret ion chambers are of Czech production and their brief description is available in Dubcakova et al. (Dubcakova et al. 2011). The system has the Type Approval and it undergoes periodical metrological verification.

The pair of chambers was placed close to the continuous monitors in every room.

Average air exchange rate measurement

The tracer gas method, first described in detail by Dietz et al. (1986), is a widely used technique for measuring the air exchange rate (ACH). This approach relies on either continuous or integral measurement of a suitable tracer gas. The tracer gas can be injected as a single pulse at the beginning of the measurement or supplied continuously at a known rate. Ideally, the background concentration of the tracer gas in the environment should be zero.

For analysis, the building can be conceptually divided into compartments, with a specific tracer assigned to each compartment. This enables determination of the average air exchange rate within each compartment as well as the airflow between compartments. When performed in combination with simultaneous radon activity concentration (RAC) measurements, the method also allows estimation of the radon entry rate.

At the start of each ACH measurement, a number of tracer gas generators are placed in each compartment, with the exact number depending on the compartment volume. At least one detection point is established per compartment, and the volume of each compartment must be measured. At the end of the ACH measurement, the weight loss of tracer gas generators is determined, chromatographic evaluation of the integral detectors is performed, and the total ACH, compartment-specific ACH, and inter-compartmental airflows are calculated.

A comprehensive overview of tracer gas-based methods is provided in a recent review by Remion et al. (2019). The method implemented by SURO is described in more detail by Hupka et al.[1] and in the Czech certified measurement protocol (Jílek and Froňka 2016).

Gamma dose rate measurement

Gamma dose rate was measured by RT-30G (Georadis, Czech Republic) which is a handheld field gamma-ray spectrometer with Type Approval and periodical metrology verification.

Measurement geometry followed the requirement of the National Guideline (State Office for Nuclear Safety 2018) which is 50 cm from the walls, 1 m above ground at several locations in each of the habitable rooms. In addition to this screening measurement, gamma dose rate was measured at all of the measurement points where electret ion chambers were located.

Meteorological data

The meteorological data in the measurement campaign T1 were obtained using a Davis Vantage Pro weather station located in the garden behind the house. In the measurement campaign T0 and T2, the meteorological data were obtained from the Open-Meteo project (Zippenfenig 2023).

Data processing

A cleaning and readjustment of the measured data was necessary before their use. First, due to initial setup oversight, only a few RadonEye+2 monitors had correctly synchronized timestamps. Loss of time synchronizations occurs after longer period (weeks) when the device is without external power supply. This could be overcome by connecting each individual device during setup, which unfortunately did not happen. To resolve this, we adjusted all devices so that the last downloaded data aligned with the timestamp from a reference device, which had the correct time settings. This adjustment introduced a slight time shift, as not all devices were switched on simultaneously, however, due to the length of measurement it is not expected to significantly affect measurement results. The measurement periods were divided into three distinct intervals for evaluation and further analysis. The T0 dataset comprised data collected between 24 May 2021, 12:00 and 7 June 2021, 10:30. The T1 dataset included data recorded from 7 May 2025, 17:00 to 14 May 2025, 08:00, while the T2 dataset consisted of measurements obtained between 29 May 2025, 14:00 and 12 June 2025, 10:45. Finally, data from each continuous monitor were multiplied by calibration factors obtained from the Authorised Metrological Centre.

For calculating the temperature gradient between the interior of the house and the outdoor environment, the closest available time point from the weather data was used. For the indoor temperature, only the measurement from a single device was selected for each room.

Results

This section provides a summary of the obtained results.

Gamma dose rate

Measurement results at none of the measurement points exceeded 80 nGy/h.

[1] Hupka, I., Jílek, K., Kotík, L., Lenk, J. (2025). Application of diffusive uptake rates of selected Volatile Organic Compounds on tubes for investigation of air exchange rate in dwellings. Manuscript submitted for publication.

Table 1 Arithmetic average of RAC recorded during the T0 measurement campaign in 2021

floor	room	MP[1]	device	average RAC (Bq/m^3)
−1	Cellar, front	2	Radim3AT (R3AT 19004)	310±47
1	Entrance	5	RadonEye+2 (PE60)	199±30
1	Kitchen	6	RadonEye+2 (PE50)	245±37
1	Living room	8	RadonEye+2 (PE54)	243±36
2	Big bedroom	12	RadonEye+2 (PE28)	126±19

[1] MP – measurement point, see Fig. 1

Radon activity concentration

Initial radon measurement T0 was carried out between 24 May 2021 and 7 June 2021 utilizing RadonEye+2 and Radim 3AT continuous monitors. The average radon activity concentration over the measurement period at each measurement site is shown in Table 1 below. From the time course of RAC displayed in Fig. 2 it is clearly visible that during the period when the house was occupied, RAC is low in habitable rooms. During the period of 30 May – 2 June, indicated in grey in the figure, the house was not occupied which resulted in ventilation drop and increase of RAC. Similar situation can be seen at the beginning of the measurement period; after setting up the measurement, the building was not occupied for almost two days.

Simultaneous measurement of RAC and temperature inside and outside enabled to visualize the time course of RAC at particular measurement points and temperature difference of indoor temperature (T_{in}) and outdoor temperature (T_{out}). Other meteorological parameters did not show any major influence on behaviour of RAC. Figure 3 displays RAC measured in the cellar which is mostly influenced by the temperature difference.

The measurement campaign results showed elevated radon concentrations, mainly when the building was unoccupied, and suggested a radon pathway from the cellar to the rest of the house, primarily through leaks around the wooden hatch covering the cellar entrance.

During the T1 measurement period (7–14 May 2025), the average RAC values were determined at selected locations in the building using Corentium Pro, RadonEye+2, and electret detectors. Each measurement point (MP) in habitable rooms was deliberately equipped with all three instrument types to allow comparison, except in the cellar. In the cellar, RadonEye+2 could not be deployed because it requires mains power and no electrical sockets were available at measurement points in the cellar. Electrets were also excluded from most cellar positions due to concerns about the high relative humidity (>95%), which could compromise their performance; they were deployed only at the front of the cellar (MP2). Instead, three Corentium Pro devices were installed at MP2 (front), MP1 (middle of the recess), and MP3 (end of the cellar).

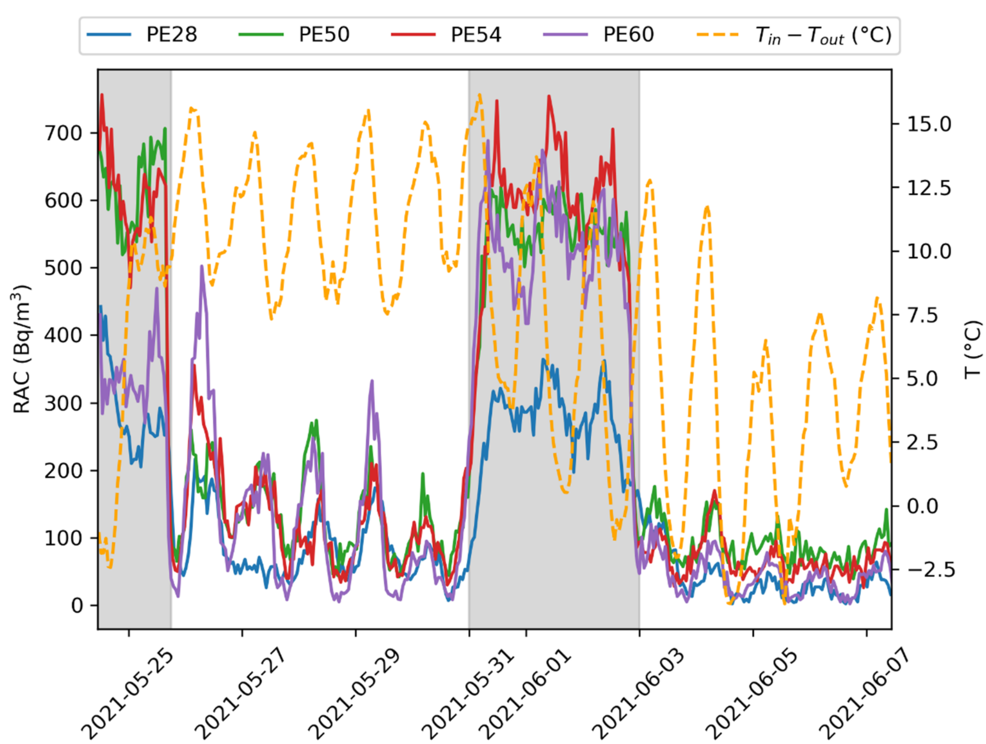


Fig. 2 Time course of RAC measured in habitable rooms during T0 measurement campaign. Grey areas highlight the period during which the house was unoccupied

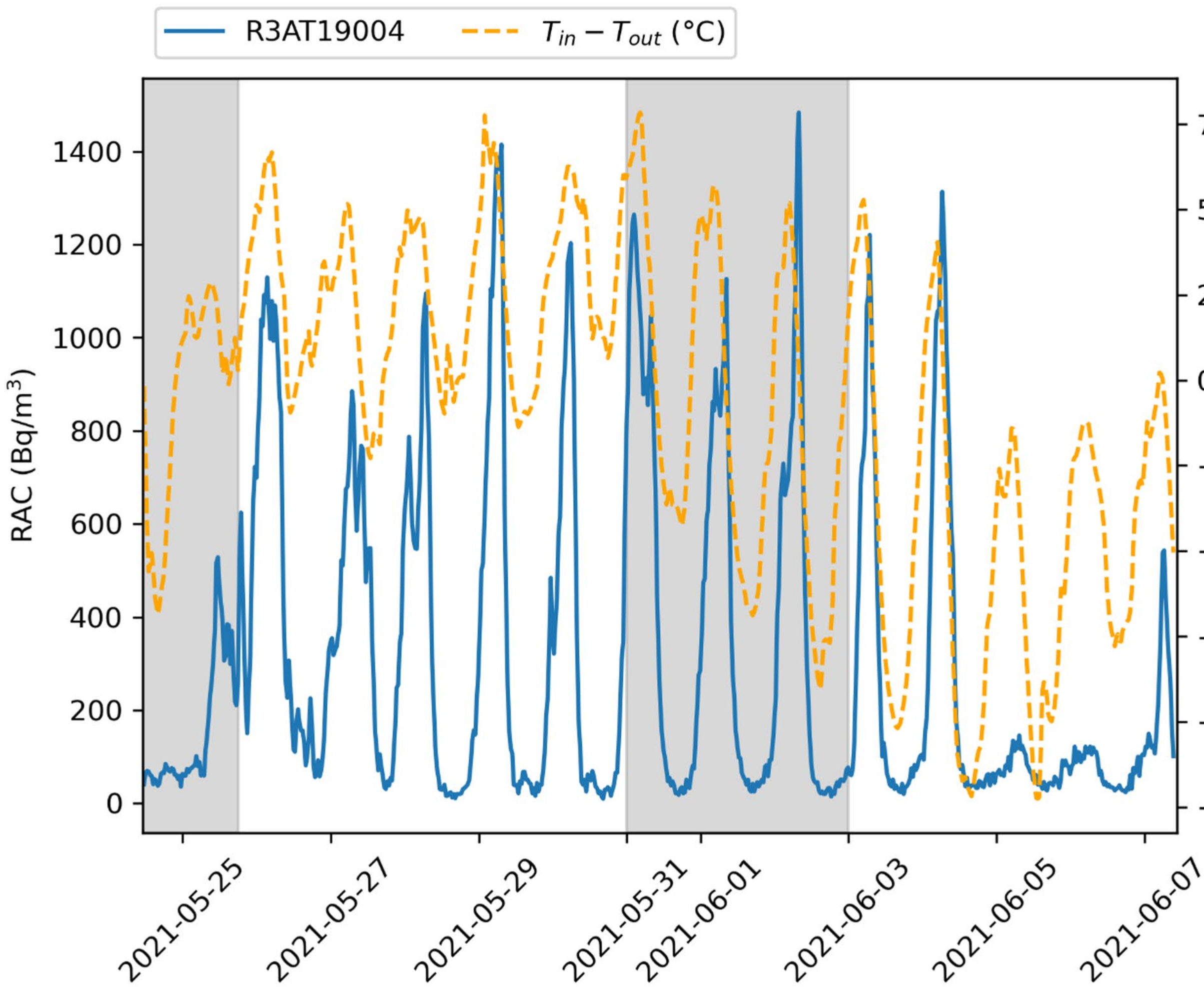


Fig. 3 Time course of RAC measured in the cellar during T0 measurement campaign. Grey areas highlight the period during which the house was unoccupied

For orientation, measurement point locations are shown in Fig. 1. The distribution of RAC results is presented as a boxplot in Fig. 4 and summarized in Table 2. A noticeable difference was observed among the three Corentium Pro units in the cellar. The hopper windows were kept closed during the first half of the measurement period and opened midway, altering ventilation. The RAC at MP1 (recess, Corentium Pro CP24) was unaffected by this change, suggesting poor ventilation within that section.

The second measurement period (T2) lasted from 29 May 2025, 14:00, to 12 June 2025, 10:45. The same measurement points were used as in T1, with the following differences: in the cellar, only the entrance (MP2) and recess (MP1) were equipped, since the results from the front and back of the cellar had been very similar. In addition, the lumber room, accessible from outside, was included. Electrets were not used during T2, as they do not provide information suitable for analyzing the RAC time course. At each measurement point, only one type of instrument was deployed—either Corentium Pro or RadonEye+2. The RAC distributions are summarized in Fig. 5.

From Figs. 6, 7 and 8, the well-known relationship is evident: when the temperature difference is above zero, indoor radon concentration increases. The most pronounced variations in both temperature and RAC were observed in the cellar. The effect of changes in cellar ventilation is clearly visible in Fig. 6. The limited variation of RAC in the living room and bathroom is mainly a result of low ventilation (see Section "Average air exchange rate" and Table 3).

Eight grab samples from suspected locations on the ground floor were collected during the T1 measurement campaign – floor-wall joint in bathroom, kitchen and living room, from space around sink pipes in bathroom and from joint floor-staircase to the first floor showed radon concentration between 3 and 7 kBq/m^3.

Soil gas samples were collected during the T1 measurement campaign from seven different measurement points located in the vicinity of the house. The average RAC from

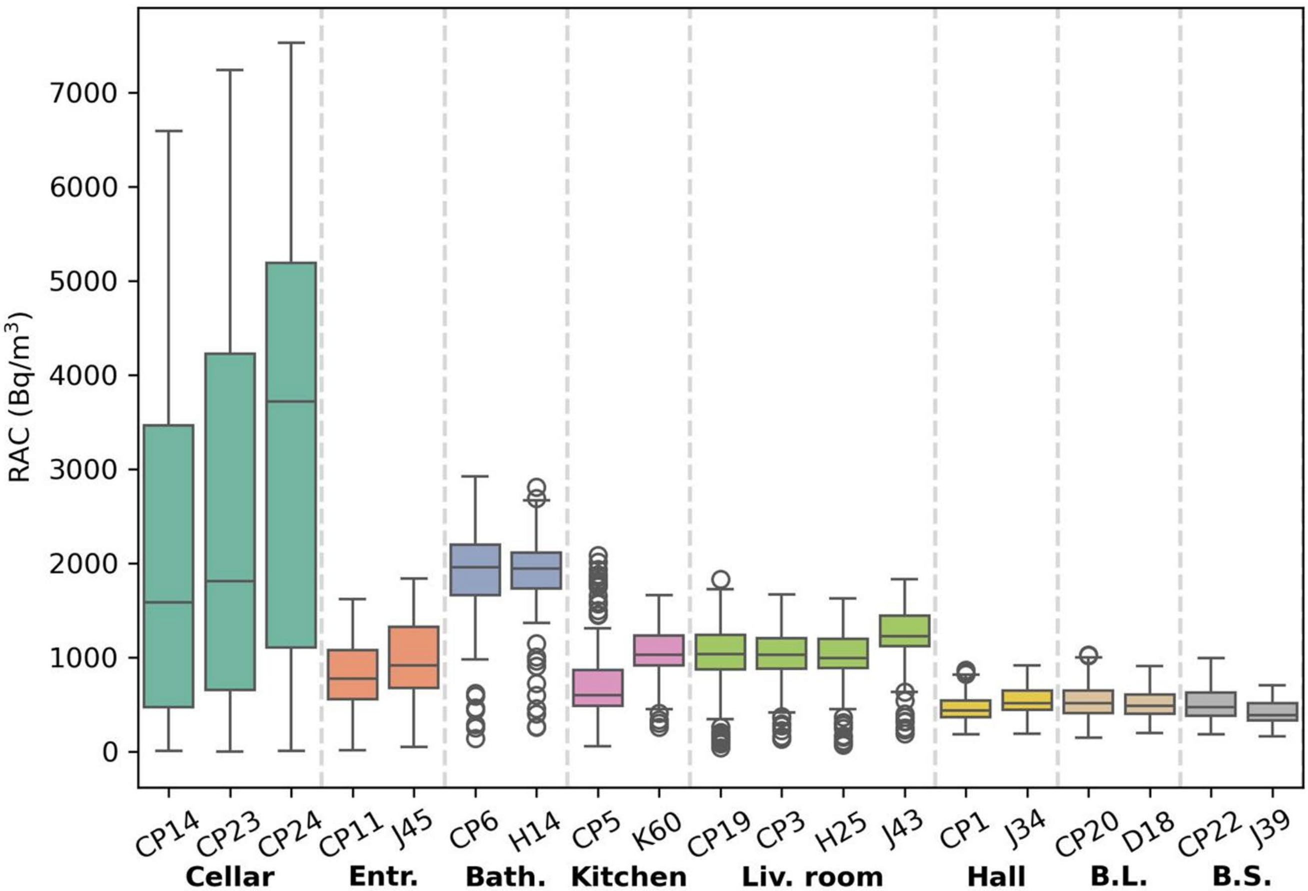


Fig. 4 Boxplot showing the distribution of radon activity concentration (RAC) values during the T1 measurement period. B.L. - Bedroom large, B.S. - Bedroom small

Table 2 Average RAC from measurement campaign T1

			RAC (Bq/m^3)		
floor	room	MP[1]	Corentium Pro	Radon-Eye+2	Electrets
−1	Cellar, middle	1	3310±490	-	-
−1	Cellar, front	2	2130±320	-	1900±290
−1	Cellar, back	3	2420±370	-	-
1	Entrance	5	830±130	990±150	err
1	Kitchen	7	760±120	1060±160	890±140
1	Living room, point 1	8	1030±160	1030±160	940±150
1	Living room, point 2	9	1030±160	1250±190	830±130
1	Bathroom	10	1920±290	1900±290	>1820
2	Hall	11	470±80	550±90	460±70
2	Small bedroom	13	500±80	420±70	480±80
2	Big bedroom	12	540±90	520±80	430±70

[1] MP – measurement point, see Fig. 1

five samples is 46.2±3.2 kBq/m^3. Two measured values we deemed to be outlier and were excluded from the calculation (8.4±1.3 kBq/m^3 and 3.8±0.8 kBq/m^3). From the consultation with the houseowner it was found that these particular points are covered by a thick layer of new soil to level uneven terrain which could have impacted the distribution of radon transported via soil air.

Average air exchange rate

Two ACH measurements were taken in the building. The first was carried out between 24th May and 7th June 2021 and the second between 29th May and 12th June 2025. In both cases the building was divided into four compartments. The cellar and the first floor were defined in the same way in both cases. The difference was in how the ground floor was divided into two compartments. In the case of the 2021 measurements, hallway was one compartment, the rest of the ground floor was the second compartment. In 2025, bathroom was set as a separate compartment because of new findings from radon diagnostics performed in T1. The house was occupied during the measurement carried out in 2021 for most of the time. The house was not occupied for the whole measurement period in 2025.

Measurement results are summarized in Table 3; Fig. 9. Measurements in both cases confirmed a dominant air flow

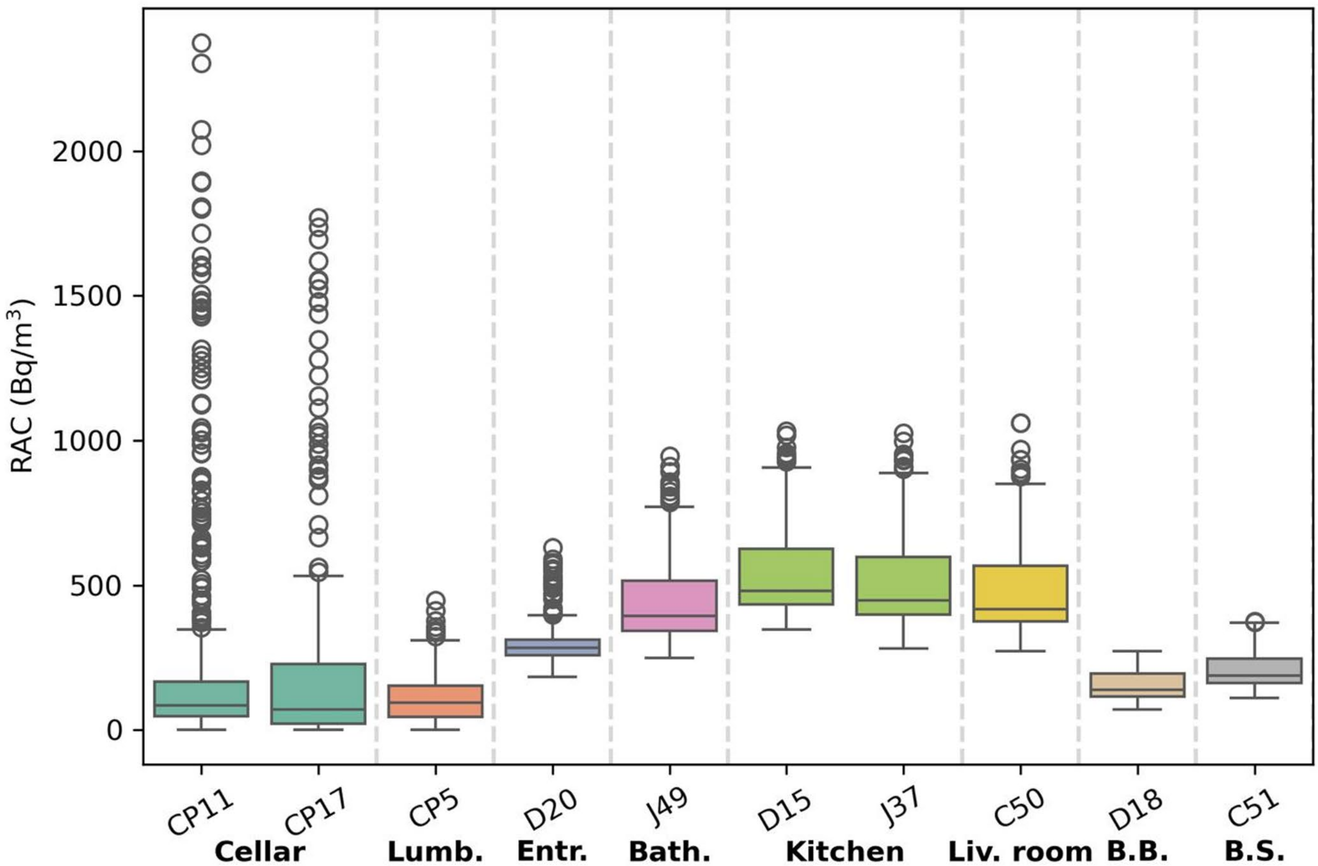


Fig. 5 Boxplot showing the distribution of radon activity concentration (RAC) values during the T2 measurement campaign. B.L. refers to Bedroom large and B.S. to Bedroom small

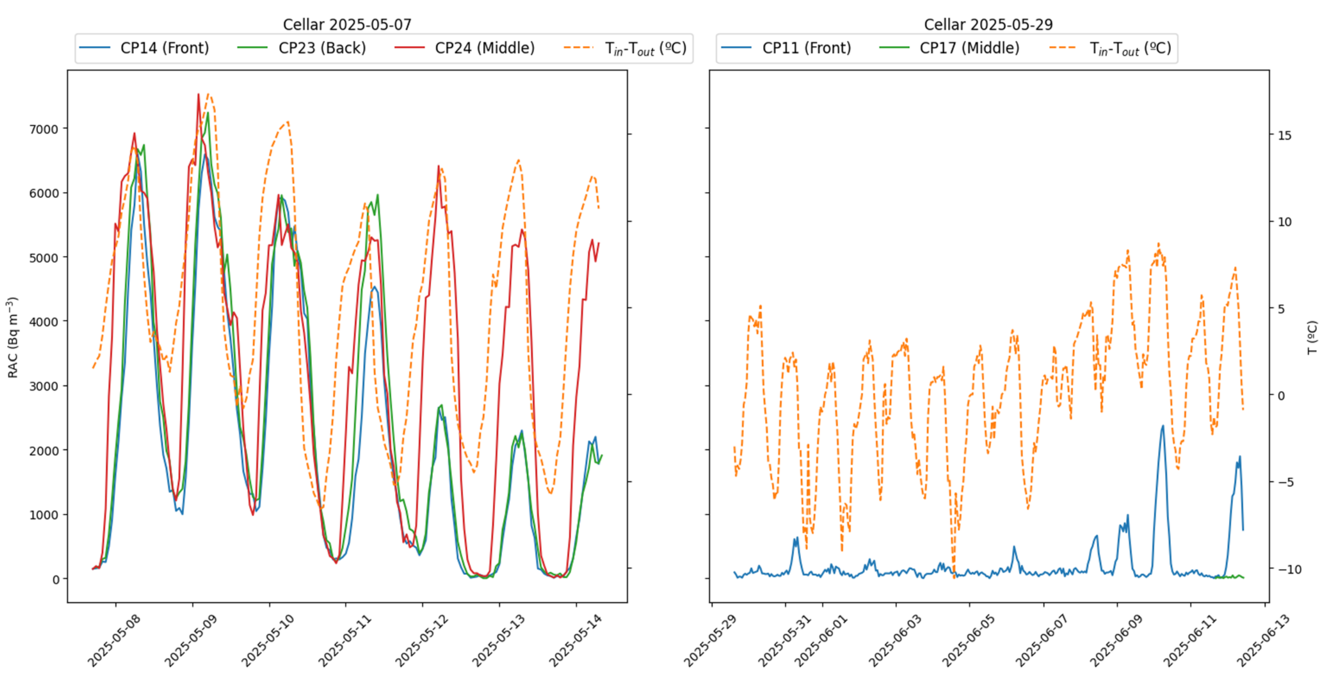


Fig. 6 Time course of temperature difference and RAC in the cellar during T1 (left) and T2 (right) measurement campaign

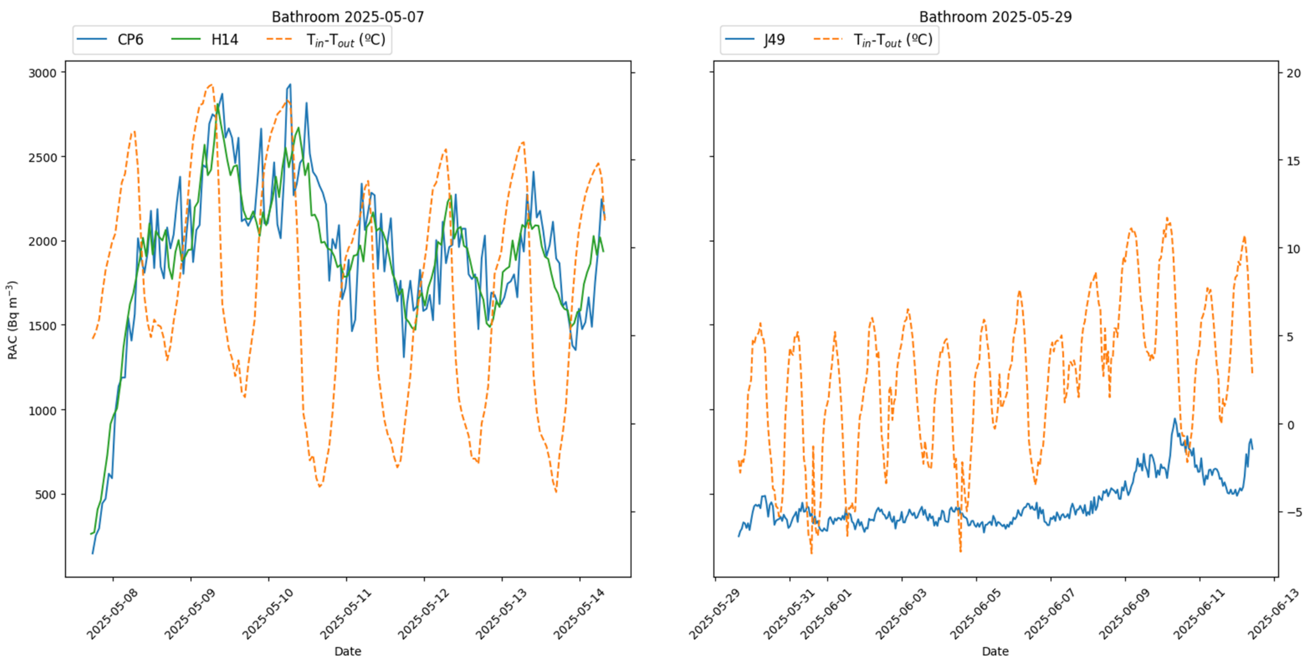


Fig. 7 Time course of temperature difference and RAC in bathroom on the ground floor during T1 (left) and T2 (right) measurement campaign

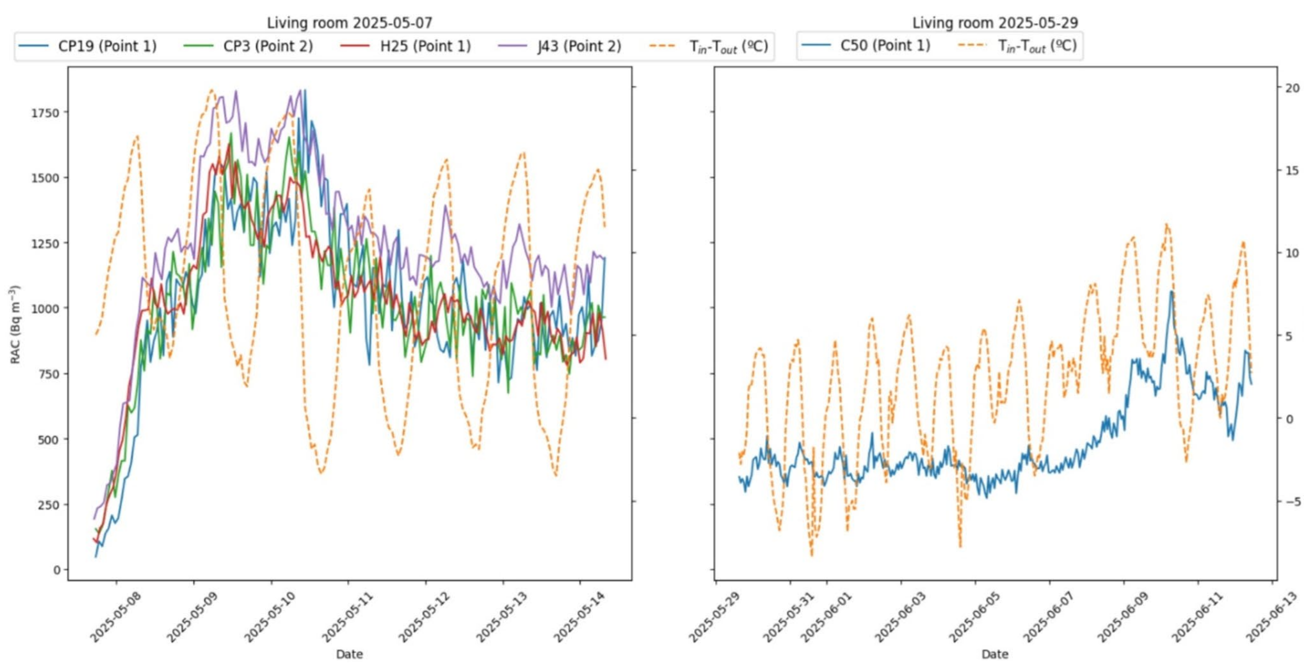


Fig. 8 Time course of temperature difference and RAC in living room on the ground floor during T1 (left) and T2 (right) measurement campaign

from lower to higher floors and very good homogeneity within the first floor. In contrast, no analytes from the upper floors were detected in the cellar. This means that a significant amount of air from both the basement and the bathroom enters the rooms of the ground and first floors.

Discussion

Availability of several types of low- and medium-price CRMs on the market have prompted a wave of dedicated research. Recent studies on low-cost CRMs fall broadly into two categories: single-device performance evaluations under varied environmental conditions (Mitev et al. 2022; Dimitrova et al. 2023; Bossew 2025) and comparative

Table 3 Results of average ACH measurements in a particular year

measurement period	2021	2025
Duration [days]	14	14
Compartment	average ACH [h^{-1}]	
Cellar	0.7 ± 0.1	0.72 ± 0.05
Ground floor – hallway	0.2 ± 0.1	-
Ground floor – bathroom	-	0.05 ± 0.01
Ground floor	0.16 ± 0.04	0.05 ± 0.02
First floor	0.24 ± 0.03	0.09 ± 0.01
Average (whole building)	0.25 ± 0.03	0.13 ± 0.05

studies assessing multiple CRM models over long-term (Rábago et al. 2024; Daraktchieva et al. 2024) or short-term periods (Fuente et al. 2018; Rabago et al. 2020; Warkentin et al. 2020; Radulescu et al. 2022), or both (Bahadori and Hanson 2024). Additionally, efforts have been made to evaluate whether consumer-grade CRMs comply with standards originally designed for professional-grade instruments (Bahadori and Hanson 2024; Beck et al. 2024).

Environmental parameters – especially temperature and relative humidity – significantly affect CRM performance. Radulescu et al. (Radulescu et al. 2022) compared three CRMs: AlphaGUARD, Pylon AB-5, and RadonScout. Of the three, only RadonScout showed sensitivity to temperature and humidity variations during short-term controlled testing. Notably, AlphaGUARD and Pylon AB-5 are considered research-grade. Beck et al. (2024) conducted a comprehensive evaluation of 14 CRM models, including the AlphaGUARD as a benchmark. Their results confirmed that temperature fluctuations tend to cause: Overestimation of radon concentrations when temperatures drop and underestimation when temperatures rise. In terms of humidity, the impact is more pronounced for devices that use electrostatic collection of radon progeny. Water vapor neutralizes charged particles, reducing collection efficiency and leading to measurement inaccuracies.

Fuente et al. (2018) observed that consumer-grade CRMs generally have slower response times compared to professional instruments. Rábago et al. (2024) tested six CRM models and found significant variability in response. In some cases, devices reached only 10% of the peak radon value with delays of up to 7 h, this is insufficient for capturing rapid fluctuations in radon levels, such as sudden increase or decrease. The lag is primarily attributed to long integration times—a necessary trade-off to ensure statistical reliability at low radon concentrations and lower sensitivity of tested CRMs compared to research-grade ones.

Performance appears to correlate strongly with device cost. Rey et al. (2025) and Lemieux et al. (2025) reported that higher-priced CRMs generally provide greater accuracy and reliability. Devices from manufacturers with a background in professional radon instrumentation consistently outperformed cheaper consumer-grade models.

Some researchers, notably Lemieux et al. (2025), emphasize the necessity of independent evaluation and regulatory oversight for low-cost continuous radon monitors; without such oversight, errors could mislead users and pose health risks by underestimating exposure. A recent study by Bahadori and Hanson (2024) evaluated eight consumer-grade CRMs against the ANSI/AARST (2022) standards and found that most met the required criteria. However, they

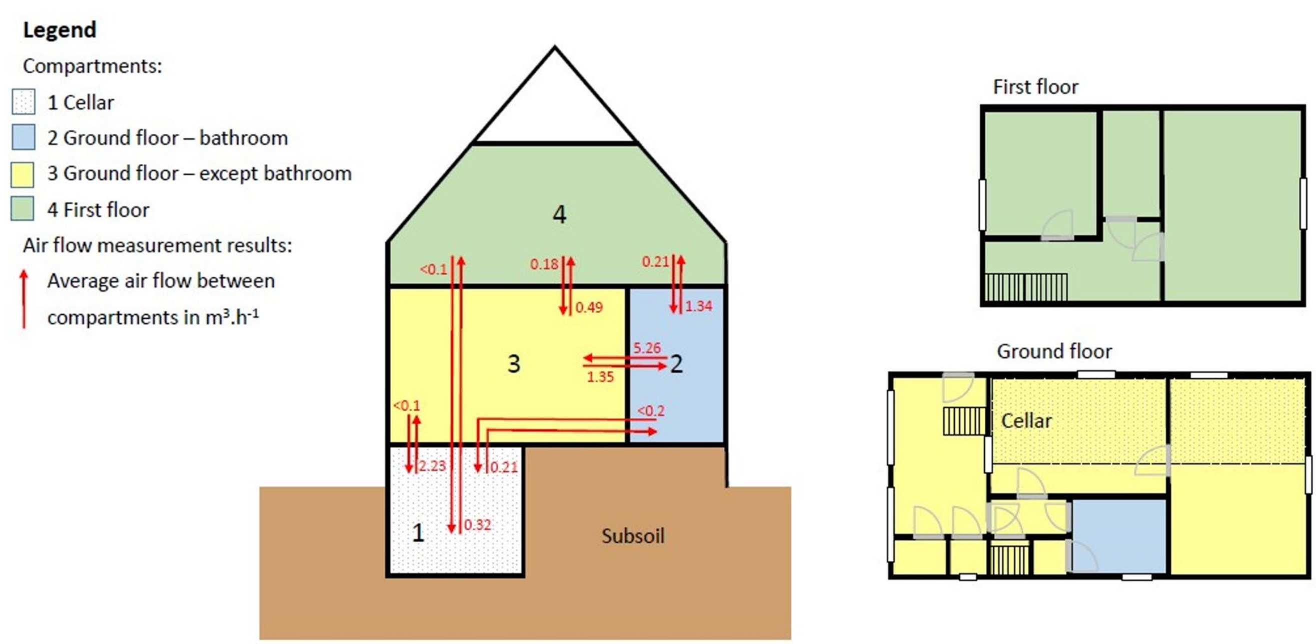


Fig. 9 Results of air exchange rate between compartments of the building collected during the measurement campaign T2 carried out in 2025. House was not occupied

raised concerns about long-term reliability. Warkentin et al. (2020) reported similar findings. In a four-year comparative study, Daraktchieva et al. (2024) examined seven types of CRMs alongside SSNTDs and concluded that most CRMs performed well at high radon concentrations, but their performance declined at lower levels. In addition, calibration factors shifted significantly over time, underscoring the need for regular recalibration and ongoing maintenance. As the consumer-grade CRMs gain popularity in homes and citizen science efforts (Martell et al. 2021), it is critical to continue rigorous testing and transparently share results not only within the scientific community, but also with regulators and citizen initiatives.

In the Czech Republic, all devices (integral detectors of radon, continuous monitors, personal dosimeters) used for the measurement, the results of which are compared with a reference level or on the basis of which the effective dose is calculated should comply with the Metrology law (Act No. 505/1990 Coll. on Metrology, as later amended), i.e. they should obtain a Type Approval and should be metrologically verified by the Authorised Metrology Centre each 2 years. This system provides a certain degree of control over the quality and reliability of the types of instruments used. All types of CRM used in this study had valid Type Approval, and each individual instrument had a valid verification from the Authorised Metrology Centre which means that their relative intrinsic error does not exceed ± 20% of the reference (correct) value, under the defined standard conditions (Czech Metrology Institute 2018).

In the present investigation, three measurement campaigns were conducted in a single-family house. Elevated radon levels were found during the initial measurement campaign in the kitchen and living room, exceeding 300 Bq/m³, mainly when the house was unoccupied or during the night. Since the measurements were taken outside the heating season, it was expected that radon levels would be higher during the winter heating period. It was also assumed that the main source of indoor radon was leakage around the frame of the wooden hatch providing access to the cellar from the entrance hallway.

The following two measurement campaigns were carried out in 2025, both in unoccupied house. A radon hotspot was identified in the bathroom during the T1 campaign, with an average radon concentration of 1920 ± 290 Bq/m³ with a range between (146–2926) Bq/m³. In the cellar, high values were recorded during T1 measurement period; however, it is important to mention that the windows in the cellar were closed for approximately two thirds of the T1 measurement period to demonstrate the effect on RAC. As can be seen from Fig. 4, the measurement point in the recess located in the middle of the cellar was not affected by the increased ventilation, which explains the observed concentrations which range from 2000 to 3000 Bq/m³ depending on CRM position in the cellar.

For the rooms on the ground floor that were analysed, it was established that all devices used recorded values exceeding 300 Bq/m³. Similarly, for the first floor, the analysed data were above 300 Bq/m^3, but lower than those recorded on the ground floor.

The Table 2 can be interpreted as a clear example of the advantages of CRMs over integrating detectors. We used both types and, in the end, obtained results that were in reasonably good agreement. However, CRMs provide time-resolved hourly values, which can offer much more information. For example, when related to temperature differences, these data can help estimate the dominant radon entry process.

Elevated radon levels were identified also during the T2 measurement campaign with highest averages on the ground floor in bathroom, kitchen and living room. Results of average RAC collected during the T2 correspond well with the average air exchange rate measurement results. The average RAC value measured during T0, under similar weather conditions but in an inhabited house, was almost half of that measured during T2 on the ground floor. On the first floor and in the basement, the average RAC values for T0 and T2 were nearly identical.

A significant difference in RAC between T1 and T2 can be observed across all locations, particularly in the cellar (Figs. 4 and 5). The RAC was much lower during T2, which may be attributed to the smaller temperature gradient compared to T1. This trend is also clearly visible in the time series showing RAC and temperature gradient in other rooms (see Figs. 6, 7 and 8). Other meteorological parameters did not show any major influence on behaviour of RAC. This is in good agreement with results by Groves-Kirkby et al. (Groves-Kirkby et al. 2015) that suggest the correlation between RAC and temperature difference to be stronger than with outdoor temperature only.

The water in the house is supplied from a public source and is therefore also monitored for radon content (State Office for Nuclear Safety 2025). The measured gamma dose rates in the building were at the level of the average gamma dose rate from natural background in the Czech Republic (Matolín 2017). All collected results indicate that the source of the radon is subsurface soil, as the radon intake is affected by pressure difference generated by the stack effect.

Two air exchange rate measurement campaigns were conducted. During the first measurement campaign the house was occupied for most of the measurement period, while during the second measurement campaign the house was unoccupied. This difference is reflected by the results of measurement, see Table 3, where the total ACH during occupancy was double the ACH for unoccupied house. The situation was even more pronounced in case of partial ACHs for ground and first floor.

Air exchange rate measurements showed that a high radon concentration was in the cellar, but it was not the main cause of elevated RAC in the building. A large volume of air moves from the bathroom to the rest of the ground floor and to the first floor. As noted, the bathroom had the highest RAC of all the above-ground rooms and is therefore considered the primary pathway for radon into the rest of the building. Therefore, better sealing of wooden hatch to the cellar or increased ventilation of the cellar would not remediate the situation in the rest of the house, as the cellar serves only as a secondary pathway for radon.

After the measurements and after discussions with a civil engineer who also reviewed the sketches and results, it was concluded, considering the ACH results obtained from the occupied house, that the mitigation based solely on increased ventilation rate will improve the air quality. However, in terms of radon concentration in the house, it would not be enough to mitigate it, unless ventilation rates were increased to uncomfortable levels. The most effective mitigation method for this situation would be sub-slab depressurization, which can be implemented preferably from the cellar to decrease the cost of the construction. Sub-slab depressurization is often the mitigation method of choice (Kouroukla et al. 2024), based on its simplicity and high efficiency (Paridaens et al. 2005; Jiranek 2014).

Conclusions

Radon diagnostic procedures aimed at identifying radon sources in a building and describing radon behaviour under different meteorological and user conditions were demonstrated using a case study of a single-family house. Simultaneous measurement of radon concentration and air exchange rate enabled a detailed characterization of radon behaviour in the building, which supports the selection of mitigation measures that will be effective for the specific structure. Based on the estimated radon entry rate, sub-slab depressurization was identified as the most cost-effective mitigation strategy for this case study house. Further action now rests with the homeowner.

In addition to identifying radon sources in the house, the objective of the measurement campaigns was to evaluate the suitability of low-cost continuous radon monitors (CRMs) for use in radon diagnostics. Two types of CRMs, Corentium Pro and RadonEye + 2, were selected for testing. Both instruments are already used in the Czech Republic and hold national Type Approval, which is a prerequisite for metrological verification. Overall, the results demonstrate that metrologically verified low-cost continuous monitors, when combined with air exchange rate measurements, provide a practical tool for radon diagnostics, supporting the evidence-based design of mitigation measures to reduce indoor radon levels in the investigated building.

Future research should include broader field intercomparisons of low-cost CRMs under varied environmental conditions, as well as assessments of their long-term stability. Clear regulatory guidance and standardized calibration procedures remain essential to ensure measurement reliability.

Acknowledgements Thanks to the homeowners' cooperation and patience, it was possible to use the house as a training facility for RadoNorm training course „From radon measurement to optimized mitigation," which allowed its participants to carry out radon diagnostics on a real building. Authors wish to thank also to Prof. Martin Jiranek, CSc. for consultation of available mitigation measures and selection of the cost-effective remedial measure for this particular house. Authors would like to thank Jan Hradecky, Stepan Fronka, Vladimir Kianicka and Vaclav Rericha for their valuable support during measurement campaigns.

Author contributions Conceptualization: Katerina Navratilova Rovenska, Radim Moznar, Miroslav Vanek, Martin Kaschner; Methodology: Katerina Navratilova Rovenska, Radim Moznar, Jan Lenk, Ondrej Parizek; Formal analysis and investigation: Katerina Navratilova Rovenska, Miroslav Vanek, Radim Moznar, Martin Kaschner, Elena Castaño Casco, Shahed Khan, Esther Osei Akuo-ko, Ilaria Rocchetti, Ondrej Parizek, Jan Lenk, Marcela Adamova, Oana Elena Peneoasu, Lukas Mareda; Writing - original draft preparation: Katerina Navratilova Rovenska, Miroslav Vanek, Radim Moznar, Martin Kaschner, Elena Castaño Casco, Shahed Khan, Esther Osei Akuo-ko; Writing - review and editing: Katerina Navratilova Rovenska, Miroslav Vanek, Radim Moznar, Martin Kaschner, Elena Castaño Casco, Shahed Khan, Esther Osei Akuo-ko, Ilaria Rocchetti; Funding acquisition: Katerina Navratilova Rovenska; Resources: Katerina Navratilova Rovenska; Supervision: Katerina Navratilova Rovenska

Funding This research was funded by the European RadoNorm project. This project received funding from the Euratom Research and Training Programme 2019–2020 under grant agreement No 900009. This work has been partially supported by the PIANOFORTE project that has received funding from the H2020-EURATOM research and innovation program under the 101061037 grant agreement. This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS24/149/OHK4/3T/14. This work has been co-funded by the Erasmus+ programme of the European Union. This work has been partially supported by the Nuclear Safety Council (CSN)-funded project "Radon exhalation from Building Materials: Radiological Impact and Corrective Measures (EXRADON)" (PR-047-2021).

Data Availability Data sets generated during the current study are available from the corresponding author on reasonable request

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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Authors and Affiliations

Katerina Navratilova Rovenska[1] · Miroslav Vanek[2] · Radim Moznar[1] · Martin Kaschner[3] · Elena Castaño Casco[4] · Shahed Khan[5] · Esther Osei Akuo-ko[6] · Ilaria Rocchetti[7] · Ondrej Parizek[1] · Jan Lenk[1] · Marcela Adamova[8] · Oana Elena Peneoasu[9] · Lukas Mareda[10]

✉ Katerina Navratilova Rovenska
katerina.rovenska@suro.cz

Miroslav Vanek
vanek@tuzvo.sk

Radim Moznar
radim.moznar@suro.cz

Martin Kaschner
kaschmar@fjfi.cvut.cz

Elena Castaño Casco
elena.castano@dci.uhu.es

Shahed Khan
shahed.khan@surrey.ac.uk

Esther Osei Akuo-ko
esther.akuoko@phd.uni-pannon.hu

Ilaria Rocchetti
ilaria.rocchetti@uniroma3.it

Ondrej Parizek
ondrej.parizek@suro.cz

Jan Lenk
jan.lenk@suro.cz

Marcela Adamova
marcela.adamova@sujb.gov.cz

Oana Elena Peneoasu
oana.peneoasu@dozimed.ro

Lukas Mareda
mareda@licon.cz

1 National Radiation Protection Institute, Prague, Czech Republic

2 Technical University in Zvolen, Zvolen, Slovakia

3 Faculty for Nuclear Sciences and Physical Engineering, Czech Technical Unversity in Prague, Prague, Czech Republic

4 Radiation Physics and Environment Group (FRYMA), Centre for Natural Resources, Health and Environment (RENSMA), University of Huelva, Huelva, Spain

5 School of Mathematics and Physics, University of Surrey, Guildford, Surrey, UK

6 Department of Radiochemistry and Radioecology, University of Pannonia, Veszprem, Hungary

7 Università degli studi Roma Tre, Roma, Italy

8 State office for Nuclear Safety, Prague, Czech Republic

9 S.C. DOZIMED S.R.L, Bucharest, Romania

10 Licon s.r.o, Stráž nad Nisou, Czech Republic