ORIGINAL ARTICLE

Experience from radon in soil gas comparison measurements held in Czech Republic and in other countries, 1992–2022

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Abstract

Radon ^{222}Rn, an inert natural radioactive gas, a daughter product in the ^{238}U natural decay series, a source of alpha radiation, together with its short-lived decay products is a dominant source of absorbed radiation doses in the population. Rocks and building materials are fundamental sources of radon in dwellings. Elevated indoor radon activity concentration in houses and workplaces, surpassing recommended reference levels, is not desirable. Since radon penetrates into the houses from the geological basement, various technical aids for protection of houses have been developed. Their individual application derives from the radon potential of a building site. Radon risk mapping of building sites became a standard procedure for gauging the local radon potential. Various instruments and techniques of measurements of radon activity concentration in soil gas (Bq/m^3) at building sites are available. Since radon in soil gas and radon measurement techniques are affected by several natural and technical conditions, resultant values of radon risk mapping by individual organizations vary, sometimes fundamentally. Radon comparison measurements at selected reference sites are an important tool for single organizations to verify their radon measuring procedures and reliability of their reported results. Based on legislative regulations, comparison measurements at established radon reference sites are a part of the obligatory activities for radon risk mapping at building sites in the Czech Republic. Experience and analyses of 30-year radon in soil gas comparison measurements in the Czech Republic show the dispersion of values reported by participating organizations and indicate that more than 10% of participants do not fulfill the established local criteria. This paper introduces requirements for the establishment of radon reference sites, documents their natural variability, recommends the procedure of radon comparison measurement, and analyses its results. A long-term experience was gained by testing organizations from the Czech Republic (1992–2022) as well as from the international comparison measurements organized in the Czech Republic and in several other countries (2010–2021).

Keywords: *radon*; *radon in soil gas*; *radon reference sites*; *radon comparison measurements*; *testing radon in soil gas data reliability*

Radon ^{222}Rn, an inert natural radioactive gas, a daughter product in ^{238}U natural decay series, a source of alpha radiation, together with its short-lived decay products, is a dominant source of absorbed radiation doses in the population. Since alpha radiation increases the destruction of cells of a human body, the long-term exposure in an environment with enhanced radon activity concentration can have adverse health consequences. People spend a substantial part of the day in their dwellings; hence, indoor radon activity concentration (Bq/m^3) is an indicative and regulated parameter in most countries. The World Health Organization (WHO) Handbook on Indoor Radon (1) describes in detail the physical properties of radon, radon activity concentration in atmospheric air and indoor air, and introduces estimates of health impact based on validated regional studies.

Rocks of the Earth's crust are a fundamental source of radon in the atmosphere. Gases in the rock environment move by diffusion and advection. Mobility of radon isotopes (^{219}Rn, ^{220}Rn, ^{222}Rn) depends on their half-lives and diffusion coefficients of the geological environment. Thus, ^{222}Rn exhibits the highest penetration capacity and can penetrate into houses. A comprehensive description on primordial radionuclides, natural decay series, radioactivity of rocks and building materials, and radon in rock environment forms the introduction of the European Atlas of Natural Radiation (2).

The indoor radon activity concentration reference level in EU is 300 Bq/m^3 (3). The new 2017 radon dose conversion factors (4) have been numerically substantially increased reflecting re-evaluation of the radon-inhalation hazard.

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Several decades of studies on indoor radon have shown that the main source of radon in houses is the geological basement (5). For newly built houses a preceding investigation of the radon risk of the building site proved to be effective and economic in the Czech Republic. A detailed local study of a building site is conducted using in-situ radon risk mapping. Fundamental parameters to be evaluated at a building site are radon activity concentration in soil gas and gas permeability of the foundation soil.

Various techniques have been developed and adapted for investigation of radon risk at building sites. The most frequent approach is the in-situ measurement of radon (^{222}Rn) activity concentration in soil gas (Bq/m^3) at an accessible depth and measurement or qualified estimate of gas permeability of the foundation soil (6). Another approach, the measurement of radon surface exhalation, mostly expressed in $mBq/s^1/m^2$, reflecting a combination of radon activity concentration in soil gas, soil gas permeability, and dynamics of gas movement in the rock environment is discussed in detail by Celikovic et al. (7). Tests of this method in various geological and soil conditions in the Czech Republic showed a low data reproducibility (6, 8). Since radon and thoron, both emitters of alpha rays, occur in similar concentrations in soil gas, their separation is required for a radon risk estimate of a site. Field radon instruments, using ionization chambers, Lucas cells, or semiconductor Si detectors, distinguish radon and thoron by specific measurements and data-processing procedures. Replacing radon measurements in soil gas by field gamma ray spectrometry of ^{226}Ra has obstacles in theory and no applicable correlation between radon in soil gas and ^{226}Ra in rocks was verified by numerous field studies (9).

Measurement of radon in soil gas is affected by several natural, physical, environmental, and operational parameters. Comparing radon measurements at a national or international scale is important to verify the reliability of the results. This paper addresses the experience gained at national and international radon comparison measurements.

Legislative for radon risk mapping in the Czech Republic

Radioactivity of building materials and indoor radon were already monitored in the Czech Republic in the second half of the last century, but systematic studies based on defined legislation (Decree of the Ministry of Health of the Czech Republic No. 76/1991 Col.) were initiated after 1989. The first *Atomic Act No. 18/1997 Col.*, issued in 1997, was reworked, completed, and issued as *Atomic Act. No. 263/2016 Col.,* which came into effect since January 2017. The institute preparing legislation and controlling radioactivity in the Czech Republic is the State Office for Nuclear Safety (SUJB). The *Atomic Act No. 263/2016. Col.* in the § 98 defines 'radon index of a site' and the need to determine the radon index of a site at all building sites. Further, State Office for Nuclear Safety issued 'A Recommendation of SUJB', based on a preceding several-year-old research (6), describing a suitable technique of radon in soil gas measurement and an estimate of gas permeability of soil at a building site and their common evaluation to define the radon index of a building site. The number of radon in soil gas measurements at a building site and the grid of measurement stations depend on the size of a future building, with a defined minimum of 15 stations per site. The number of 15 stations is a compromise between sufficient number in a data set and the costs of the field work (6). The depth of soil gas sampling should be 0.8 m which corresponds to attainable depth at most places and soil conditions. The third quartile of observed data set is recommended as a suitable statistical parameter reflecting radon concentration or gas permeability distribution at a site. The resulting 'radon index of a site' has categories low, medium, and high and serves for planning of the consequent protection of a house against penetration of radon from the ground. Professional organizations, more than a 100 in the Czech Republic, determining the radon index of building sites, must have a permission from the State Office for Nuclear Safety. Requirements for the professional service of this type include a 3 day preparatory course, examination at SUJB, calibration of radon instrument at the national radon chamber, and a test of a radon in-situ measurement at the national radon reference sites.

Radon reference sites in the Czech Republic

Radon reference sites serve for investigation of radon and thoron in soil gas, their long-term and short-term temporal variation, climatic effects on radon activity concentration in soil gas, lateral and vertical distribution of radon in soil, and the study of various techniques of soil gas sampling. The principal use of radon reference sites in the Czech Republic is for proficiency tests of professional organizations measuring and assessing the radon index at building sites.

Physical and logistics requirements that radon reference sites should fulfill include different levels (low, medium, high) of radon activity concentration at each reference site, acceptable homogeneous radon distribution over a site, thickness of soil enabling soil gas sampling up to the depth of 1 m, acceptable temporal radon variation, a tectonically undisturbed underlying bedrock, acceptable mutual short distance among radon reference sites, access for cars, and a long-term rent agreement as a condition to accumulate radon data and form a radon database of each reference site. In addition, lateral distribution and level of uranium and thorium in the soil should be determined, and reference sites should not be a cultivated land or a forest.

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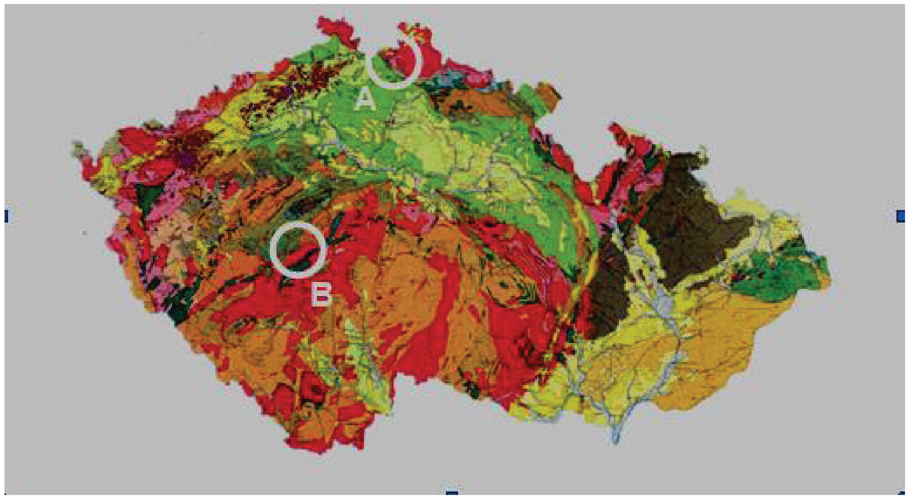

Fig. 1. Geological map of the Czech Republic and placement of radon reference sites.

Table 1. Characteristics of radon reference sites, Czech Republic

Reference site	^{222}Rn (kBq/m³)	Permeab. of soil	Basement Rock	Soil	U (ppm)	Terrain	Access for cars
Cetyne	39	L, (M), H	orthogneiss	SL	2.0	meadow	+
Bohostice	49	(L), (M), H	orthogneiss	LS,CS	2.3	meadow	+
Buk	126	H	granodiorite	LS	3.6	meadow	+

Legend: Permeability of soil: L-low, M-medium, H-high Soil: S-sandy, L-loamy, C-clayey.

Originally, four radon reference sites that were established in the northern part of the Czech Republic, close to the city of Liberec, served for the period 1991–1999 (Fig. 1a). Three new radon reference sites named Cetyne, Bohostice, and Buk were established in central Bohemia, 60 km southwest from Prague, close to the city of Milin, and serve since the year 2000 (Figs. 1b and 2). Different levels of their radon activity concentration in soil gas reflect their respective magmatic and metamorphic geological basement environment (Table 1). Each radon reference site has 15 fixed stations in a 5 × 5 m grid. Selection of radon reference sites was based on a 1 year geophysical investigation of 48 localities and their assessment over the period 1999–2000. Detailed geophysical investigation of three final selected radon reference sites Cetyne, Bohostice, and Buk included measurement of radon and thoron in soil gas, gamma-ray spectrometry determination of uranium and thorium concentration in soil, determination of soil gas permeability, and investigation of bedrock tectonic features and rock parameters using seismic, geoelectrical, and electromagnetic methods. Temporal variation of radon and thoron in soil gas, soil temperature and moisture, and soil gas permeability were determined by 14 repeated measurements in-situ over the period September 2000–August 2001 and completed by laboratory analyses of soil samples. Radon reference sites of Cetyne, Bohostice, and Buk are situated on meadows and their mutual distance of 12 km enables their measurement within 1 day (10).

Radon data standardization in the Czech Republic

Deviations in reporting radon in soil gas data by individual authorized professionals are caused by the heterogeneity of measured geological objects and by differences of used measuring techniques. In order of uniformity of radon risk assessment at building sites performed by numerous organizations in the Czech Republic, two fundamental requirements must be fulfilled. All radon instruments must be calibrated and periodically verified (every second year) at the national radon chamber and field radon measurement operation should pass the tests at radon reference sites.

The national radon chamber is installed and operated by the National Institute for Nuclear, Chemical and Biological Protection in the village of Kamenna in central Bohemia. The radon chamber has a volume of 10 m³ and the 36.8 mg ^{226}Ra source generates radon gas. The radon chamber is in accordance with the calibration facilities in Germany and United Kingdom and has the accreditation of the Czech Metrological Institute. The radon chamber enables the calibration of instantly measuring radon instruments as well as of detectors using long-term exposures.

Fig. 2. Location of radon reference sites Cetyne, Bohostice, and Buk in the Czech Republic.

Field radon measurements can differ in soil gas sampling, transfer of soil gas sample into the detector chamber, its timing and use of filters, control of contamination of single-detection cells, selection of operation programmes, way of thoron elimination, and in data processing. Quality and compatibility of field radon measurement of individual authorized professional subjects are tested by comparing radon measurement at radon reference sites.

Comparison radon measurements at radon reference sites

Comparison measurements at radon reference sites are organized and evaluated by the Department of Applied Geophysics of the Charles University, Faculty of Science, Institute of Hydrogeology, Engineering Geology and Applied Geophysics, Prague, which is the administrator of the radon reference sites. Comparison radon measurements are organized for a group of participants; each participant measures 15 field stations at each of three radon reference sites using its instrument and techniques and reports the data expressed in kBq/m^3 at each of the 45 stations. All participants of a 1 day radon comparison measurement and the administrator measure at identical meteorological conditions.

The reliability of data on radon activity concentration in soil gas (c_A) reported by individual organizations is tested by the computer programme TestMOAR. Three tests are based on comparison of radon data of each participant with radon data of the administrator, with radon data of other participants of radon comparison measurement in a given day, and with the radon database of each radon reference site. The administrator verifies its radon instrument at the national radon chamber periodically with a relative difference always inferior to 4%. The radon databases of the three radon reference sites are formed and updated gradually by successful measurements of organizations, starting from the year 2000. At present (year 2023), the radon database of each reference site is

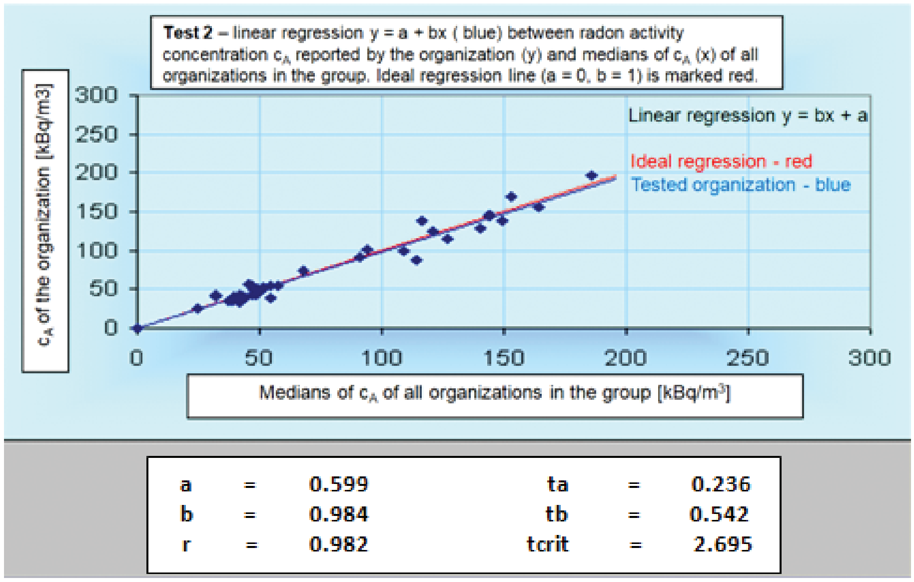

Fig. 3. TestMOAR, Test 2 – linear regression y = a + bx between radon data of the tested organization (y) and medians of radon data reported by the group (x); an example of a good fit of radon data of the tested organization with radon data of the group of organizations which were measured the same day.

Legend: r, coefficient of correlation; ta, computed value by testing of the parameter a; tb, computed value by testing of the parameter b; tcrit, critical value that should not be overpassed.

based on radon data reported by N = 334 organizations that were successful in preceding radon comparison measurements.

Test 1 (of orientation) is based on enumeration of differences between radon data of the tested organization at single stations (N = 15) of each reference site and medians of radon data at identical stations derived from radon data reported by other participants and the administrator.

Test 2 (of orientation) assesses the parameters of linear regression y = a + bx between radon data at single stations of three reference sites (N = 3 × 15 = 45 stations) reported by the tested organization (y) and medians of radon data (x) computed from reports of other participants and the administrator at identical stations. Figures 3 and 4 are examples of a good fit and of a poor fit of radon in soil gas data of tested organizations with medians of radon data reported by the group at the same day of measurement. The parameters a and b of the linear regression are subjects of statistical testing, using criterion ta < tcrit, tb < tcrit for the acceptable values.

Test 1 and Test 2 are approximate because the whole group of random participants of a 1 day radon comparison measurement may report radon data that can be deviated from the theoretical correct value. However, a long-term experience shows that for a group of 15–20 participants of radon comparison measurement at radon reference sites the Test 2, for the parameter a close to zero, already indicates an underestimation (b < 1) or an overestimation (b > 1) of reported radon activity concentration in soil gas by the tested organization.

Test 3 (decisive) compares the radon data of the tested organization with the radon database of the reference site developed using radon data of all successfully tested preceding organizations (N = 334 in 2023). Test 3 uses the parameters R1 and R2. R1 is the ratio of the mean value (N = 15) of radon activity concentration in soil gas at a reference site reported by the tested organization over the radon mean value for the corresponding reference site reported by the administrator (R1 = radon mean of tested organization/radon mean of administrator). Parameter R2 is the mean of all ratios R1 already stored in the database of the relevant reference site since the year 2000. The resultant parameter R1/R2, having an ideal value of 1, serves as a testing criterion; acceptable deviations are in the range 0.7–1.3 (30%). The criterion R1/R2 double norming eliminates the effect of temporal variations of radon in soil gas, as well as possible administrator's radon data inaccuracies. Thus, by the Test 3, mean radon data of an organization are tested to mean radon data of all preceding successful organizations at each reference site, with gradually increasing reliability based on the number of successfully measuring organizations. The Test 3 is sensitive to the stability of the administrator´s radon measurements; however, the long-term evidence (2000–2022) of the parameter R2 at all three reference sites indicates its good numerical stability enabling the Test 3 adopted procedure. Table 2 illustrates testing of a group of 14 organizations that underwent the

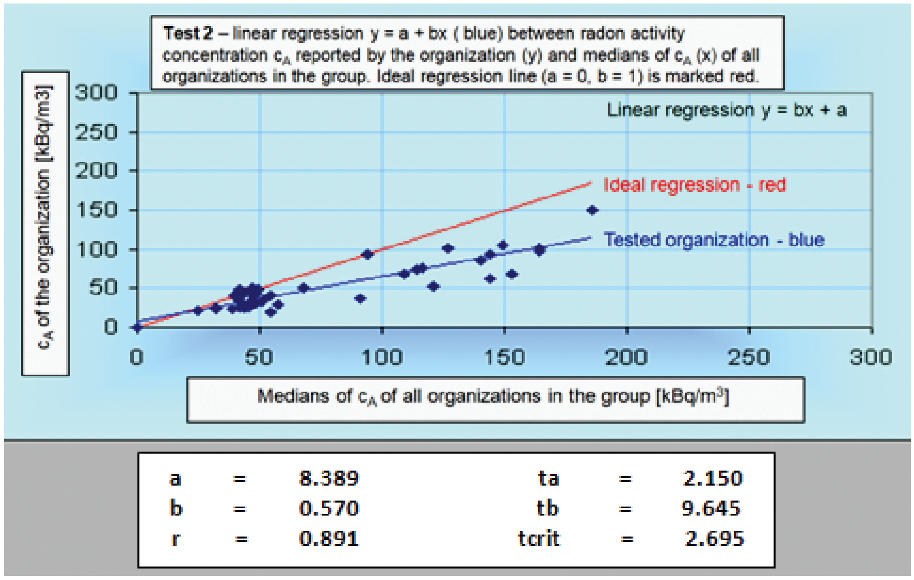

Fig. 4. TestMOAR, Test 2 – linear regression y = a + bx between radon data of the tested organization (y) and medians of radon data reported by the group (x); an example of a poor fit of radon data of the tested organization with radon data of the group of organizations which were measured the same day. The tested organization underestimates radon data.

Legend: r, coefficient of correlation; ta, computed value by testing of the parameter a; tb, computed value by testing of the parameter b; tcrit, critical value that should not be overpassed.

Table 2. Programme TestMOAR, Test 3: assessment of radon comparison measurement at radon reference sites by the Test 3 criterion R1/R2 having an ideal value of 1 and acceptable deviation in the range 0.7–1.3

Datum	Organization	R1/R2				Result
		Cetyne	Bohostice	Buk	Mean	
19.07.2005	Participant 1	0.896	1.122	1.040	1.019	accepted
19.07.2005	Participant 2	0.889	0.924	1.154	0.989	accepted
19.07.2005	Participant 3	0.913	0.910	0.856	0.893	accepted
19.07.2005	Participant 4	1.021	1.280	1.102	1.134	accepted
19.07.2005	Participant 5	0.975	0.987	1.073	1.012	accepted
19.07.2005	Participant 6	0.948	1.026	1.003	0.992	accepted
19.07.2005	Participant 7	0.874	1.135	1.012	1.007	accepted
19.07.2005	Participant 8	0.913	0.868	1.106	0.962	accepted
19.07.2005	Participant 9	0.927	0.859	0.979	0.922	accepted
11.10.2005	Participant 1	0.969	0.882	0.857	0.903	accepted
11.10.2005	Participant 2	1.104	1.257	1.063	1.142	accepted
11.10.2005	Participant 3	1.192	**1.375**	1.065	1.211	failure
11.10.2005	Participant 4	1.085	**1.336**	1.051	1.157	failure
11.10.2005	Participant 5	**0.663**	0.994	0.934	0.864	failure

radon comparison measurement in the year 2005 using the programme TestMOAR, Test 3.

Radon comparison measurements at radon reference sites with relatively larger group of participants opened a problem of destruction of soil at points of common soil gas sampling.

Fourteen organizations from the Czech Republic participated in the radon comparison measurement on September 30th, 2004. For a minimal contamination of radon detection chambers, a standard 1 day measurement at radon reference sites starts at the reference site Cetyne with the lowest radon activity concentration in soil gas, and continues at the reference sites of Bohostice and Buk. The administrator, in order to keep the required high quality of radon measurement applies a long time measurement per station, and gradually delays with respect to the group. Thus, in the

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year 2004, the administrator, being the last for soil gas sampling at the reference site Buk undertook the soil gas sampling at non-standard conditions of perforated soil at all 15 fixed stations, affected by atmospheric air. This led to possible underestimation of radon in soil gas data. The following study of the effect of a gradual penetration of soil at fixed positions by 26 organizations in the course of 4 consequent days of measurement in 2004, in a sequence of 5, 8, 7, 6 sampling organizations per day, showed the decrease of radon activity concentration in the fourth day by approximately 15% at the reference site Cetyne, 24% at Bohostice, and 9% at Buk. Additional tests, comparing radon data at fixed stations after their soil destruction and radon data 1 m apart showed the mean difference of about +18 kBq/m³ at the imperforated soil, and proved the effect of the destruction of a compact soil on the registered radon activity concentration. The effect of destruction of soil by sampling of soil gas by several sampling rods at the same place (station) led to the introduction of a new system of soil gas sampling on regulated individual points for each organization around the centre of the station (Fig. 5).

Test 3, based on comparison with statistics of a large group of successfully tested organizations, $N = 334$ for the testing in the year 2023, indicates with a good confidence the reliability of radon reported values of the tested organization. Test 3 criterion R1/R2, with the ideal value of 1, and acceptable relative range of deviation ± 30% (R1/R2 in the range 0.7 – 1.3), satisfactorily takes into consideration the influence of soil heterogeneity affecting the soil gas sampling. A long-term statistics (2000–2023) of radon comparison measurements of organizations from the Czech Republic at radon reference sites exhibits that approximately 91% of tested organizations were successful, and 9% of organizations reported radon data deviating more than the range of tolerance of the Test 3 testing criterion (Fig. 6). It should be emphasized that all radon instruments used in radon comparison measurements were uniformly calibrated and periodically verified at the Czech national radon chamber, which eliminates discrepancies in calibration sources and procedures, and contributes to the uniformity of radon measurements.

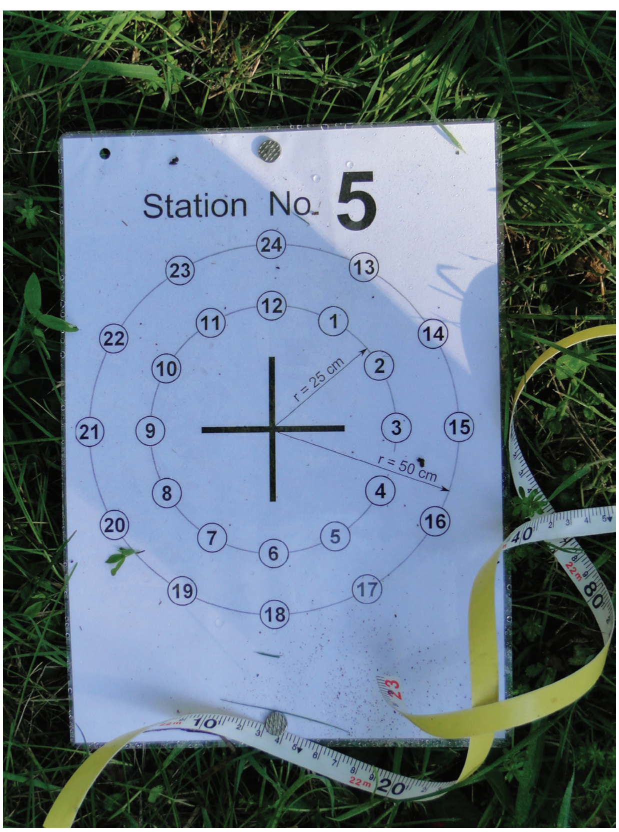

Fig. 5. Schema of marked positions (points 1–24) for soil gas sampling of single organizations participating in a radon comparison measurement at station No. 5 of a radon reference site.

Temporal radon variations

Radon activity concentration (c_A) in soil gas is affected by atmospheric parameters and by the dynamic tension of the massive rocks. Temperature, atmospheric pressure, air and soil humidity, precipitation, and wind speed are the causes of temporal variation of radon activity concentration in soil gas in a year cycle (11–13). Long-term observation in the climatic conditions of the Czech Republic generally show a direct proportionality of radon in soil gas and soil moisture and preceding precipitations, while indirect proportionality was observed for air and soil temperature, wind speed, and atmospheric air pressure.

Figures 8 and 9 illustrate temporal radon variation in soil gas at fixed stations of radon reference sites of Cetyne, Bohostice, and Buk over the period 2000–2022 based on the measurements of the administrator of the reference sites with soil gas sampling at the depth of 0.8 m. Data are reported as medians (Fig. 8) and arithmetical means (AM) (Fig. 9) of 15 registered radon observations at each reference site. The measurements were taken using a field radon monitor LUK 3A with Lucas cells. The instrument was periodically calibrated and verified at the national radon chamber with deviations inferior to 4% relative to the radon chamber data. A common trend of radon temporal changes at all three radon reference sites was confirmed by mutual data correlation (Figs. 10 and 11). High temporal radon variability at the radon reference site Buk (Figs. 8 and 9), having a granite basement and an eluvial sandy soil, shows the magnitude of weather effects in a permeable sandy soil environment.

A general common trend of radon temporal changes at all three radon reference sites is visible in Figs. 8 and 9 and specified by mutual radon data correlation (Figs. 10 and 11). A large dispersion of single data around the regression lines, specified also by low values of the coefficient of

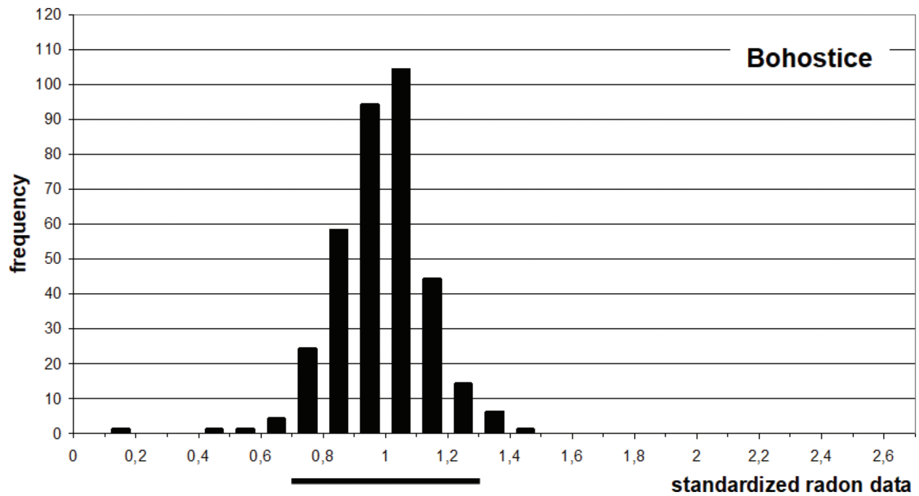

Fig. 6. Frequency distribution of means of ^{222}Rn activity concentration in soil gas determined by measurements of 352 organizations at the reference site of Bohostice, Czech Republic, over the period 2000–2022. Radon data are presented in standardized ratios R1/R2 with an ideal value equal to 1; the band of acceptable deviations has the range 0.7–1.3.

Fig. 7. Radon in soil gas comparison measurement of 22 organizations at the radon reference site of Cetyne, Czech Republic.

correlation R = 0.619 (Fig. 10), and R = 0.499 (Fig. 11), might be ascribed to varying atmospheric effects at single radon reference sites having differences in soil characteristics.

Extreme c_A data min and max of medians and of AM enumerated from 15 measurements per reference site over 40 days of repeated measurement at radon reference sites over the period 2000–2022 under various weather conditions (Figs. 8 and 9) and corresponding ratios max/min (Table 3) show the range of radon temporal variations in soil gas. Analyses of these radon data indicate a limited reliability of radon measurements at building sites for random days and weather conditions. However, since radon activity concentration in soil gas and soil gas permeability, two parameters used for assessment of the radon risk of a site, have opposite proportionality to weather changes, their common evaluation generally compensates the weather effects. Despite this, the reports on radon risk mapping at building sites must document the temperature, estimate of wind speed and of soil humidity,

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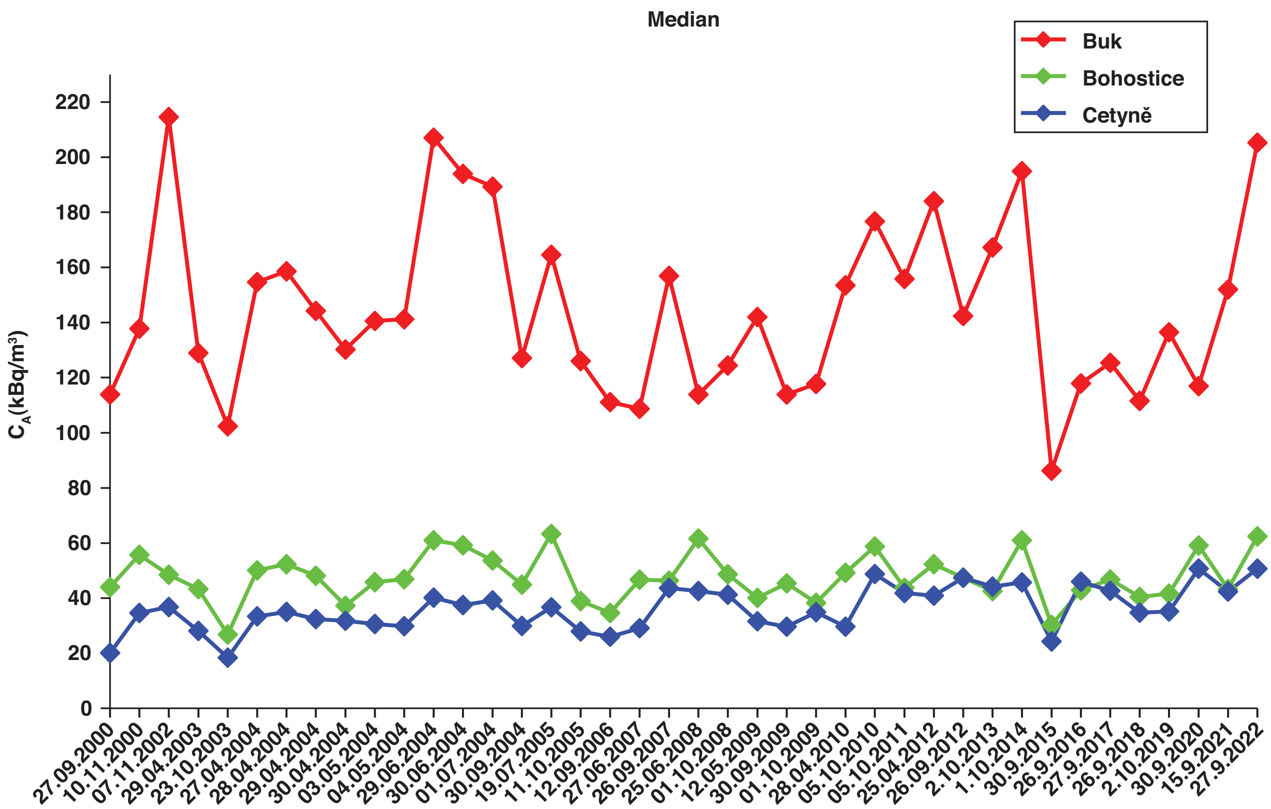

Fig. 8. Medians of temporal variation of radon activity concentration in soil gas at radon reference sites of Buk, Bohostice, and Cetyne in the Czech Republic derived from measurements at 15 stations of each reference site over the period 2000–2022.

and any preceding day precipitation that may be taken into consideration in the final radon risk assessment of a site. Extremely high radon activity concentration in soil gas, observed on 27 September 2022 (Figs. 8 and 9), was registered after preceding rains.

Temporal variations of radon activity concentration in the soil gas were studied in the Czech Republic repeatedly in detail at various areas with different geological conditions and vertical profiles, in order to check the reproducibility of the uniform method for radon index classification. The results showed a similar range of temporal variability (14, 15), never larger, which was crucial for the reproducibility of any assessment of radon index.

International radon comparison measurements at radon reference sites RIM 2010 – 2021

In the frame of the International Workshops on the Geological Aspects of Radon Risk Mapping, organized by the Radon v.o.s., Prague, comparison measurements of radon in soil gas at the radon reference sites in the Czech Republic (RIM) were performed over the years 2010, 2012, 2014, 2018, and 2021. Participating institutions were from China, Croatia, Czech Republic, Belgium, Estonia, Germany, Hungary, Italy, Japan, Luxembourg, Poland, Portugal, Romania, Serbia, Slovenia, South Africa, Spain, and Sweden. Table 4 introduces an overview of fundamental information on these activities. The intention of the international comparison measurements of radon in soil gas was a desirable unification of reported radon data applied in radon risk mapping in single countries using European and world limits in radiation protection. One-day field radon measurement at radon reference sites is also an exhibition of types and progress in development of radon instruments, soil gas sampling techniques, facilities for improving of relatively hard field manual work, and, at RIM 2021, adaptation of some field instruments for radon and soil gas permeability common in-situ determination.

RIM measurements were performed at established radon reference sites of Cetyne, Bohostice, and Buk on a fixed grid of stations similar to the standard radon comparison measurement in the Czech Republic. Points of soil gas sampling at the depth of 0.8 m for the single organizations were marked individually in the radius of 0.5 m around each station of the grid (Fig. 5). This system eliminates duplicity of soil gas sampling of several organizations from one hole. Due to a limited time and measurement capacity of some organizations, the number of 15 measured stations in 2010 was reduced to 10 stations per reference site over the period 2012–2021. Despite this, some organizations applying a time

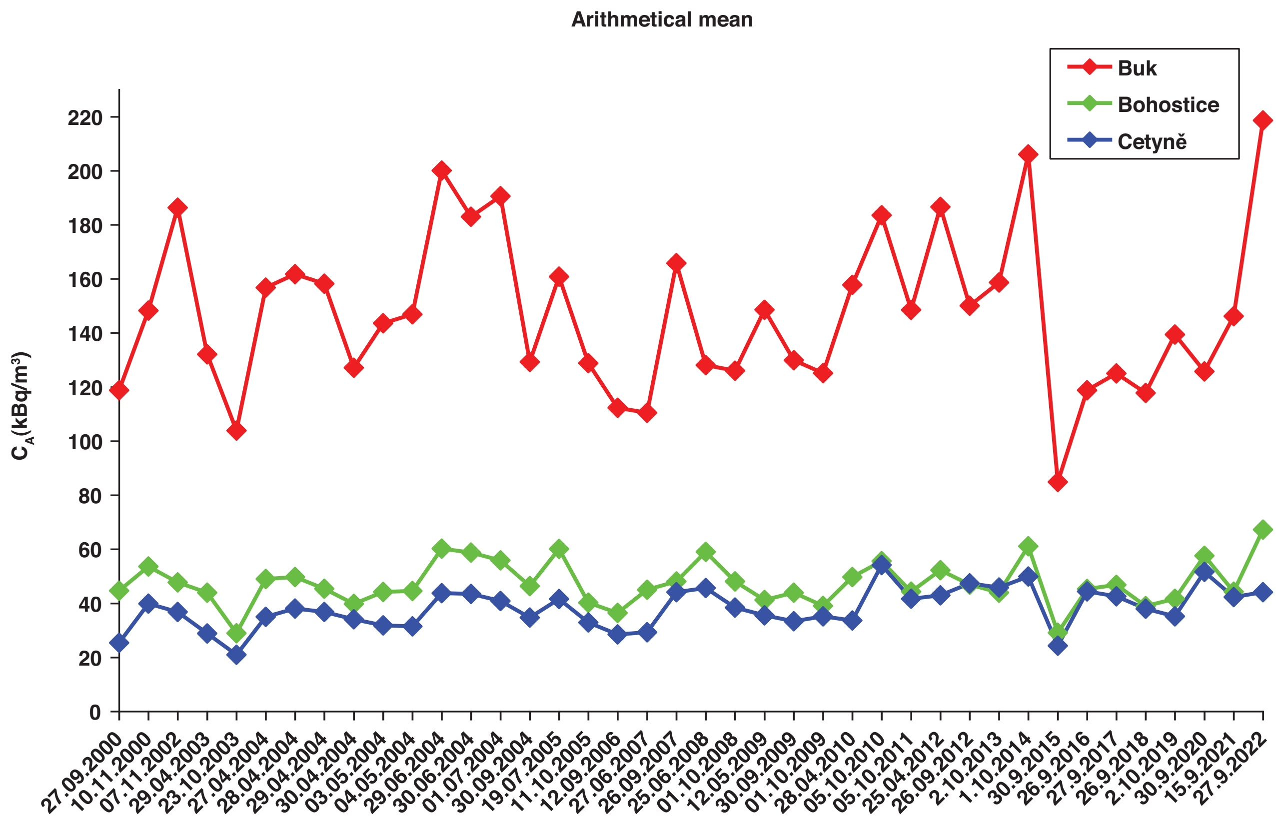

Fig. 9. Arithmetical means of temporal variation of radon activity concentration in soil gas at radon reference sites of Buk, Bohostice, and Cetyne in the Czech Republic derived from measurements at 15 stations of each reference site over the period 2000–2022.

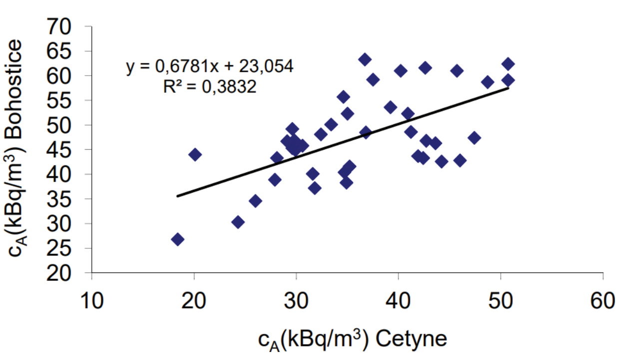

Fig. 10. Time correlation of medians of radon in soil gas data (*N* = 15) registered simultaneously at the reference sites of Cetyne and Bohostice over the period 2000–2022.

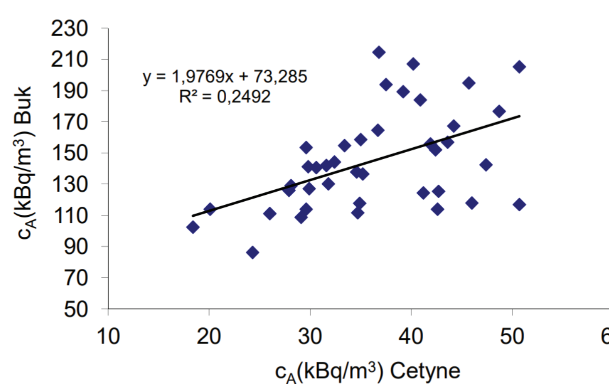

Fig. 11. Time correlation of medians of radon in soil gas data (*N* = 15) registered simultaneously at the reference sites of Cetyne and Buk over the period 2000–2022.

consuming technique of soil gas sampling and radon measurement covered only a part of stations of the grid. Every organization measured using its own radon instrument and technique. Mostly, portable radon monitors with ionization chambers, Lucas cells, or alpha semiconductor detectors were used for the radon measurement in-situ, exceptionally a 1 day exposure measurement with film detectors CR-39 positioned in soil was applied. The majority of organizations used soil gas grab sampling, while the minority used continuous soil gas transfer into detectors. Resultant values on radon activity concentration c_A in soil gas at each station were reported in kBq/m³. Testing was conducted using the computer programme TestMOAR, identical to standard evaluations described earlier in the text.

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Table 3. Statistical parameters arithmetical mean (AM), standard deviation (SD), and coefficient of variation (SD/AM) of radon activity concentration in soil gas (c_A) at radon reference sites of Cetyne, Bohostice, and Buk in the Czech Republic enumerated from temporal changes of 40 medians and arithmetical means of c_A determined over the period 2000–2022.

Statistical symbols	Units	Median			Arithmetical mean		
		Cetyne	Bohostice	Buk	Cetyne	Bohostice	Buk
AM	(Bq/m^3)	36.2	47.6	144.8	38.1	47.5	147.3
SD	(kBq/m^3)	7.9	8.7	31.4	7.4	8.2	29.5
SD/AM	(%)	21.8	18.3	21.7	19.4	17.3	20.0
min	(kBq/m^3)	18.4	26.8	86.2	21.0	28.9	84.9
max	(kBq/m^3)	50.7	63.3	214.6	54.2	68.3	218.6
max/min		2.76	2.36	2.49	2.58	2.36	2.57

Table 4. Overview on the international comparison measurement of radon in soil gas (RIM) at radon reference sites in the Czech Republic

Date	No. of participating countries	No. of participating organizations	Radon reference sites
21–22 September 2010	10	13	Cetyne, Bohostice, Buk
17 September 2012	9	16	Bohostice, Buk
15 September 2014	7	12	Cetyne, Buk
17 September 2018	12	23	Cetyne, Buk
20 September 2021	10	23	Cetyne, Buk

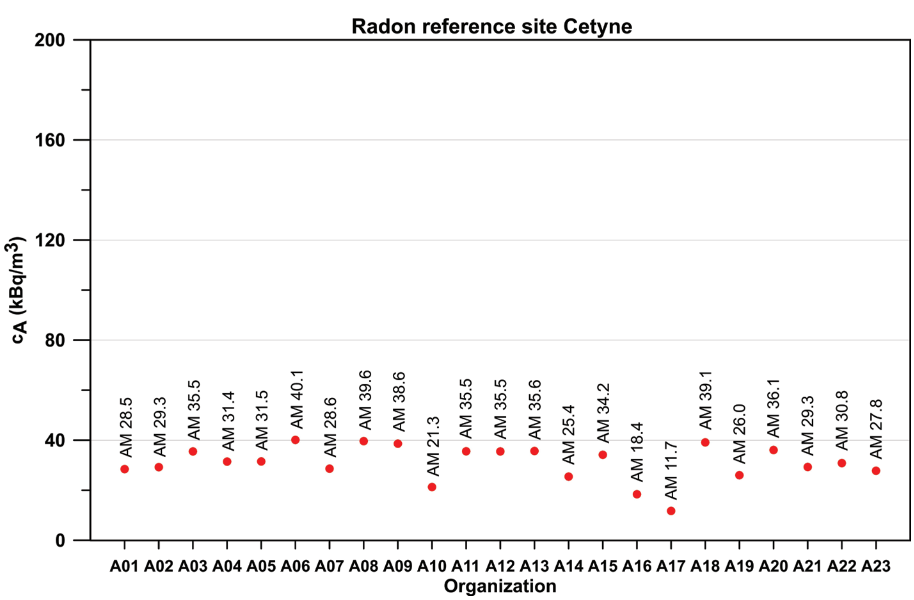

Fig. 12. Arithmetical means of radon activity concentration in soil gas (c_A) at the reference site Cetyne reported by 23 organizations at RIM in the year 2018.

In the final reports on the international radon in soil gas comparison measurement (RIM) the participating organizations were marked anonymously using codes (Figs. 12 and 13), while issued Protocols for single participating organization introduced their full identification, observed radon data, and detailed evaluation. This applied system enabled comparison of the reported radon data for each participating organization with the group of participants (Test 1 and Test 2) and comparison with the radon database of each reference site based on numerous ($N = 10^2$) successful preceding radon measurements of Czech organizations (Test 3). It should be reminded that the Test 3 based on its

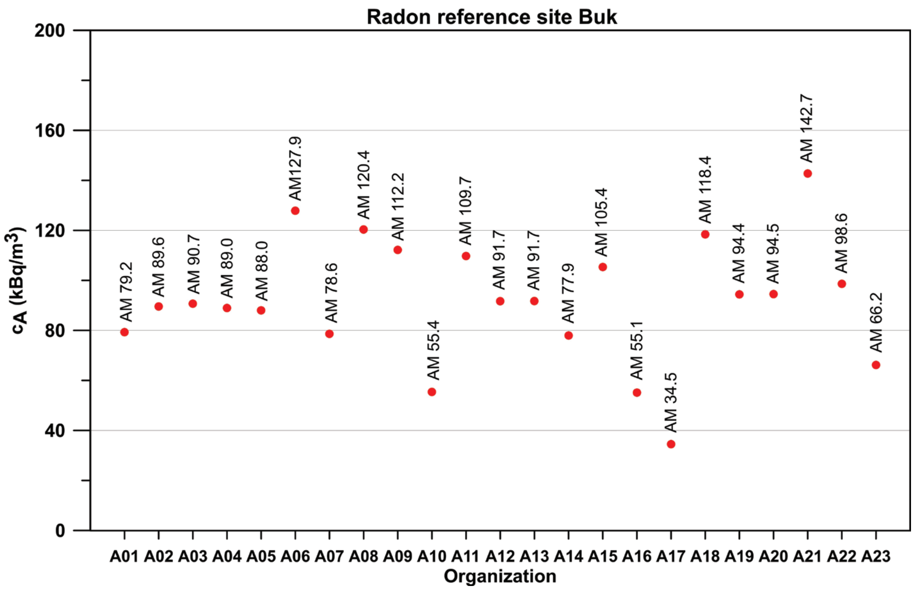

Fig. 13. Arithmetical means of radon activity concentration in soil gas (c_A) at the reference site Buk reported by 23 organizations at RIM in the year 2018.

algorithm eliminates temporal radon variations at radon reference sites, yielding radon reference sites databases independent of weather variations (Figs. 8 and 9). Using the R1/R2 (0.7; 1.3) testing criterion of the decisive Test 3 at measured reference sites, the numbers of RIM unsuccessful organizations were as follows: 3 in 2010, 1 in 2012, 1 in 2014, 8 in 2018, and 6 in 2021.

Twenty-three organizations, marked by codes A01–A23, participated at the radon in soil gas intercomparison measurement RIM 2018 at radon reference sites of Cetyne and Buk. Ten stations were fixed for measurements at each reference site. Resultant reported mean values (AM) of radon activity concentration in the soil gas show the distribution of radon data of RIM 2018 participants and some considerable deviations (Figs. 12 and 13). Extreme observed radon activity concentrations in the soil gas were a minimum of 11.7 kBq/m^3 and maximum of 40.1 kBq/m^3 at the reference site Cetyne, and minimum of 34.5 kBq/m^3 and maximum of 142.7 kBq/m^3 at the reference site Buk. Test 3 of the computer programme TestMOAR, based on radon data testing against radon databases of reference sites with deviation tolerance ±30%, indicated that organizations A10, A16, and A17 did not fulfill testing criteria at the reference site of Cetyne (Fig. 12) and organizations A06, A08, A09, A10, A16, A17, A18, and A21 did not fulfill testing criteria at the reference site Buk (Fig. 13). Since the algorithm of the decisive Test 3 uses the ratio of radon data R1 (organization/administrator), it is supposed that the administrator´s radon data are reliable and close to the mean of participating organizations. For an orientation in Figs. 12 and 13, the code A03 has the administrator and the code A04 has the RADON v.o.s. company, the authors of this publication. Organization A17 used the 1 day passive exposure measuring technique with film detectors CR-39 positioned in shallow holes. Test 3 algorithm uses AM of reported radon data; however, for a standard radon characteristics of a site preferably the median or the third quartile of radon data set should be used. The main reasons of deviations of reported mean radon data at reference site (Figs. 12 and 13) are heterogeneity of soil and of ^{226}Ra distribution in soil, the mode of soil gas sampling, and transfer of the representative gas sample into the detector chamber, the way of elimination of background contamination of detector chambers, the possible effect of dilution of soil gas sample by generally radon free atmospheric air, and the effect of not well-eliminated ^{220}Rn (thoron) present at significant content value in soil gas at all reference sites. A low number of measured stations per reference site is quite crucial. In addition to these, the calibration of radon instruments plays a fundamental role. While instruments of all Czech organizations participating at radon comparison measurements at reference sites are uniformly calibrated at the Czech national radon chamber, the RIM activity compares radon data fundamentally dependent upon respective national calibration standards. However, significant radon deviations, perceptible in Figs. 12 and 13, mark deviations from results of an international community, and indicate some problem in the overall applied approach of radon measurement. A positive result of such indications at RIM 2010–2021 measurements was confirmed by subsequent corrections in the measurement technique of some participants, what is a prerequisite for participation in large scale projects, as is, for example, the compilation of the European Atlas of Natural Radiation (2). In order to minimize calibration

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discrepancies, RIM 2021 offered for the participants of radon comparison measurement at reference sites the calibration at the nearby situated Czech national radon chamber, which was in accordance with radon calibration standards in Germany.

Experience from other comparison measurements of radon activity concentration in the soil gas

Besides the experiences from the Czech Republic, the representatives of RADON v.o.s. participated in several previous international intercomparison measurements – in Badgastein, Austria, 1991, during the International Intercomparison Measurements of Radon and Radon Decay Products; in New York, U.S.A., 1995, during the Sixth International Radon Metrology Programme Intercomparison Test and Workshop; and co-organized or organized other international intercomparison measurements – in Prague, Czech Republic, 1996, during the 3rd International Workshop on the Geological Aspects of Radon Risk Mapping; in Buk, Czech Republic, 2002 (idea coming from the ERRICCA 2 kick-off meeting in London in February 2002); in Saelices el Chico, Spain, 2011 (16), in Brazil in May 2014 during the Latin American Symposium on Radon and II Symposium on Radon in Brazil; and in Serbia in 2014, as a part of the Second East European Radon Symposium (SEERAS).

As for the experiences from Badgastein (17), the site for the measurement of radon activity concentration in the soil gas was sloping, with an inclination of 35 to 40 degrees, partly a meadow, partly under trees. There was a thin soil layer at the site, with the underlying rock having high permeability and porosity. Radon activity concentrations in the soil gas were reported by seven participants. Large spectrum of methods was used, for example soil gas sampling using a small diameter hollow steel probe and Lucas cells × radon activity concentration in the soil gas calculated from measured radium concentration (assuming emanation coefficient 0.3–0.4 and porosity 0.4); and the sampling depth also varied from 0.15 to 0.80 m. All those mentioned differences caused a very large variability of radon activity concentrations in the soil gas at the test site and in fact no comparison was possible at all.

On the other hand, the intercomparison measurements in New York (18, 19) were prepared with good knowledge of the factors influencing the measured parameter. The sampling area was an open field (meadow), bordered by woods on two sides and a paved parking area and a paved road on the other two sides. The site had a 2-m deep soil layer underlain by a 17-m layer of marl and sand, which was situated on top of the metamorphic bedrock. The soil had alternating layers that were clay-rich and sand-rich. Radon activity concentrations in the soil gas were reported by 11 participants, using different sampling depths: 0.4–0.5 m; 0.6–0.75 m; 0.9–1.0 m (some of them all of those depths). Variability of results, described by the SD/mean ratio, decreased with increasing sampling depth (1.20 in the depth of 0.4–0.5 m; 0.36 in the depth 0.6–0.75 m and 0.27 in the depth 0.9–1.0 m resp.).

Similar results were achieved during the comparison measurements in Prague in 1996 (20). Participants representing 10 organizations from eight countries took part in the measurements at the area located in the northern outskirts of Prague, at an open field that was agriculturally cultivated. The bedrock at the site is formed by Cretaceous Lower Turonian marlites, with relatively homogeneous weathering profile formed by clays, covered by Tertiary sandy gravels and Quaternary loess with the thickness of about 4 m. The homogeneity was checked before the intercomparison through relatively detailed preliminary measurements (radon activity concentration in the soil gas, soil gas permeability, gamma spectrometry analysis of loess samples). Although a large number of different methods was compared (various types of detectors and of sampling techniques), different target volumes of soil/soil gas were measured (the volume of soil gas samples used for measurements ranged from 30 mL to 1 L), and the depth of sampling also varied from 0.6 to 1.0 m, the agreement among participants was very good. If all single values that were obtained over the whole area were taken into account, the difference expressed as a ratio SD/mean was 0.24. A more detailed analysis including the spatial variability at the test site resulted in a more exact estimate of the differences about 20% (ratio SD/mean 0.2).

The intercomparison in 2002 was focused not only on radon activity concentration in the soil gas, but also on radon exhalation rate from the ground (7). The test site was situated closely to the site Buk (used for standard comparison measurements in the Czech Republic and described in detail in previous parts). As for the radon activity concentration in the soil gas, due to the (known) increase with depth at this area and due to the differences in the sampling depth used by various participants (10 institutions from eight countries), the differences were higher in comparison with the differences observed in 1996 – ratio SD/mean 0.33 for all single values. The spread of radon exhalation rate data was larger with the ratio of SD/mean 0.43, which corresponds to experiences with larger spatial and temporal variability of this parameter (21).

International intercomparison measurement of radon activity concentration in the soil gas in Serbia, Niska Banja, 2014

Various problems associated with the preparation and realization of meaningful intercomparison measurements of radon activity concentration in the soil gas can be illustrated using our experiences from the international intercomparison measurement of radon activity concentration in the soil gas, which was held in Niska Banja, Serbia, in

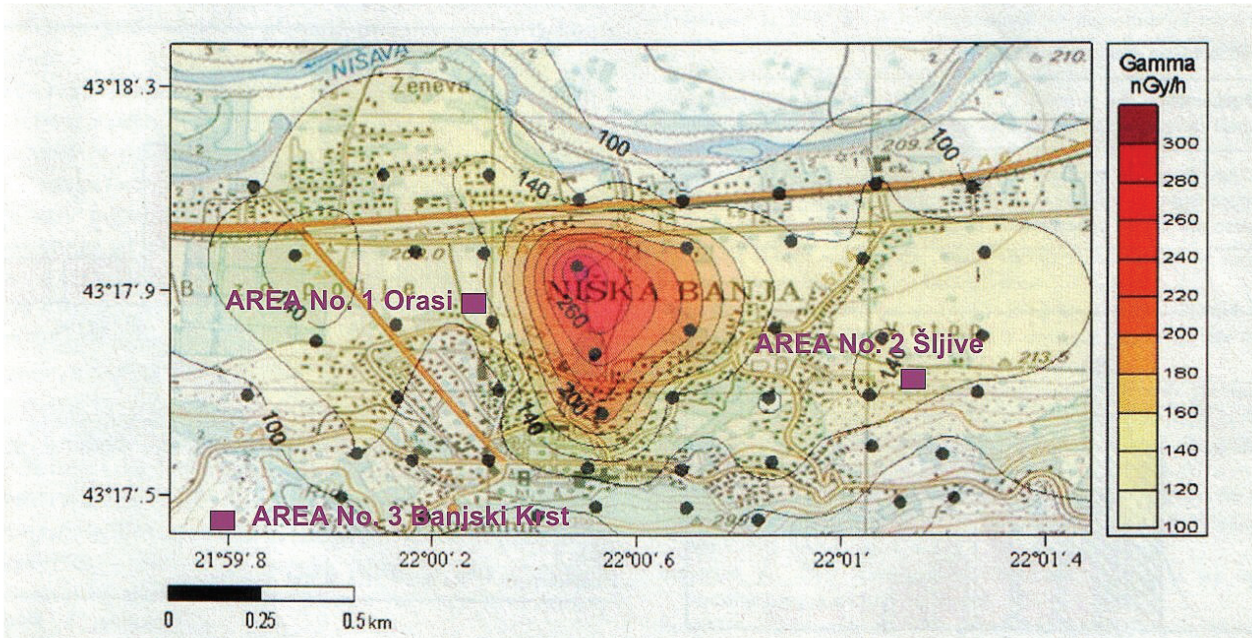

Fig. 14. Location of tested areas for radon comparison measurements in Serbia, 2013, on the background of ambient gamma dose rate contour map (22).

May, 2014. Comparatively detailed results from the previous survey realized in October, 2013 with the goal to find the most suitable area/terrain for this SEERAS intercomparison, were available for the assessment as well. Both field activities were in this region (22) initiated by professionals from Serbia.

The test site was chosen after detailed measurements of the radon activity concentration in the soil gas, which had been realized at three areas in Niska Banja, Serbia, from October 21 to October 22, 2013. At first, three areas – called 'Orasi' (No. 1), 'Sljive' (No. 2), and 'Banjski Krst' (No. 3) – were chosen by Serbian colleagues for initial tests (Fig. 14). All those three areas were private, open, and accessible for cars. During the initial measurements, 15 soil gas samples were collected from the depth of 0.8 m below the ground surface at each area. Measuring points were placed in a regular grid 10 × 10 m.

The results of initial tests were analyzed and the area of Sljive was selected for further investigation. A repeated soil gas sampling was performed in the basic scale 10 × 10 m and due to the spatial variability in a more detailed scale in the smaller subarea (regular grid 5 × 5 m); to be able to choose the most suitable points for the intercomparison.

Due to those measurements, relatively detailed information about spatial variability and temporal changes during 2 days period was available. Finally, in selected points, the soil gas samples were collected from two different sampling depths, 0.5 and 0.8 m.

As for the spatial variability of radon activity concentration in the soil gas, basic statistical parameters of different data sets of radon activity concentration in the soil gas at the depth of 0.8 m (area Sljive, October 21 and area Sljive – subarea A, October 22) are presented in Table 5 (2nd and 4th column). Parameters of maximum/minimum ratio and SD/mean ratio can be used as indicators of homogeneity. If we compare the values given in Table 5, we can conclude, that the most homogeneous conditions were found at the subarea A of area Sljive: maximum/minimum ratio lower than 2, SD/mean ratio lower than 0.20.

Due to the fact that the soil gas samples were collected from two different sampling depths (0.5 and 0.8 m) in selected points at the whole area Sljive during the second day of the survey, it is possible to also evaluate the variability of radon activity concentration in the soil gas with depth at this area. The radon activity concentration in the soil gas generally increased with depth between 50 and 80 cm below the ground surface at the area Sljive, but the changes were not dramatic. It is possible to expect that small changes of sampling depth are not accompanied by substantial changes of radon activity concentration in the soil gas at the area.

Data of radon activity concentrations in the soil gas obtained at the area Sljive during the first and the second day of the survey in October 2013 can be used for the evaluation of short-term temporal changes of radon activity concentration in the soil gas in the depth of 0.8 m at the area. In this case, only values of radon activity

Table 5. Spatial and temporal variability of radon activity concentration in the soil gas, area/subarea Sljive, October 21 + 22, 2013

Statistical parameter	Value – Sljive October 21, 2013	Value – Sljive October 22,2013	Value – Sljive, subarea A October 22, 2013
Number	15	15	15
Minimum	37.1 kBq/m^3	41.8 kBq/m^3	57.4 kBq/m^3
Maximum	120.3 kBq/m^3	112.4 kBq/m^3	110.4 kBq/m^3
Max/Min	3.24	2.69	1.92
Median	66.7 kBq/m^3	61.7 kBq/m^3	86.4 kBq/m^3
Third quartile	81.5 kBq/m^3	86.4 kBq/m^3	95.2 kBq/m^3
Arithmetic mean	69.5 kBq/m^3	68.9 kBq/m^3	85.3 kBq/m^3
SD	22.4 kBq/m^3	23.8 kBq/m^3	16.8 kBq/m^3
SD/mean	0.322	0.346	0.197

Fig. 15. Radon intercomparison measurement, subarea Sljive, May 30, 2014.

concentration in the soil gas from the basic scale 10 × 10 m are considered. Results are presented in Table 5 (2nd and 3rd column). It should be noted that the results do not describe the 'clear' temporal variability. As the sampling probes were not inserted in exactly the same places during the 2 subsequent days, the results may also be partly influenced by horizontal spatial changes of radon activity concentration in the soil gas.

If we take into account all potential sources of uncertainty, it is evident that the short-term reproducibility of radon activity concentration in the soil gas was very good. Relative changes of all main statistical parameters (median, third quartile, arithmetic mean, SD) were lower than 10%.

The intercomparison measurement of radon activity concentration in the soil gas in May 30, 2014 (Fig. 15), was attended by participants representing 12 different institutions (Belgium 1, Bulgaria 1, Croatia 1, Czech Republic 1, Germany 1, Japan 2, Romania 2, Slovenia 1 and Serbia 2). Finally only 10 participants declared their results, while the remaining two participants announced serious problems with soil gas sampling and they informed the organizers that they will not participate in the final assessment.

'Active' participants are marked by following codes: P-1, P-2, P-3, P-4, P-5, P-6, P-7, P-8, P-9, and Organizer. Except the Organizer (RADON v.o.s.), the evaluation of results was anonymous, based on measurement reports. A sample measurement report was prepared by the organizers, filled in by all participants and sent for the evaluation. Unfortunately, the quality of several measurement reports was poor and some important data and information were thus missing.

The spectrum of radon measurement techniques tested during the intercomparison exercise was large

Table 6. Intercomparison of radon activity concentration in the soil gas (data reported by different participants), subarea Sljive, May 30, 2014

Participant	Number of meas.	Minimum (kBq/m³)	Maximum (kBq/m³)	Median (kBq/m³)	Ar.mean (kBq/m³)	SD (kBq/m³)	SD / mean
P-1	7	4.4	131.2	40.0	57.3	42.8	0.75
P-2	15	2.4	85.0	23.3	29.2	25.9	0.89
P-3	15	0.9	82.0	19.7	31.9	31.1	0.98
P-4	15	8.0	93.0	55.0	49.7	27.6	0.56
P-5	8	18.0	123.0	68.5	66.8	30.0	0.45
P-6	4	0.0	0.5	0.1	0.2	0.2	1.22
P-7	6	19.3	86.6	73.9	66.4	25.2	0.38
P-8	9	0.8	79.0	27.4	35.7	34.6	0.97
P-9	6	35.5	81.0	60.0	58.4	17.5	0.30
Organizer	15	36.1	132.1	79.4	83.4	27.4	0.33

(electrostatic collection of alpha-emitters with spectral analysis, scintillation and ionization measuring methods; Neznal probe, Alpha Guard probe and/or various steel probes, syringes or pumps). The volume of collected soil gas samples was also very variable (from 0.1 L to several liters).

The intercomparison exercise of radon activity concentration in the soil gas was organized at a chosen subarea of the test site 'Sljive' in Niska Banja, previously determined in October, 2013. Fifteen basic reference stations (numbered 1–15) were marked at the test site (former subarea) in the grid 5 × 5 m. The participants were asked to take samples primarily in the surroundings of those 15 reference stations.

It should be stressed that long and heavy rains caused floods in the vicinity of Niska Banja before the intercomparison measurement. The intercomparison measurement was thus performed under unexpected extreme conditions. Although the geological environment at the test site is normally highly permeable and enables an easy soil gas sampling, during the intercomparison measurement the water saturation was very high. Consequently, the effective porosity was very low and the amount of 'free' soil gas – available for sampling – was limited.

Due to problems with soil gas sampling and due to the time spent for measurement using several techniques, not all participants were able to measure at all 15 sampling stations. The intercomparison of all participating laboratories, which declared their results, is given in Table 6.

As can be seen in Table 6, median values reported by different participants/institutions ranged from 0.1 to 79.4 kBq/m³ (median of reported median values was equal to 47.5 kBq/m³ and SD/ar.mean of reported median values was 0.59). Even excluding the implausible results from participant P-6, median values reported by the rest of participants ranged from 19.7 to 79.4 kBq/m³ (median of those median values was equal to 55.0 kBq/m³ and SD/ar.mean of those median values was 0.46).

In our opinion, the variability of results was caused by a combination of following reasons:

- Extreme conditions during the intercomparison measurement – mainly high water saturation and low effective porosity, causing serious problems with soil gas sampling. All participants announced problems with sampling and participants representing two institutions decided not to report their results.
- Under such conditions, the requirements on the perfect sealing of all parts of sampling equipment are most important. The sampling itself needs longer time and any leakage can cause a 'contamination' of the soil gas sample by the atmospheric air.
- Higher water content could increase the spatial variability of radon activity concentration in the soil gas over the test site. During the initial measurements in October 2013, the spatial variability expressed by the maximum/minimum ratio was lower than 2, SD/mean ratio lower than 0.20, while during intercomparison measurements the maximum/minimum ratio was about 3.5, and SD/mean ratio 0.39 (using the data from Organizer). Nevertheless the Organizers results could be influenced by high water content and problems with sampling as well.
- The number of measurements performed by different participants ranged from 4 to 15 measuring stations. Due to the spatial variability over the test site, a low number of measurements is not sufficiently representative – the results do not cover the whole area.
- Intercomparison participants used different sampling methods and different volume of collected soil gas samples. These differences are more important just in case of low permeability (apart from the heterogeneity of the geological environment, the limited amount of soil gas available for sampling can result in larger variability).

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- Varying depths of sampling may also increase the variability of data.
- In case of some participants, no information of primary calibration of instruments was available.

Several influencing factors are discussed in more detail.

Conditions during the intercomparison

The extreme conditions at the test site and at the whole region had a major impact on the radon intercomparison measurement. Unusually heavy rains with high rainfall totals before the measurement significantly changed the properties in the whole vertical profile of soil layers and substantially increased the soil moisture and water saturation.

In such conditions, when we assume:

- ideal homogeneous soil environment;
- sampling the soil gas at the end of the probe from a sphere;
- following soil properties: porosity 0.4 and water saturation 0.95;
- volume of soil gas extracted from the soil during the soil gas sampling in the first case 0.2 L and in the second case 2 L;

we can calculate the radius of the sampling sphere:

$$r = ((3 . V_s) / (4 . \pi . n . (1 - s)))^{1/3},$$

where

V_s is the volume of the soil gas extracted from the soil during the soil gas sampling, in cubic meter;

V_{soil} is the volume of a sphere of a homogeneous soil, which contains the volume of soil gas available for extraction, in cubic meter;

r is the radius of the sphere of a homogeneous soil, V_{soil}, in meter;

s is the water saturation of soil, that is the part of soil pores filled with water;

n is the soil porosity, that is the ratio of the volume of soil pores and the volume of soil.

In case of the sample volume 0.2 L (0.0002 m^3), the sampling sphere has a radius of 13.4 cm; while in case of the sample volume 2 L (0.002 m^3), the sampling sphere has a radius of 28.8 cm.

The water saturation during the intercomparison was probably even higher, and using the water saturation value of 0.98, the sampling sphere has a radius of 18.1 cm in case of 0.2 L sample volume and 39.1 cm in case of 2 L sample volume.

In fact, the soil environment is never homogeneous. Instead of an ideal homogeneous sphere, there is always some heterogeneity in the soil. The heterogeneities may provide more permeable pathways for sampling. If the sampling depth is not large enough, there is always a possibility that the soil gas sample will be diluted either by atmospheric air or by not representative gas from upper soil layer.

In addition, when the water saturation is closed to 100%, taking of a soil gas sample requires not only longer time, but much higher negative pressure as well. The perfect sealing of all parts of the sampling equipment is necessary.

When a syringe is used for sampling, the perfect sealing is often a question of experience. The tightness of the syringe must be tested frequently. The movement of the piston should be as straight as possible.

Using of pumps in such low permeable environment is even more complicated. The risk of an underestimation of real soil gas concentration values is even higher, because the pumps are usually not able to produce a sufficient negative pressure.

Note: As can be seen from Table 5 (last column) and Table 6 (last line), despite the extreme conditions during the intercomparison measurement, the statistical data from the Organizer were not substantially influenced by extreme conditions and were very well comparable with the results from previous measurements in 2013.

Spatial variability

The radon activity concentrations in the soil gas measured by all participants in the surroundings of different measuring stations varied across the area. Median values corresponding to stations 5, 8, 10, 13, 14, and 15 were substantially lower than median values at the rest of the test site.

If we consider the problems with soil gas sampling and the possibility of underestimation the radon potential, we can divide the test site into two subareas (surroundings of stations 1, 2, 3, 4, 6, 7, 8, 9, 11, 12; surroundings of stations 5, 10, 13, 14, 15), and compare data for the subarea with stations 1, 2, 3, 4, 6, 7, 8, 9, 11, and 12. Comparison of data reported by different participants in such subarea is shown in Table 7.

If we exclude a part of the test site with measured local anomalies (lower values) and if we evaluate only measurements performed in the surrounding of stations 1, 2, 3, 4, 6, 7, 8, 9, 11, and 12, the agreement among participants is better. In this case, median values reported by different participants ranged from 0.0 to 102.2 kBq/m^3 (median of reported median values was equal to 70.3 kBq/m^3 and SD/ar.mean of reported median values was 0.43). Excluding the implausible results from participant P-6, median values reported by the rest of participants ranged from 42.1 to 102.2 kBq/m^3 (median of those median values was equal to 70.5 kBq/m^3 and SD/ar.mean of those median values was 0.24).

Table 7. Intercomparison of data of radon activity concentration in the soil gas reported by different participants in the surroundings of selected stations, Sljive, Serbia, 2014

Participant	Number of meas.	Minimum (kBq/m^3)	Maximum (kBq/m^3)	Median (kBq/m^3)	Ar.mean (kBq/m^3)	SD (kBq/m^3)	SD / mean
P-1	5	4.4	131.2	79.6	67.5	47.8	0.71
P-2	10	3.2	85.0	42.1	38.6	26.8	0.69
P-3	10	1.5	82.0	52.0	44.8	30.6	0.68
P-4	10	13.0	93.0	70.5	59.9	24.2	0.40
P-5	7	18.0	123.0	70.0	69.7	31.1	0.45
P-6	3	0.0	0.5	0.0	0.2	0.3	1.42
P-7	5	58.9	86.6	73.9	75.9	11.4	0.15
P-8	7	1.3	79.0	63.9	45.6	33.0	0.72
P-9	2	64.0	81.0	72.5	72.5	12.0	0.17
Organizer	10	58.9	132.1	102.2	100.5	25.2	0.25

Conclusions

Radon in soil gas is subjected to variability caused by the natural environment and atmospheric conditions. In addition, field measurement of radon activity concentration in soil gas differ due to use of various instruments, their calibration, heterogeneity of the geological environment and the choice of measurement points, technique of soil gas sampling and the stochastic character of any radiometric measurement. Since resultant values of radon risk mapping at building sites are compared to national levels and regulations, the reliability of radon assessment at building sites is fundamental. Uniformity and deviations of radon in soil gas measurements can be tested by radon comparison measurements at established radon reference sites.

The homogeneity and the knowledge of characteristics of the areas for the radon comparison measurement should be as large as possible. Only in such case, does the radon intercomparison measurement makes it possible to reveal differences and errors in measurements of radon activity concentration in the soil gas and/or in the soil gas sampling. Investigation of the geological setting of radon reference sites should apply a complex of geological and geophysical methods that determine the depth of the hard rock basement, the thickness and type of the soil cover, the basement rock tectonic features, the depth of the water level, and the variability of radon and soil moisture in a year cycle. Irregularity in physical parameters of radon reference sites complicate the radon data comparison and the reliability of tests. The measurement organisations that have successfully passed the intercomparison measurement can later rely on their procedures used further in standard measurements (where very often the variable conditions and inhomogeneity of geological setting cause the differences in single values of radon activity concentration in the soil gas).

Suitable radon reference sites should be established at plane meadows accessible for cars, their radon activity concentration should differ, vertical soil thickness should enable soil gas sampling to the depth of 1 m. Lateral and vertical heterogeneity of the soil environment at radon reference sites must be tested ahead of their use. Lateral homogeneity of radon soil gas data, defined by coefficient of variability, should be preferably less than 20%, mutual distance of reference sites should be short, and their long-term repeated use is preferable. The number of fixed field stations for radon measurement should be as large as possible, with a minimum number of 10 stations per single radon reference site.

A sufficient large number of participants at radon comparison measurements contributes to their purpose, however the perforation of soil at fixed common places of soil gas sampling can lead to a decrease in recorded radon activity concentration. A system of independent stations for soil gas sampling should be applied (Fig. 5).

Preparation and detailed investigation is necessary at any test site before the radon comparison measurement. Additionally, as can be seen from results from Niska Banja, Serbia, extreme precipitation conditions before or during the comparison measurements can significantly influence the assessment. High water saturation of the soil causes serious problems with soil gas sampling resulting in higher variability of reported radon data. A low speed of field operation of some participants, limiting the number of observed field points, yields lower representativeness of their reported results. Further, comparison measurement at several distinct reference sites is preferable to comparison measurement at one reference site.

Realistic estimates of deviations in radon activity concentration in soil gas due to heterogeneous soil, random choice of measurement points, and stochastic fluctuation of radon measurement show the relative differences of repeated investigations in the range up to 10% in a homogeneous geological environment and sufficient number of

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points of field measurement, while differences up to ±40% for a heterogeneous geological environment and a critically low number of measured field stations ($N \leq 5$) can be expected.

The calibration of single radon instruments based on available national calibration standards may play a fundamental role in radon comparison measurement. National radon comparison measurements in the Czech Republic and international radon comparison measurements at various test sites revealed some unacceptable deviations in reported radon values. While national radon comparison measurements reflect the measurement techniques, various calibration standards in single countries may contribute to radon data deviations at international radon comparison measurements.

Radon in soil gas comparison measurements usually test 10 to 20 participants based on their reported radon data deviations. Experience shows that such an approach already identifies underestimation or overestimation of reported radon data of single participants; however, the absolute deviation or errors are not quantified. Radon comparison measurement tested at the background of a large number ($n \cdot 10^2$) of participants or using the radon databases of radon reference sites, accumulated in longer time of repeated measurements, have the capacity to check the reliability of the reported radon data or absolute deviations of single organizations. In the case of radon databases, algorithms of radon data testing must eliminate long-term temporal variations at used reference sites.

A 30 year experience from radon comparison measurements at reference sites in the Czech Republic showed the most frequent errors in the procedure of radon risk mapping, namely low tightness of soil gas sampling circuit and of transfer of a gas sample into the radon detector, dilution of soil gas sample by atmospheric air, bad evacuation of the detector chamber, high background contamination of the detector chamber, insufficient elimination of thoron, too short measurement with respect to radiometric signal fluctuations, incorrect calibration constant of instrument, and instrument instability in humid air field conditions. A low number of measured field points devaluates any test. The fundamental profit from radon comparison measurement is the indication of unacceptable deviation of data reported by the tested organization and subsequent correction.

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Conflict of interest and funding

The authors have not identified any conflicts of interest during this study.

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