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# Intercomparison of equipment measuring radon activity concentration in the air—an example from a hydrotechnical structure in Dobromierz (SW Poland)

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## Abstract
The semi-conductor SRDN-3a probe, an AlphaE detector with a silicon diode in a diffusion chamber, an AlphaGUARD monitor with an ionization chamber and CR-39 track detectors had been tested simultaneously in long-term measurements conducted in the technical corridor of Dobromierz dam. The passive detectors were exposed twice: for 56 days, and 117 days, others in parallel, with a 1-h data recording interval. The data distribution was tested with the Shapiro–Wilk test and outliers in the critical region were identified using Shewhart control charts. The correctness was evaluated by a z-score test recommended by the IAEA. The characteristics of outliers for each detectors are determined by the location of the critical region (a two-sided region and a positive skew). These are 13.0% and 13.5% for AlphaE, and 9.81% for SRDN-3a. For the reference device, these are 15.8% and 10.5%. The z-score test confirm that all the detectors can be successfully used both in commercial and scientific monitoring measurements.

**Keywords** Screening tests of $^{222}$Rn · AlphaGUARD · AlphaE · Solid state nuclear track detector CR-39 · Semiconductor detector SRDN-3a · Water dam

## Introduction

The amendment of radiological protection regulations in Poland resulting from the implementation of Council Directive 2013/59 Euratom [1] into national guidelines obliged departments heads to control the mean annual level of $^{222}$Rn activity concentration in workplaces [2, Art. 23c sec. 1]. Recommendations for measurement specification, measurement methods and measuring instruments, as well as a list of laboratories specialized in $^{222}$Rn activity concentration measurements in workplaces, were issued by the Chief Sanitary Inspector: GIS [3]. To coordinate their activities, a team for national action plan in case of radon exposure was established in compliance with the Minister of Health Announcement of 22 January 2021 [4].

Recording a $^{222}$Rn activity concentration exceeding the mean annual value of 300 Bq/m$^3$ recommended by Polish law [2, Art. 23b] and by international organizations [5–9] obliges the employer (unit head) to take specific measures. These are: reducing workers' exposure, providing them with written information on increased radon exposure and presenting the results of conducted radiological measurements [2, Art. 23c Sect. 2 and Art 23c sec. 3]. Also, laboratories conducting measurements are obliged to immediately notify GIS departments of the recorded exceedance of the reference value [2, Art. 23d Sect. 5]. Special protection in this respect was granted to workplaces in 6 Polish voivodships, including 12 powiats

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(counties) and 2 cities with powiat rights in the area of Lower Silesia specified in the Minister of Health Regulation [10].

The goal is checking the possibility of getting precise and accurate measurements with the available techniques and verifying which instruments should be used for the GIS recommendations be followed by users. It is particularly important when choosing the optimal measuring instrument, which should accord with the varied character of the measurement. Its key parameters should be measurement precision, exposure time and the degree of execution difficulty. The latter parameter comprises conducting measurement in two stages (time-consuming) in the case of passive technology, or continuously (on an ongoing basis; user-friendly but expensive) when using an active measurement technique. What has also been noted is a possibility of modifying the measurement by a client, e.g. due to changing the workplace or working time in a particular workplace, including the time of ionizing radiation exposure. Thus, a possibility of comparing results for two measurement methods by devices used for different purposes (commercial or scientific) has been ensured. The authors checked the sensitivity of the tested devices and the exposure criteria recommended in order to maintain the appropriate measurement conditions. This is of particular importance as checks of multiple devices and measurement methods used by different laboratories are rarely conducted in field conditions. Usually, individual devices are checked during interlaboratory comparative measurements organized by the Chief Sanitary Inspector [2]. Their exposure is carried out in known and monitored radon concentration conditions in a laboratory calibration chamber [11–14].

## Theory

Following the GIS guidelines published in materials available on the official website [15], tests were conducted for several instruments recommended for measuring radon activity concentration inside a technical space used as workplace located entirely under a water reservoir. The devices used in short-term and long-term tests were a new AlphaE detector, not used in radiological measurements in Poland so far, semiconductor SRDN-3a detectors, already tested in long-term exposure, a more sensitive and the standard reference instrument for many laboratories: AlphaGUARD radon monitor, and track detectors CR-39 recommended for measuring mean annual values of $^{222}$Rn activity concentration. The track detectors had been tested in intercalibration measurements in 2016 and 2022.

## Object description

The place of intercomparison tests of four radon concentration detectors was the technical corridor of a dam in Dobromierz in Lower Silesia (SW Poland). The technical corridor chosen for the research is part of a dam on the river Strzegomka in Dobromierz. The dam is intended for flood prevention and water supply for the residents of Świebodzice area. It is situated within Książ Landscape Park, in the area of the Bolków and Wałbrzych Foothills in the Central Sudetes. The dam was built in 1978–1988. Currently the maximum area of the reservoir is 1 km$^2$ and its total capacity—11.65 million m$^3$, including 8.3 m m$^3$ usable capacity. The average depth of the reservoir is 10.25 m at the maximum impoundment of 27 m, and 3.6 m at the minimum water level of 10 m [16, 17] (Fig. 1).

The corridor serves as space intended for temporary stay of people engaged in periodic operation, inspection and maintenance of the machinery and devices, such as a pump and pipeline assembly, in the technological chain of the dam. The dam is 28 m high and its lowest section, with a length of 400 m, is a technical corridor running entirely inside reinforced concrete casing. The asymmetry of the reservoir basin determines the shape and the character of the designed technical corridor. It is situated at varying levels, and its longest section runs anti-clockwise, following the course of the dam crest. On either side there of the corridor there are entrances starting with a flight of stairs. For safety reasons, one of the entrances is closed permanently, and the other is opened at the overflow channel of the dam (Fig. 1B1).

The authors located the measuring station at a distance of c. 200 m from the main entrance to the dam. It is situated at the lowest point of the technical corridor, near the dam centre. The location and thereby the place of measurement optimization was chosen in a way enabling maintaining relatively stable conditions in the corridor space, independent of changes in ventilation or organization of work. Information on starting radon measurements and the location of detectors, as well as on the purpose of these measurements, was communicated to the employees before starting the measurement campaign. The detectors were placed at a height of c. 1.5 m above the floor and a distance of c. 20 cm from the wall, in a safe way which did not affect the work of employees or people present in the corridor for other reasons. Consequently, there was no need to move or open them, turn off power supply or perform other actions that might have affected the result of measurement. At the same time, the place chosen for measurements ensured that the result was representative of the entire space of the corridor. The measuring station did not limit or disturb the free flow of air around the detectors. During the measurements, the time spent inside the space by people employed to operate the technical equipment of the dam was taken into consideration. It was expected to be at least 2 h per week i.e. 104 h a year.

The station was equipped with one semiconductor detector SRDN-3a placed on a stand at the height of the workers' breathing zone (Fig. 1C). The AlphaE detector

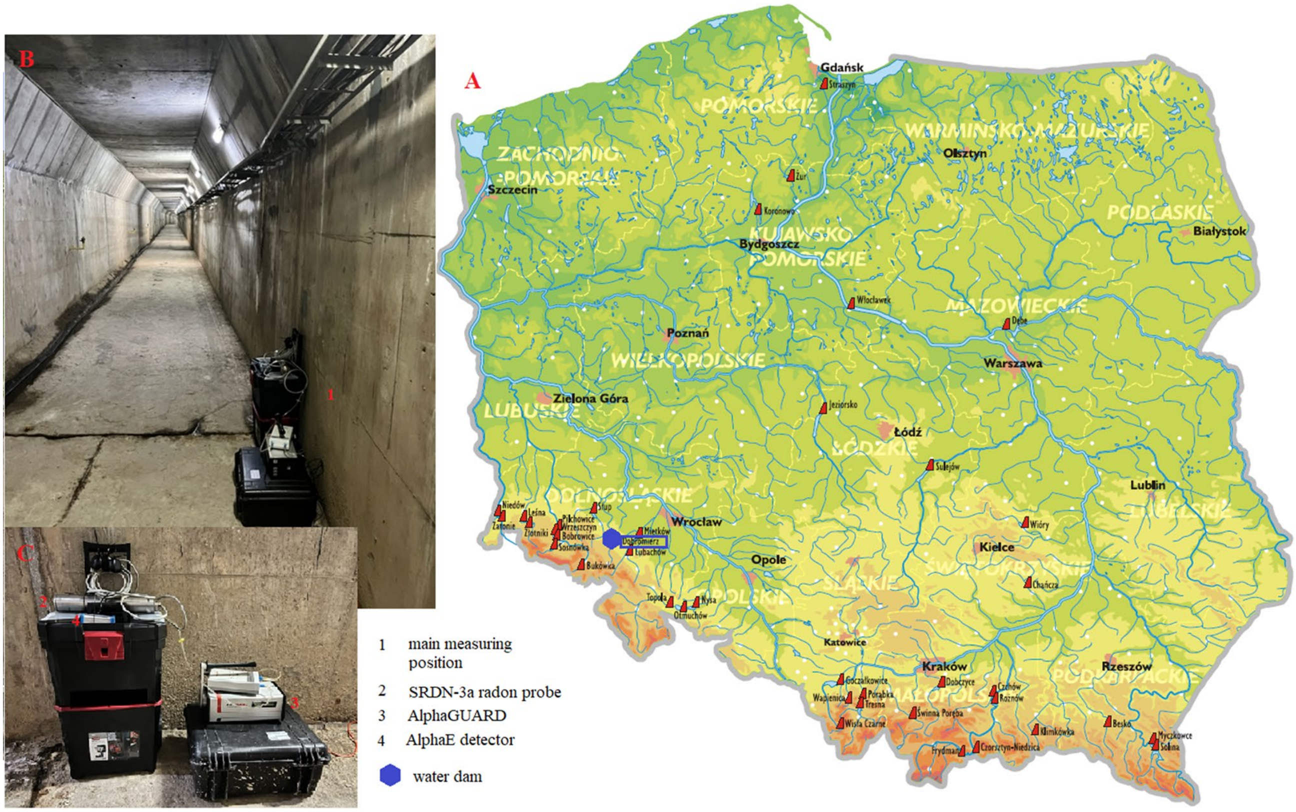



**Fig. 1** The location of Dobromierz dam in relation to other dams in Poland (**A**) with a height of more than 15 m [based on 16] with location of the measuring station (**B**) inside the corridor with the used measuring devices (**C**)

was mounted in the same way. Three track detectors were mounted together. The AlphaGUARD device, used in three 3-h measurement cycles, was placed beside the main measuring station, at the recommended distance from the corridor walls (Fig. 1C3). The air was driven through silicone tube (Fig. 1C3) located at the height of the workers' breathing zone (at height of c. 1.5 m above the floor) into the ionization chamber with a gas-tight pump AlphaPUMP.

## Radon measurements

Measurements of $^{222}$Rn activity concentration in the technical corridor of the dam were conducted under permit No. WR.ZUW.1.071.41 m.2020.AS issued by the State Water Holding "Wody Polskie", Catchment Management Board in Legnica on December 4, 2020.

The measurements were carried out by two research institutes performing measurements of radon activity concentration in the air. One of them is the Central Laboratory for Radiological Protection in Warsaw holding an accreditation certificate No. AB 450 covering measurements of $^{222}$Rn isotope activity concentration in the air. The other research team is represented by two faculties of Wrocław University of Science and Technology, whose employees have been continuously, since the 1990s, conducting measurements of radon activity concentration in the air and have actively participated (e.g. in 2016) in interlaboratory comparative measurements of mean annual concentration of radioactive radon in the air, organised by the GIS.

## AlphaGUARD monitor—the reference instrument

As the reference measuring instrument the authors used radon monitor AlphaGUARD PQ 2000PRO produced by German company Bertin [18]. In this device, ionizing radiation coming from $^{222}$Rn and its progeny is detected by an ionization chamber with an active capacity of 0.56 dm$^3$. During the conducted measurements, the air was driven into the ionization chamber with a gas-tight pump AlphaPUMP by the same manufacturer. The pump worked with a capacity of 1 dm$^3$/min. and the AlphaGUARD device performed measurements in 10-min. FLOW mode. This means that the results for mean $^{222}$Rn activity concentration expressed in Bq/m$^3$ were registered in the device memory for every 10-min period. The measuring range of the device is from 2 to 2 000 000 Bq/m$^3$ and the measurement uncertainty does not exceed 10%. The measurement data were stored in the device memory and then transferred to computer memory by means of dedicated software (DataEXPERT). The data were analysed statistically using MicroSoft Excel software. Such a measuring set is widely used as a reference device in many laboratories performing measurements of $^{222}$Rn activity concentration in different environments round the world. Its advantages are accuracy and measurement precision combined with time-stable calibration quality. The device had been calibrated by the manufacturer and calibration results have been repeatedly verified during interlaboratory comparative measurements [11].

## AlphaE detector

The AlphaE S/N AE001330 by German company Bertin is a complete device with a certificate of in-factory calibration performed in the manufacturer's calibration laboratory using a gas-tight chamber with reference device AlphaGUARD S/N EF 1851, whose correct operation is confirmed by certificate No. 6.13-98-4068479 issued in May 2014 (Table 1). According to the calibration certificate, its measurement uncertainty is ± 10%, and the recording accuracy of a single result reaches 0.1 Bq/m$^3$ [19, 20]. The measuring range of this device starts at 20 Bq/m$^3$ and ends at 10 MBq/m$^3$, with the detection level (LLD) < 100 Bq/m$^3$ for 12-h measurement [20].

The AlphaE device is equipped with a semiconductor detector with a silicon diode operating according to EN/IEC standards for electromagnetic compatibility. Radon enters the chamber through openings accounting for 1.3 cm$^2$ of the device casing surface covered entirely with Gore-Tex membrane. Alpha radiation emitted during $^{222}$Rn decay is registered by the detector as voltage pulses, which are amplified, and then counted and converted to required units according to the performed calibration (Table 1). Then the obtained data are stored by a microcontroller. Apart from $^{222}$Rn activity concentration, the AlphaE device can determine a cumulative dose of ionizing radiation relative to the equilibrium concentration factor (EEC). These factors are pre-set in the device menu, but they can be changed in the software communication panel [20]. The preview of basic menu settings is possible by calling the function on the device display unit by multiple selection of the Mode button.

Before starting the actual measurements, the device needs to be charged for at least 6 h. The manufacturer recommends recharging the device every 3 months in case of power failure during operation. This primarily applies to the situation when the device is solely battery-powered. After the first initiation of the device [20], the proper measurement result is obtained after 2 h (the response is faster with higher radon concentrations). This is also the case when measurement parameters are changed [20].

**Table 1** The results of in-factory calibration of AlphaE device as compared to the reference device AlphaGUARD PQ 2000PRO according to the manufacturer's calibration certificate No. 210824 for AlphaE No. S/N AE001330 [based on 19]

| AlphaGUARD–reference device | | AlphaE–tested device | |
|---|---|---|---|
| $^{222}$Rn value (kBq/m$^3$) | Untercainty (kBq/m$^3$) | $^{222}$Rn value (kBq/m$^3$) | Untercainty (kBq/m$^3$) |
| 10.45 | ± 0.052 | 10.93 | ± 0.155 |

## CR-39 track detectors

Track detectors CR-39 were also used in the measurements. Each detector is composed of a diffusion chamber, into which ambient air diffuses, and a plate made of allyl diglycol polycarbonate (PADC) known under the trademark CR-39 inserted in it. Radon and its progeny produced in the diffusion chamber emit alpha particles, which damage chemical bonds while diffusing through the detector material and form an invisible latent track. As a result of chemical etching in concentrated sodium hydroxide solution, this track becomes visible under a microscope. The density of thus created tracks is counted using an automatic reading system. It corresponds to the number of alpha particles which created them, so it is proportional to the concentration of radon in the examined air.

Before starting the actual measurements, the CR-39 track detectors were calibrated in reference radon atmosphere. The aim of the exposure was to determine a coefficient allowing the measured track density to be assigned to radon concentration integrated over time. The PADC detectors register α particles over a wide range of energies, from c. 0.1–20 MeV, while being insensitive to β and γ radiation [21]. They do not show dependence on temperature or humidity. Track detectors enable a one-time measurement, but after being etched, they can be kept as a carrier of information about the exposure. A detailed description of the measurement methodology using track detectors has been presented by Olszewski [22]. During each of the two exposure times, 3 track detectors were used.

## Semiconductor detector SRDN-3a

The SRDN-3a device (otherwise known as a radon probe) is a measurement instrument fitted with a semiconductor detector entirely designed and built by the Institute of Chemistry and Nuclear Physics (ICHiTJ) in Warsaw (Poland) [23]. Its operation is based on an active measuring technique enabling practically maintenance-free measurement during the life of its powering batteries, i.e. two lithium batteries type LSH–20, 13Ah. It is highly resistant to corrosion, dust and mechanical damage, and intrinsically safe. The SRDN-3a probe is used to measure and record data, while reading them is possible thanks to the PSR-2 programmer (portable result memory) dedicated to the measuring set.

The measurement quality of the SRDN-3a probe was checked by its calibration in the radon chamber of the PAN Institute of Nuclear Physics in Cracow, in $^{222}$Rn concentrations of $0.72 \pm 0.05$ kBq/m$^3$, $4.16 \pm 0.16$ kBq/m$^3$, $8.98 \pm 0.31$ kBq/m$^3$, $20.32 \pm 0.62$ kBq/m$^3$ and $55.24 \pm 1.3$ kBq/m$^3$ [24]. Based on them, measurement uncertainty of the detector was determined, amounting to 15.5, 9.0, 6.8, 5.5 and 5.1% respectively. For lower $^{222}$Rn activity concentrations, ranging from $\leq 100$ to $\leq 500$ Bq/m$^3$, the measurement uncertainty increases to 20% [25].

## Results and discussion

A detailed comparative analysis was conducted on 4 data sets. The correctness of the conducted measurements using radon detectors was checked by verifying the parametric of two hypothesis: $H_0$ (about the normality of data distribution) and $H_1$ (about the alternative data distribution). In both cases, a decision about rejecting the $H_0$ hypothesis was made on the basis of the value of probability level *p* in relation to the significance level $\alpha = 0.05$. The acceptable analysis error (5 errors per 100 measurement results) was indicated, thus not increasing the plausibility of the alternative $H_1$ hypothesis. The verification decisions were based on two assumptions. For $p < \alpha$, the $H_0$ hypothesis may be rejected in favour of the alternative $H_1$ hypothesis. When $p > \alpha$, there are no grounds for rejecting the $H_0$ hypothesis. The verification of $H_0$ hypothesis was based on the result of Shapiro–Wilk test shown on normality plots. For the $H_0$ hypothesis, the values of random variable in the so-called critical region (two-sided in a range of $\pm 3$ standard deviations from the average: SD) were indicated.

When finding grounds for rejecting the $H_0$ hypothesis, the alternative $H_1$ hypothesis, suggesting a positively skewed ($A_s > 0$) data distribution in relation to the (average) value expected from the exposure, was verified. For the alternative $H_1$ hypothesis, the critical region was described as + 3SD in relation to the mean value. After the verification of the hypotheses, the number of outliers occurring in the critical regions of the symmetrical (normal) and skewed distribution was checked. In this respect, verification was performed using frequency tables and Shewhart control charts. The analysis was supplemented with variability characteristics of radon activity concentration in a 1-h cycle relative to values recorded by the reference device. The consistency of the results obtained for radon detectors was verified based on the z-score test guidelines.

No validation of the passive method was carried out, as it had been described in the calibration laboratory procedure and confirmed by its accreditation certificate.

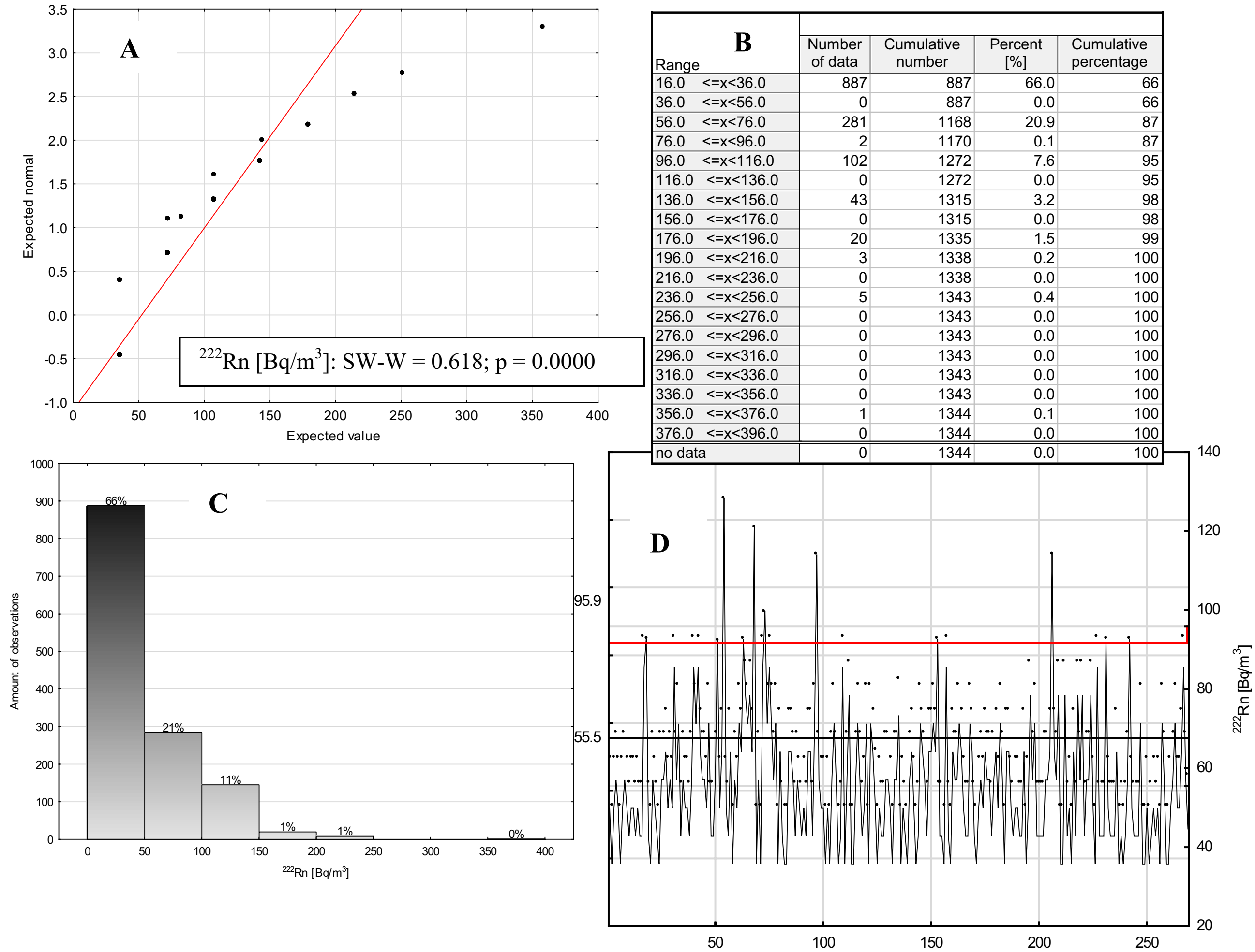
The obtained results were collated and discussed in stages for exposures No. 1 and 2 No. of semiconductor detectors and the ionization chamber together, and separately for exposure No. 3 and for track detector exposures.

The whole presented analysis for the SRDN-3a device is only based on the results of exposure No. 1. The results for exposure No. 2 are not presented separately, as they were comparable to those for exposure No. 1, which has been confirmed by the verification of both data sets. In each of the two measurement cycles: 56 days (1334 h) versus 117 days (2808 h), the probe worked in the atmosphere with radon concentration of 0–c. 250 Bq/m$^3$. Almost 55% of the data were clearly scattered results, with values below the average. Additionally, 21.5% of this data set were values below the lower detection limit (LLD) of the SRDN-3a probe. It has been found that operation in conditions with such a small $^{222}$Rn activity concentration is affected by large, even over 20% measurement error. Therefore, in order to achieve greater result reliability, the authors recommend, based on their years of experience, that radon probe measurements should be performed in the atmosphere in which radon concentration is at least twice as high as the LLD of the probe (preferably in a range $\geq 500$ Bq/m$^3$).

### Exposure No. 1 of devices with a semiconductor detector and an ionization chamber (devices for screening tests)

Exposure No. 1 lasted 1344 h from 12 noon on 25 March 2022 to 9 a.m. on 20 May 2022. Three detectors were subjected to it in parallel, and the fourth one was included as a reference device in 3-h measurements on the first and the last day of the exposure (with a 10-min data recording interval).

The results of the Shapiro–Wilk test conducted on 1-h exposure data from AlphaE detector showed dispersion of the recorded $^{222}$Rn activity concentrations relative to the measurement average (Fig. 2A). Data far from the average accounted for as much as 87% of all the results. These are both $^{222}$Rn activity concentrations lower than the average (66%) and those higher than the average (21%). The former group comprises values in the range 0–50 Bq/m$^3$, and the latter—from 50.0 to 100.0 Bq/m$^3$ (Fig. 2B, C). The remaining 13% of the data were outliers assigned to the critical region defined by the upper control limit UCL = 95.9 Bq/m$^3$ (Fig. 2B, D).




| Range | Number of data | Cumulative number | Percent [%] | Cumulative percentage |
|---|---|---|---|---|
| 16.0 <=x<36.0 | 887 | 887 | 66.0 | 66 |
| 36.0 <=x<56.0 | 0 | 887 | 0.0 | 66 |
| 56.0 <=x<76.0 | 281 | 1168 | 20.9 | 87 |
| 76.0 <=x<96.0 | 2 | 1170 | 0.1 | 87 |
| 96.0 <=x<116.0 | 102 | 1272 | 7.6 | 95 |
| 116.0 <=x<136.0 | 0 | 1272 | 0.0 | 95 |
| 136.0 <=x<156.0 | 43 | 1315 | 3.2 | 98 |
| 156.0 <=x<176.0 | 0 | 1315 | 0.0 | 98 |
| 176.0 <=x<196.0 | 20 | 1335 | 1.5 | 99 |
| 196.0 <=x<216.0 | 3 | 1338 | 0.2 | 100 |
| 216.0 <=x<236.0 | 0 | 1338 | 0.0 | 100 |
| 236.0 <=x<256.0 | 5 | 1343 | 0.4 | 100 |
| 256.0 <=x<276.0 | 0 | 1343 | 0.0 | 100 |
| 276.0 <=x<296.0 | 0 | 1343 | 0.0 | 100 |
| 296.0 <=x<316.0 | 0 | 1343 | 0.0 | 100 |
| 316.0 <=x<336.0 | 0 | 1343 | 0.0 | 100 |
| 336.0 <=x<356.0 | 0 | 1343 | 0.0 | 100 |
| 356.0 <=x<376.0 | 1 | 1344 | 0.1 | 100 |
| 376.0 <=x<396.0 | 0 | 1344 | 0.0 | 100 |
| no data | 0 | 1344 | 0.0 | 100 |

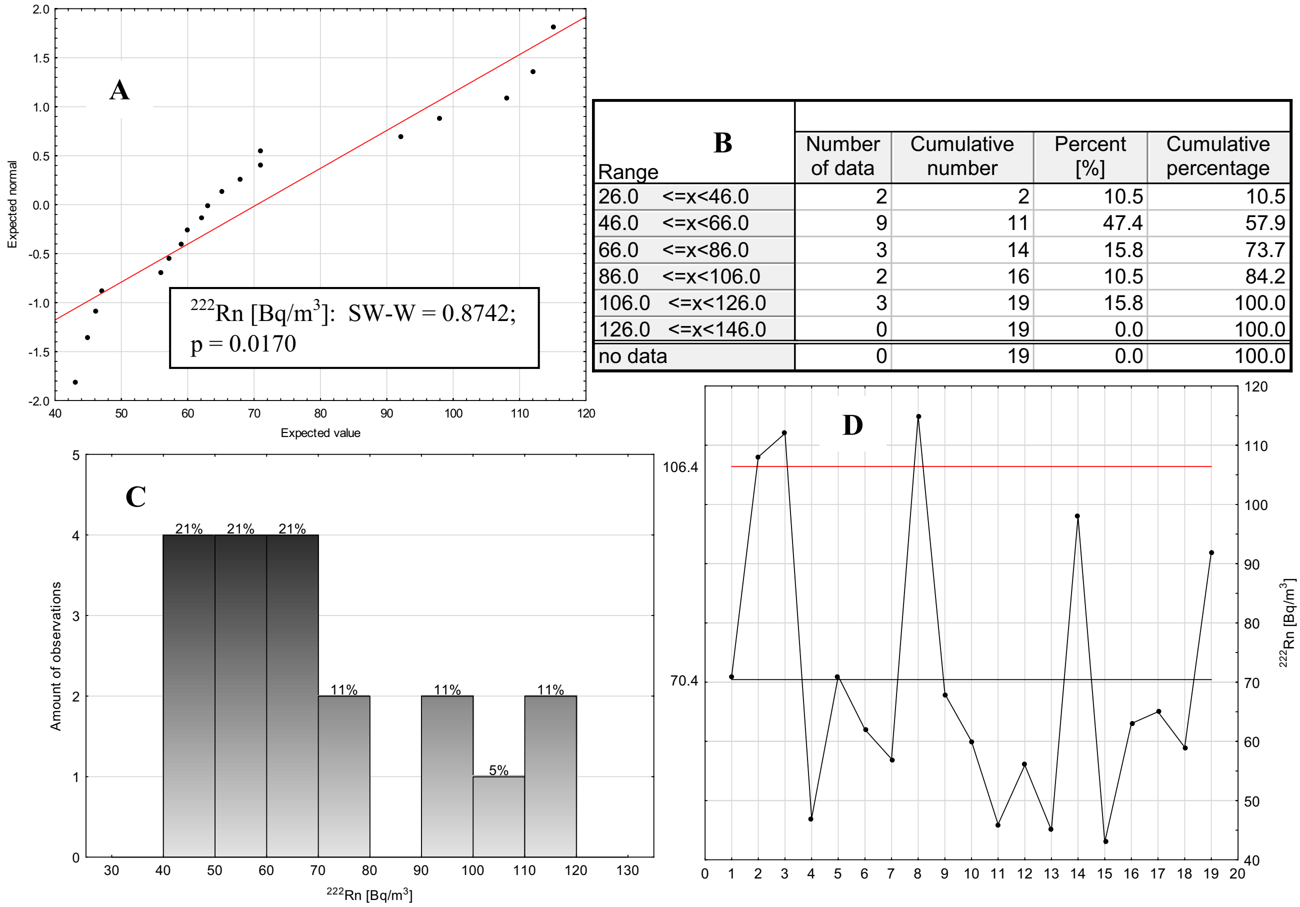
**Fig. 2** Overview of statistical analysis results for $^{222}$Rn activity concentration measurements during the first exposure of AlphaE detector: normality plot with Shapiro–Wilk test SW-W (**A**), data frequency tables for each class (**B**), their distribution histogram (**C**) and Shewhart control chart of outliers in the critical region + 3SD (**D**). The central (black) line indicates the mean value of 55.5 Bq/m$^3$. The critical region is delimited by the upper UCL (red) control line (+3SD) equal to 95.9 Bq/m$^3$. The critical region contains 13.0% of the data, regarded as outliers

A statistical analysis based on 19 data from AlphaGUARD radon monitor exposure demonstrated equally strong dispersion of $^{222}$Rn activity concentrations relative to the measurement average (Fig. 3A). As many as 63% of the results were attributed to values from the range 40.0–70.0 Bq/m$^3$, i.e. below the measurement average (70.4 Bq/m$^3$) (Fig. 3B, C). The fewest results (from 5% to the maximum of 10.5%) correspond to $^{222}$Rn activity concentrations in the range from 90.0 to 110.0 Bq/m$^3$ (Fig. 3B, C). 15.8% of the results were assigned to the outlier region classified above the upper control limit (UCL > 106.4 Bq/m$^3$) (Fig. 3B, D).

The data from the SRDN-3a radon probe are characterized by clear dispersion relative to the mean. The result of the Shapiro–Wilk test (SW-W) for the probability level $p < \alpha$ explicitly confirms lack of data distribution normality (Fig. 4A). Over 50% of the results are below the average of 107.6 Bq/m$^3$ (Fig. 4B). Only 477 results (35% of all the data) are larger than the mean and lower than the UCL = 176.1 Bq/m$^3$ (Fig. 4B, C). The outliers (132 results) account for less than 10% of the total data set (Fig. 4D).

In the next stage, data registered in a 1-h cycle by the AlphaE detector were analysed (Fig. 5).

The statistical population structure of $^{222}$Rn activity concentrations recorded in successive hours of the day is characterised by positive skew of data distribution (Table 2). The greatest variation in $^{222}$Rn activity concentration was recorded from 4 a.m. and 5 a.m., at 7 a.m., from 6 p.m. to 7 p.m. and at 10 p.m. (Fig. 5A). At these times, the range of radon concentration variation reached ± 2δ relative to the measurement average. For the rest of the day, this range did not exceed ± 1δ relative to




| Range | Number of data | Cumulative number | Percent [%] | Cumulative percentage |
|---|---|---|---|---|
| 26.0 <=x<46.0 | 2 | 2 | 10.5 | 10.5 |
| 46.0 <=x<66.0 | 9 | 11 | 47.4 | 57.9 |
| 66.0 <=x<86.0 | 3 | 14 | 15.8 | 73.7 |
| 86.0 <=x<106.0 | 2 | 16 | 10.5 | 84.2 |
| 106.0 <=x<126.0 | 3 | 19 | 15.8 | 100.0 |
| 126.0 <=x<146.0 | 0 | 19 | 0.0 | 100.0 |
| no data | 0 | 19 | 0.0 | 100.0 |

**Fig. 3** Overview of statistical analysis results for $^{222}$Rn activity concentration measurements during the first exposure of AlphaGUARD radon detector: normality plot with Shapiro–Wilk test SW-W (**A**), data frequency tables for each class (**B**), their distribution histogram (**C**) and Shewhart control chart of outliers in the critical region + 3SD (**D**). The central (black) line indicates the mean value of 70.4 Bq/m$^3$. The critical region is delimited by the upper UCL (red) control line (+ 3SD) equal to 106.4 Bq/m$^3$. The critical region contains 15.8% of the data, regarded as outliers

the 1-h mean (Fig. 5A). Exceedance of the upper control limit (UCL) of the critical region occurred irregularly at many times during the day, i.e. from 2 a.m. to 5 a.m., from 8 a.m. to 9 a.m., at 11 a.m., at 2 p.m., at 4 p.m., and from 7 p.m. to 12 midnight (Table 2).

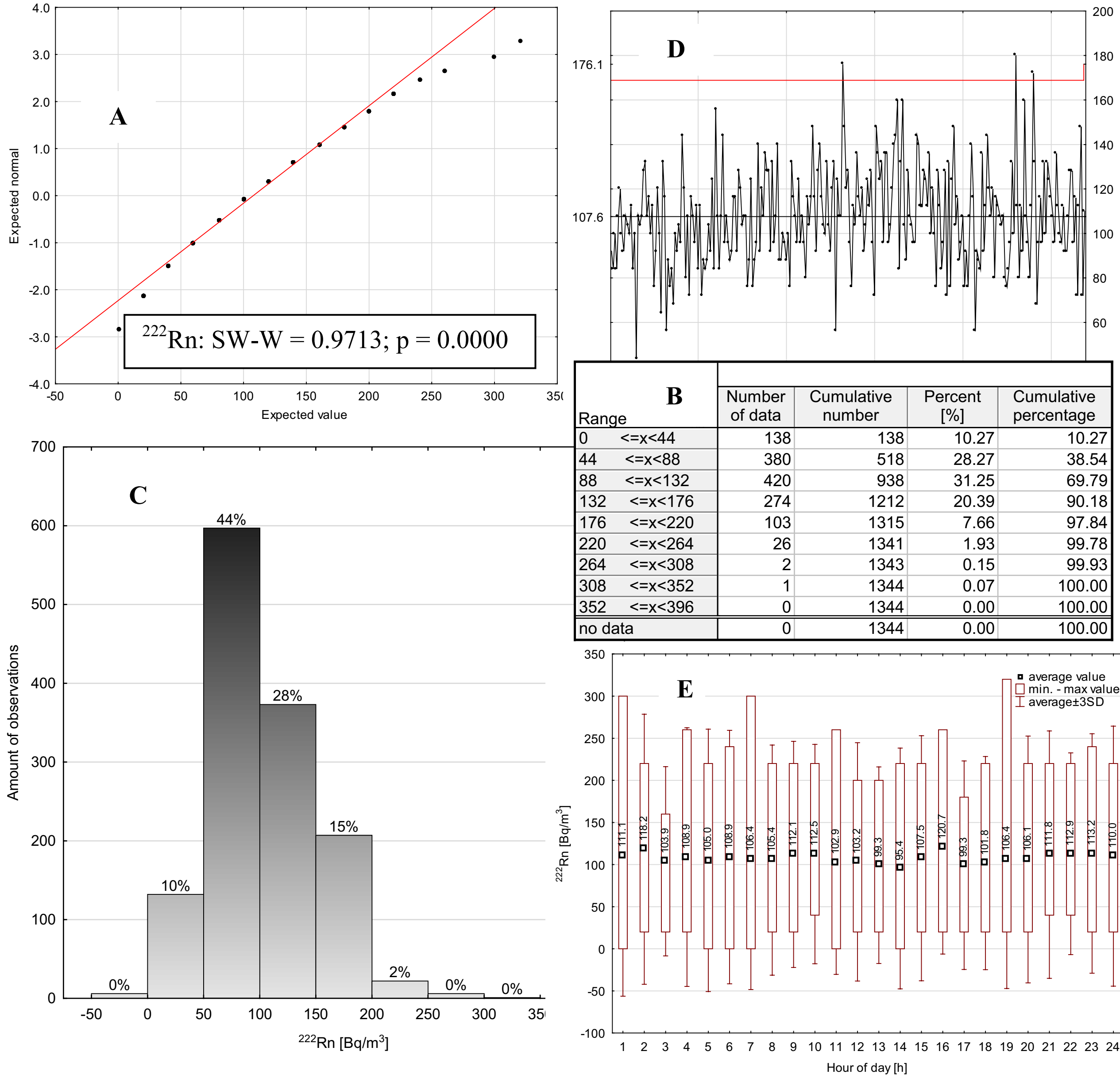
The analysis results of data from the SRDN-3a radon probe are comparable to the results obtained from the AlphaE device. The widest range of results (> ± 1δ) was recorded at 1 a.m., 7 a.m. and 7 p.m. The smallest spread of values in the range under ± 1δ relative to the mean is characteristic of the remaining times of the day (Fig. 4E).

A distinct dispersion of values around the mean (in the range ± 2δ) was also assigned to results from the reference device AlphaGUARD. It is best seen at 9 a.m., 10 a.m. and 11 a.m. (Figs. 9A, B, 10A). A comparable level of mean $^{222}$Rn activity concentration was recorded from 9 a.m. to 10 a.m. (Fig. 9) and from 11 a.m. to 12 a.m. (Fig. 10).

## Exposures No. 2 and 3 of devices with a semiconductor detector and an ionization chamber (devices for screening tests)

The second exposure of the AlphaE detector lasted for 2808 h from 9 a.m. on 20 May 2022 to 10 a.m. on 14 September 2022. In accordance with the conditions of exposure No. 1, the reference AlphaGUARD device was included in the measurements twice: at the start and the end of the exposure period. The detector worked for 3 h (9:40–12:40), on 20 May 2022 (exposure No. 2) and 14 September 2022 (exposure No. 3) at a 10-min data recording interval. The obtained results were analysed in the same way as the results from exposure 1.

The results of the Shapiro–Wilk test confirmed distinct dispersion of observations around the mean value from the




| B Range | Number of data | Cumulative number | Percent [%] | Cumulative percentage |
|---|---|---|---|---|
| 0 <=x<44 | 138 | 138 | 10.27 | 10.27 |
| 44 <=x<88 | 380 | 518 | 28.27 | 38.54 |
| 88 <=x<132 | 420 | 938 | 31.25 | 69.79 |
| 132 <=x<176 | 274 | 1212 | 20.39 | 90.18 |
| 176 <=x<220 | 103 | 1315 | 7.66 | 97.84 |
| 220 <=x<264 | 26 | 1341 | 1.93 | 99.78 |
| 264 <=x<308 | 2 | 1343 | 0.15 | 99.93 |
| 308 <=x<352 | 1 | 1344 | 0.07 | 100.00 |
| 352 <=x<396 | 0 | 1344 | 0.00 | 100.00 |
| no data | 0 | 1344 | 0.00 | 100.00 |

**Fig. 4** Overview of statistical analysis results for $^{222}$Rn activity concentration measurements during the first exposure of SRDN-3a radon probe: normality plot with Shapiro–Wilk test SW-W (**A**), data frequency tables for each class (**B**), their distribution histogram (**C**), Shewhart control chart of outliers in the critical region + 3SD (**D**) and a box-and-whiskers plot for values throughout 1 day (**E**). The central (black) line indicates the mean value of 107.6 Bq/m$^3$. The critical region is delimited by the upper UCL (red) control line (+ 3SD) equal to 176.1 Bq/m$^3$. The critical region contains 9.81% of the data, regarded as outliers

measurements (Fig. 6A). The positive skew of the distribution indicates that 66% of the $^{222}$Rn activity concentration results range from 0.0 to 50.0 Bq/m$^3$ (Fig. 6B, C). Fewer than 1/3 as many (19%) results correspond to values above the average described by the range of 50.0–100.0 Bq/m$^3$ (Fig. 6B, C). In the critical region (+ 3SD) above the upper control limit (UCL = 98.5 Bq/m$^3$), there are outliers, which account for 13.5% of the data (Fig. 6B, D).

The results of the Shapiro–Wilk test performed on the data from the AlphaGUARD device did not give grounds for rejecting the $H_0$ hypothesis (Fig. 7A). The recorded values are evenly distributed around the mean representing the expected value for *n* data. As many as 99.7% of the results correspond to the range 62.6 Bq/m$^3$ ± 3SD (Fig. 7C). Distribution normality is also confirmed by the results of the third exposure of the AlphaGUARD radon monitor (Fig. 8A, B,

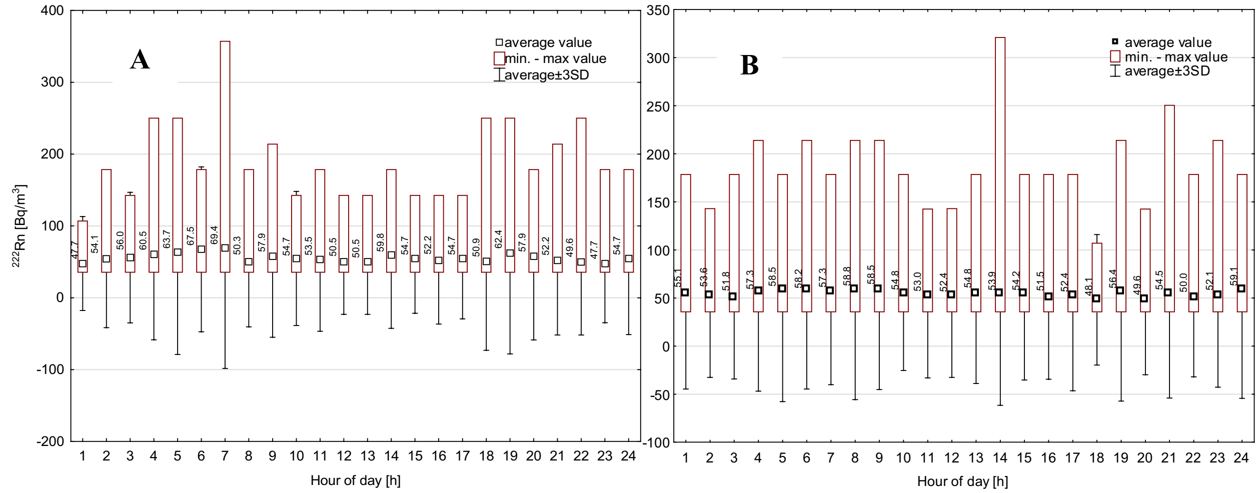
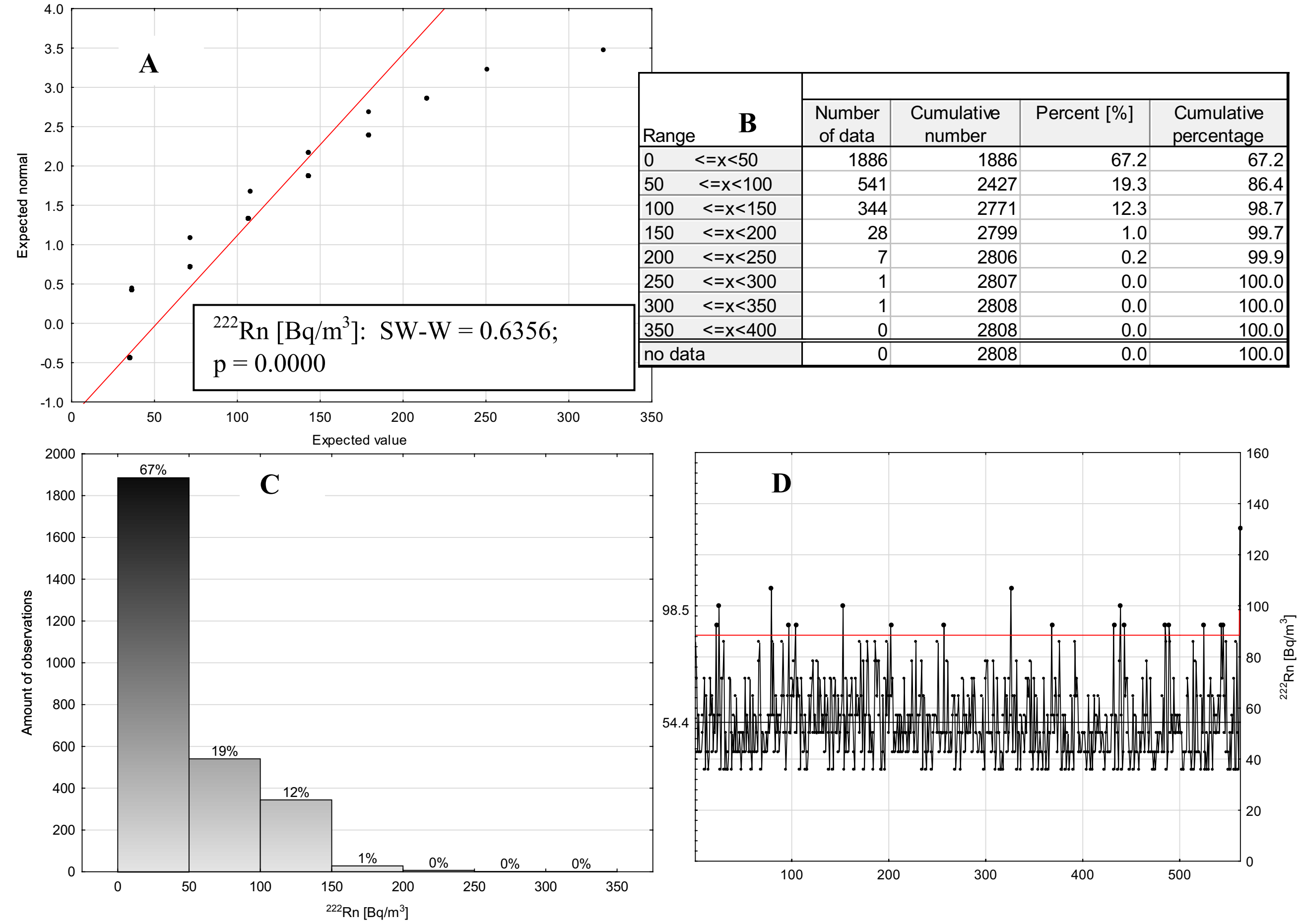



**Fig. 5** A box-and-whiskers plot for $^{222}$Rn activity concentrations recorded within one day during the first (**A**) and the second (**B**) exposure of AlphaE detector

**Table 2** Descriptive statistics for values registered during each hour of measurements during the first and the second exposure of AlphaE sensor. Bold p values are lower than significance level $\alpha = 0.05$; for $p < \alpha$ $H_0$ is rejected in favour of $H_1$. The mode value for exposures 1 and 2 is 35.6 Bq/m$^3$

| Hour (h) | Valid N | | Mean value of $^{222}$Rn (Bq/m$^3$) | | Standard deviation SD (Bq/m$^3$) | | Median value (Bq/m$^3$) | | Shapiro–Wilk test | | | | Skewness factor (−) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of exposure | | | | | | | | 1 | | 2 | | 1 | 2 |
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | SW-W | p value | SW-W | p value | | |
| 1:00 | 56 | 117 | 47.7 | 55.1 | 21.8 | 33.3 | 35.6 | 35.6 | 0.59 | **0.00** | 0.64 | **0.00** | 1.6 | 1.9 |
| 2:00 | 56 | 117 | 54.1 | 53.6 | 31.9 | 28.7 | 35.6 | 35.6 | 0.63 | **0.00** | 0.66 | **0.00** | 2.1 | 1.5 |
| 3:00 | 56 | 117 | 56.0 | 51.8 | 30.3 | 28.7 | 35.6 | 35.6 | 0.70 | **0.00** | 0.62 | **0.00** | 1.3 | 2.0 |
| 4:00 | 56 | 117 | 60.5 | 57.3 | 39.6 | 34.7 | 35.6 | 35.6 | 0.65 | **0.00** | 0.67 | **0.00** | 2.5 | 1.7 |
| 5:00 | 56 | 117 | 63.7 | 58.5 | 47.5 | 38.8 | 35.6 | 35.6 | 0.65 | **0.00** | 0.65 | **0.00** | 2.2 | 1.7 |
| 6:00 | 56 | 117 | 67.5 | 58.2 | 38.3 | 34.3 | 71.2 | 35.6 | 0.79 | **0.00** | 0.69 | **0.00** | 1.0 | 1.7 |
| 7:00 | 56 | 117 | 69.4 | 57.3 | 55.9 | 32.4 | 35.6 | 35.6 | 0.63 | **0.00** | 0.70 | **0.00** | 3.0 | 1.6 |
| 8:00 | 56 | 117 | 50.3 | 58.8 | 30.2 | 38.2 | 35.6 | 35.6 | 0.55 | **0.00** | 0.66 | **0.00** | 2.6 | 1.9 |
| 9:00 | 56 | 117 | 57.9 | 58.5 | 37.6 | 34.6 | 35.6 | 35.6 | 0.64 | **0.00** | 0.69 | **0.00** | 2.3 | 1.6 |
| 10:00 | 56 | 117 | 54.7 | 54.8 | 31.1 | 26.7 | 35.6 | 35.6 | 0.65 | **0.00** | 0.70 | **0.00** | 1.4 | 1.5 |
| 11:00 | 56 | 117 | 53.5 | 53.0 | 33.3 | 28.7 | 35.6 | 35.6 | 0.60 | **0.00** | 0.65 | **0.00** | 2.0 | 1.6 |
| 12:00 | 56 | 117 | 50.5 | 52.4 | 24.5 | 28.3 | 35.6 | 35.6 | 0.65 | **0.00** | 0.64 | **0.00** | 1.7 | 1.6 |
| 13:00 | 56 | 117 | 56.0 | 54.8 | 34.6 | 31.2 | 35.6 | 35.6 | 0.64 | **0.00** | 0.66 | **0.00** | 2.1 | 1.8 |
| 14:00 | 56 | 117 | 59.8 | 53.9 | 34.1 | 38.5 | 35.6 | 35.6 | 0.73 | **0.00** | 0.53 | **0.00** | 1.5 | 3.7 |
| 15:00 | 56 | 117 | 54.7 | 54.2 | 25.4 | 29.8 | 35.6 | 35.6 | 0.72 | **0.00** | 0.67 | **0.00** | 1.3 | 1.7 |
| 16:00 | 56 | 117 | 52.2 | 51.5 | 29.6 | 28.7 | 35.6 | 35.6 | 0.61 | **0.00** | 0.61 | **0.00** | 1.9 | 2.1 |
| 17:00 | 56 | 117 | 54.7 | 52.4 | 28.0 | 33.0 | 35.6 | 35.6 | 0.69 | **0.00** | 0.58 | **0.00** | 1.5 | 2.1 |
| 18:00 | 56 | 117 | 50.9 | 48.1 | 41.3 | 22.6 | 35.6 | 35.6 | 0.43 | **0.00** | 0.59 | **0.00** | 3.4 | 1.6 |
| 19:00 | 56 | 117 | 62.4 | 56.4 | 46.8 | 37.8 | 35.6 | 35.6 | 0.64 | **0.00** | 0.61 | **0.00** | 2.1 | 2.1 |
| 20:00 | 56 | 117 | 57.9 | 49.6 | 38.8 | 26.5 | 35.6 | 35.6 | 0.62 | **0.00** | 0.59 | **0.00** | 2.0 | 1.9 |
| 21:00 | 56 | 117 | 52.2 | 54.5 | 34.7 | 36.2 | 35.6 | 35.6 | 0.52 | **0.00** | 0.58 | **0.00** | 3.1 | 2.9 |
| 22:00 | 56 | 117 | 49.6 | 50.0 | 33.8 | 27.3 | 35.6 | 35.6 | 0.46 | **0.00** | 0.57 | **0.00** | 4.2 | 2.6 |
| 23:00 | 56 | 117 | 47.7 | 52.1 | 27.5 | 31.6 | 35.6 | 35.6 | 0.51 | **0.00** | 0.59 | **0.00** | 2.8 | 2.4 |
| 24:00 | 56 | 117 | 54.7 | 59.1 | 35.3 | 37.8 | 35.6 | 35.6 | 0.60 | **0.00** | 0.67 | **0.00** | 1.8 | 1.6 |




| Range | Number of data | Cumulative number | Percent [%] | Cumulative percentage |
|---|---|---|---|---|
| 0 <=x<50 | 1886 | 1886 | 67.2 | 67.2 |
| 50 <=x<100 | 541 | 2427 | 19.3 | 86.4 |
| 100 <=x<150 | 344 | 2771 | 12.3 | 98.7 |
| 150 <=x<200 | 28 | 2799 | 1.0 | 99.7 |
| 200 <=x<250 | 7 | 2806 | 0.2 | 99.9 |
| 250 <=x<300 | 1 | 2807 | 0.0 | 100.0 |
| 300 <=x<350 | 1 | 2808 | 0.0 | 100.0 |
| 350 <=x<400 | 0 | 2808 | 0.0 | 100.0 |
| no data | 0 | 2808 | 0.0 | 100.0 |

**Fig. 6** Overview of statistical analysis results for $^{222}$Rn activity concentration measurements during the second exposure of AlphaE radon detector: normality plot with Shapiro–Wilk test SW-W (**A**), data frequency tables for each class (**B**), their distribution histogram (**C**) and Shewhart control chart of outliers in the critical region + 3SD (**D**). The central (black) line indicates the mean value of 54.4 Bq/m$^3$. The critical region is delimited by the upper UCL (red) control line (+3SD) equal to 98.5 Bq/m$^3$. The critical region contains 13.5% of the data, regarded as outliers

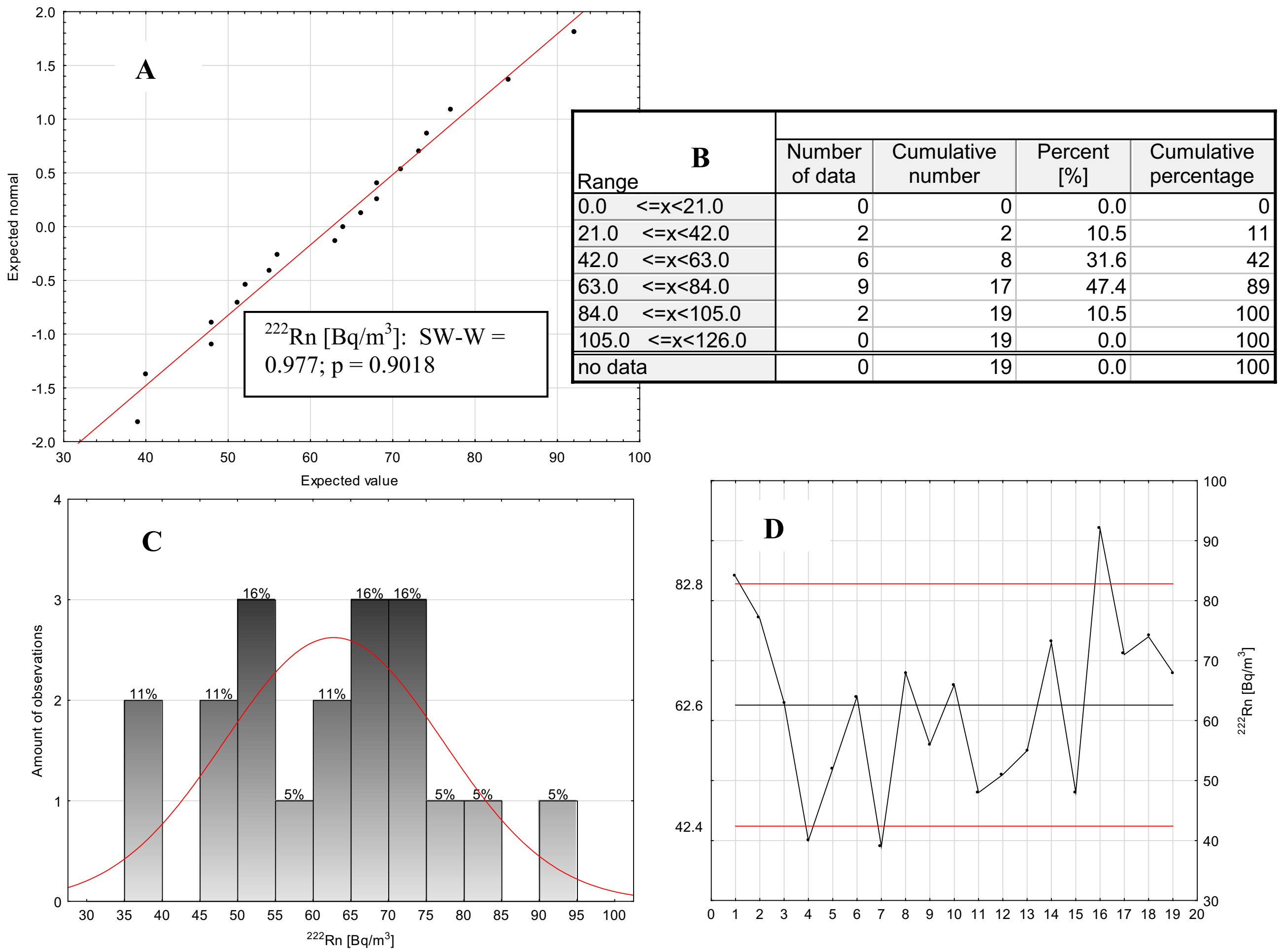
C). $^{222}$Rn activity concentrations of 73.9 Bq/m$^3$ ± 3SD are recorded with a probability of 0.997, and those of 73.9 Bq/m$^3$ ± 2SD—with a probability of 0.95 (Fig. 8C). As many as 10.5% of the data, regarded as outliers, have been assigned to the lower and the upper control limits of 42.4 and 82.8 Bq/m$^3$ respectively (Fig. 7B, D). In the third exposure, the data considered outliers were 15.8% of the results accumulated below the lower (46.7 Bq/m$^3$) and 15.8%—above the upper (101.2 Bq/m$^3$) control limits (Fig. 8B, D).

The results from a 1-h cycle of the second exposure of the AlphaE detector are comparable to those from exposure No. 1 (Fig. 5). The greatest dispersion around the mean is observed early in the morning, from 4 a.m. to 6 a.m., from 8 a.m. to 9 a.m. and in the evening and at night – at 7 p.m., 9 p.m. and 11 p.m. (Fig. 5B). Values exceeding the upper control limit (UCL) are visible at times with the largest dispersion around the mean. No outliers were identified for the remaining time (Table 2).

The ranges of $^{222}$Rn activity concentrations recorded by the AlphaGUARD during 1-h cycles of exposures No. 2 and 3 are comparable (Table 3). The spread of values around the mean in range ± 1δ is observed from 9 a.m. to 11 a.m. (Figs. 9A, B, 10A). During exposure 3 such dispersion lasts longer, i.e. it occurs at 9 a.m. and from 11 a.m. to 12 noon (Figs. 9, 10). A ± 2δ exceedance of the mean value occurred twice: at 10 a.m. during the third exposure and at noon during the second exposure (Figs. 9B, 10B). It has been observed that the mean $^{222}$Rn activity concentration for both exposure times was comparable at 9 a.m. and from 11 a.m. to 12 a.m. (Table 3).

## Track detector CR-39 exposure

Simultaneous exposure of three track detectors was carried out twice. The first lasted from 25 March 2022 to 20 May 2022 and the second one—from the end of exposure




| Range | Number of data | Cumulative number | Percent [%] | Cumulative percentage |
|---|---|---|---|---|
| 0.0 <=x<21.0 | 0 | 0 | 0.0 | 0 |
| 21.0 <=x<42.0 | 2 | 2 | 10.5 | 11 |
| 42.0 <=x<63.0 | 6 | 8 | 31.6 | 42 |
| 63.0 <=x<84.0 | 9 | 17 | 47.4 | 89 |
| 84.0 <=x<105.0 | 2 | 19 | 10.5 | 100 |
| 105.0 <=x<126.0 | 0 | 19 | 0.0 | 100 |
| no data | 0 | 19 | 0.0 | 100 |

**Fig. 7** Overview of statistical analysis results for $^{222}$Rn activity concentration measurements during the second exposure of AlphaGUARD radon detector: normality plot with Shapiro–Wilk test SW-W (**A**), data frequency tables for each class (**B**), their distribution histogram (**C**) and Shewhart control chart of outliers in the critical region ± 3SD (**D**). The central (black) line indicates the mean value of 62.6 Bq/m$^3$. The critical region is delimited by the lower (LCL) and the upper UCL (red) control lines (± 3SD) equal to: 42.4 Bq/m$^3$ and 82.8 Bq/m$^3$. Each range contains 10.5% of data, regarded as outliers

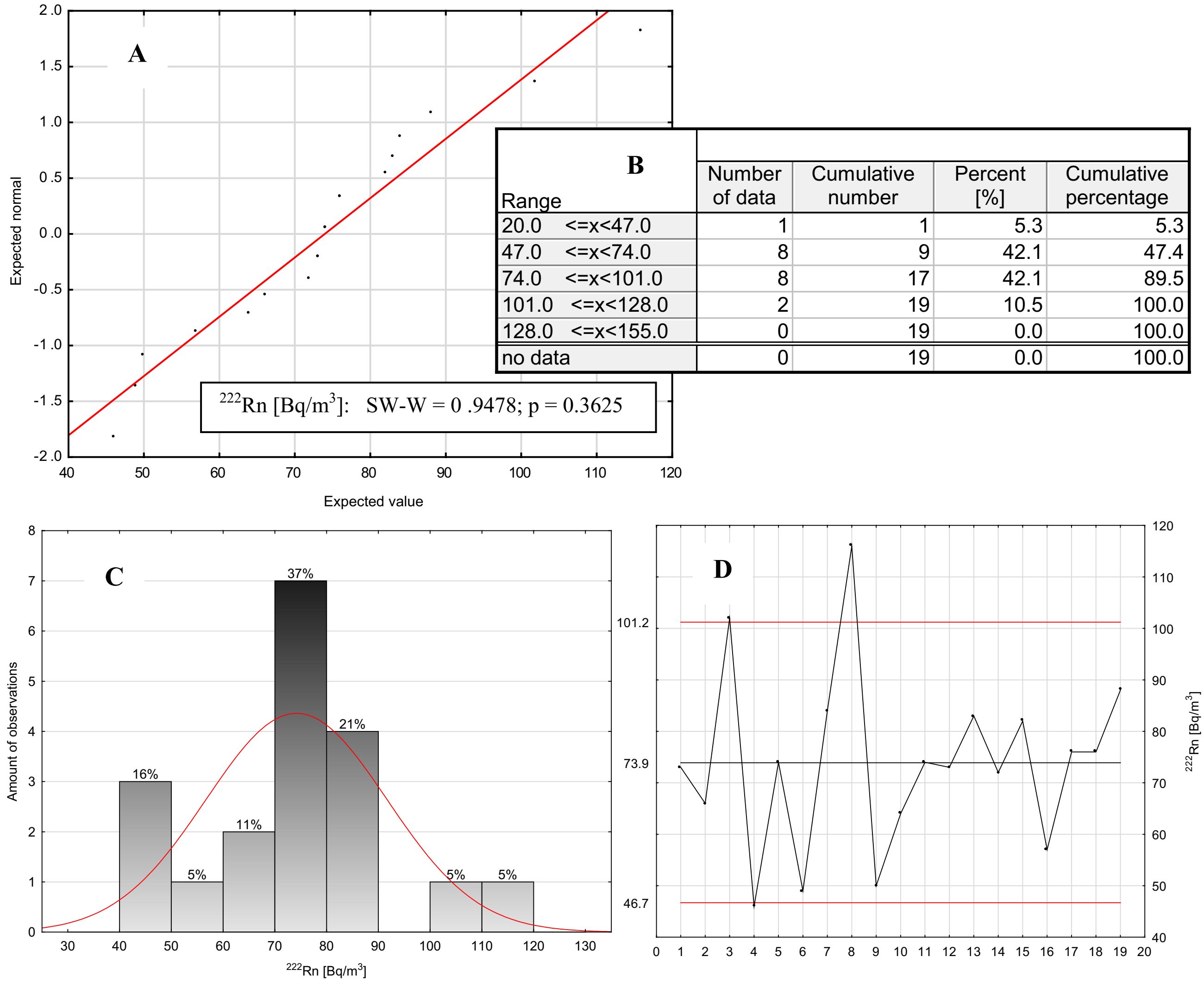
No. 1 to 14 September 2022. They lasted 56 days, i.e. 1344 h and 117 days, i.e. 2808 h respectively. The measurement results for the three detectors in the first exposure showed that successive mean $^{222}$Rn activity concentrations in the technical corridor at the appointed times were 193 ± 32 Bq/m$^3$, 343 ± 47 Bq/m$^3$ and 203 ± 33 Bq/m$^3$. For the second exposure of the detectors placed at the same measurement points as during exposure No. 1, $^{222}$Rn activity concentrations reached 86 ± 15 Bq/m$^3$, 78 ± 14 Bq/m$^3$ and 114 ± 18 Bq/m$^3$. The spread of the measured values for detectors placed at the same measurement points, designated as 1, 2 and 3, is the largest on detector 2 and amounts to as much as 265 Bq/m$^3$, and the smallest – on detector 3 (89 Bq/m$^3$). For detector 1, the spread between the mean $^{222}$Rn activity concentration in the first and the second exposure was 107 Bq/m$^3$.

Because of the insufficient size of the data set, verification of statistical data distribution hypotheses for the CR-39 detectors was not carried out.

## Evaluation of results

Measurement of $^{222}$Rn activity concentration was regarded as a process whose control was based on assessment of variation in $^{222}$Rn activity concentrations obtained within a user-defined duration of a measurement cycle (hour, day, quarter) relative to the results from the reference AlphaGUARD device.

The adopted criterion of measurement result evaluation for each detector was the value of $z$ index in the z-score test, recommended for comparative measurements by the




| Range | Number of data | Cumulative number | Percent [%] | Cumulative percentage |
|---|---|---|---|---|
| 20.0 <=x<47.0 | 1 | 1 | 5.3 | 5.3 |
| 47.0 <=x<74.0 | 8 | 9 | 42.1 | 47.4 |
| 74.0 <=x<101.0 | 8 | 17 | 42.1 | 89.5 |
| 101.0 <=x<128.0 | 2 | 19 | 10.5 | 100.0 |
| 128.0 <=x<155.0 | 0 | 19 | 0.0 | 100.0 |
| no data | 0 | 19 | 0.0 | 100.0 |

**Fig. 8** Overview of statistical analysis results for $^{222}$Rn activity concentration measurements during the third exposure of AlphaGUARD radon detector: normality plot with Shapiro–Wilk test SW-W (**A**), data frequency tables for each class (**B**), their distribution histogram (**C**) and Shewhart control chart of outliers in the critical region ± 3SD (**D**). The central (black) line indicates the mean value of 73.9 Bq/m$^3$. The critical region is delimited by the lower (LCL) and the upper UCL (red) control lines (± 3SD) equal to: 46.7 Bq/m$^3$ and 101.2 Bq/m$^3$. Both ranges contain the total of 15.8% of data, regarded as outliers

**Table 3** Descriptive statistics for values registered during each hour of measurements during three exposures or radon monitor AlphaGUARD PQ 2000PRO

| Hour (h) | Valid N (–) | Mean value of $^{222}$Rn (Bq/m$^3$) | | | Standard deviation SD (Bq/m$^3$) | | | Maximum value (Bq/m$^3$) | | | Shapiro–Wilk test SW-W p | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Exposure | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 9:00 | 2 | 89.5 | 80.5 | 69.5 | 26.2 | 4.9 | 4.9 | 108 | 84.0 | 73 | – | – | – |
| 10:00 | 6 | 77.3 | 54.3 | 78.5 | 29.1 | 12.7 | 28.1 | 115 | 68.0 | 116 | 0.85<br>0.16 | 0.87<br>0.21 | 0.94<br>0.65 |
| 11:00 | 6 | 62.2 | 68.2 | 69.3 | 19.6 | 9.5 | 11.2 | 98 | 73.0 | 83 | 0.86<br>0.19 | 0.92<br>0.51 | 0.92<br>0.51 |
| 12:00 | 5 | 64.4 | 70.6 | 75.8 | 17.7 | 15.7 | 11.6 | 92 | 92.0 | 88 | 0.92<br>0.56 | 0.95<br>0.77 | 0.90<br>0.41 |

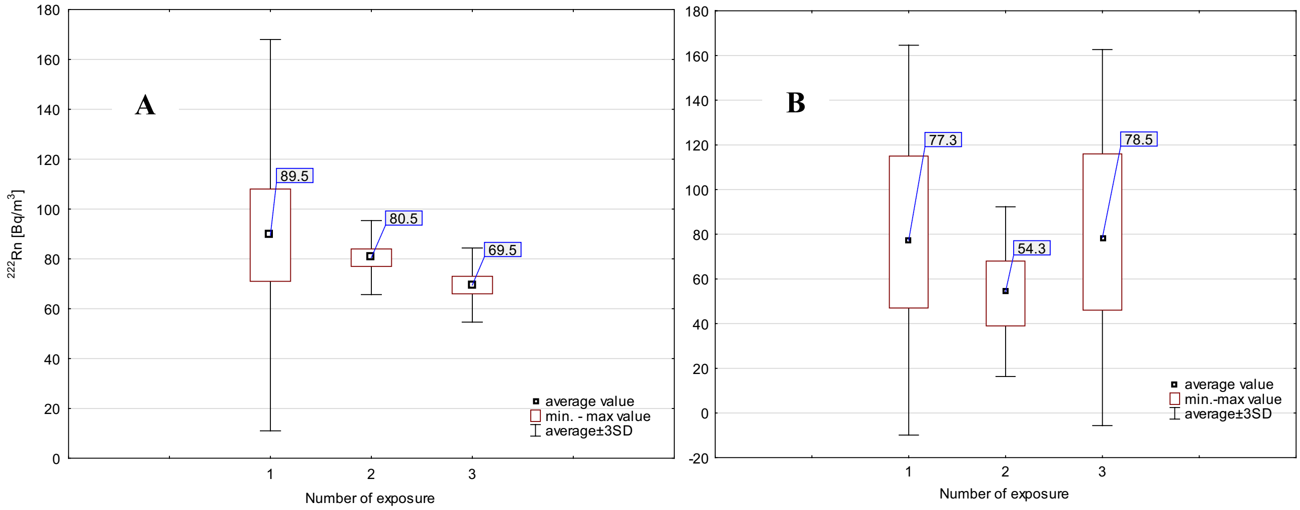



**Fig. 9** A box-and-whiskers plot for $^{222}$Rn activity concentrations registered at 9 a.m. (**A**) and 10 a.m. (**B**) during 3 successive exposures of the reference radon monitor AlphaGUARD on 20 March 2022, 25 March 2022 and 14 September 2022

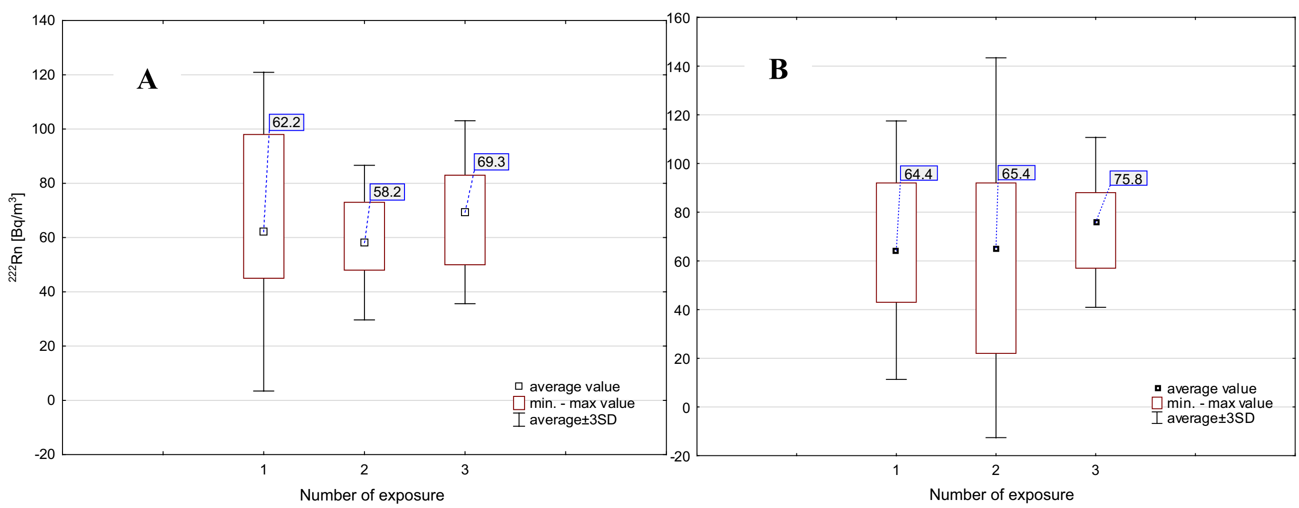



**Fig. 10** A box-and-whiskers plot for $^{222}$Rn activity concentrations registered at 11 a.m. (A) and 12 noon (B) during 3 successive exposures of the reference radon monitor AlphaGUARD on 20 March 2022, 25 March 2022 and 14 September 2022

International Agency of Atomic Energy [5], calculated according to formula (1):

$$z = \frac{x_i - x_{\mathrm{ref}}}{U_{\mathrm{ref}}} \tag{1}$$

where $x_i$—mean result from a single detector; [Bq/m$^3$], $x_{ref}$—mean reference value of $^{222}$Rn radioactive activity concentration registered by the AlphaGUARD; [Bq/m$^3$], $U_{ref}$—expanded uncertainty of the reference $^{222}$Rn radioactive activity concentration for the AlphaGUARD (coverage factor k = 2 corresponding to confidence level 0.05α); [Bq/m$^3$].

The determined absolute value of $z$ index enables determining result acceptability expressed in 3 degrees: satisfactory ($|z| \leq 2$), uncertain ($2 < |z| < 3$) or unsatisfactory ($|z| \geq 3$). The obtained results of $z$ index are represented by "+" indicating a satisfactory result, "±"—an uncertain but acceptable result, or "–"—an unsatisfactory assessment of measurement result (Table 4).

A comparison using a z-score test was also carried out for semiconductor detector exposures in a 1-day cycle (Table 5). The authors used unchanged evaluation criteria, where, according to formula (1), the mean $x_i$ value, the reference $x_{ref}$ value and the expanded uncertainty $U_{ref}$ referred to the mean value at a given measurement time for a single detector, the

**Table 4** The results of z-score test of detector exposure during the whole measurement period. Satisfactory result ( ), uncertain but acceptable result (±), unsatisfactory result (−). The z-values have been rounded to integer numbers

| Value of z indicator \|z\| | | | | |
|---|---|---|---|---|
| Radon detector | Exposure no. 1 | Exposure no. 2 | Score evaluation | |
| | | | Exposure no. 1 | Exposure no. 2 |
| AlphaE | 2.0 | 1.0 | + | + |
| SRDN-3a | 3.0 | comparable to exposure 1 | ± | ± |
| CR-39 no. 1 | 11.0 | 3.0 | − | + |
| CR-39 no. 2 | 25.0 | 1.0 | − | + |
| **CR-39 no. 3** | 12.0 | 6.0 | − | − |

**Table 5** The results of z-score of detector exposure in a 1-day cycle with a 1-h interval. Satisfactory result (+), uncertain but acceptable result (±), unsatisfactory result (−). The z-values have been rounded to integer numbers

| Value of z indicator \|z\| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Radon detector | | Hour (h) | Exposure no. 1 | | Exposure no. 2 | Score evaluation | | |
| | | | | | | Exposure no. 1 | | Exposure no. 2 |
| AlphaE | SRDN-3a | 01:00 | 3.0 | 3.0 | 1.0 | ± | ± | + |
| | | 02:00 | 2.0 | 4.0 | 2.0 | + | − | + |
| | | 03:00 | 2.0 | 3.0 | 2.0 | + | ± | + |
| | | 04:00 | 1.0 | 3.0 | 1.0 | + | ± | + |
| | | 05:00 | 1.0 | 3.0 | 1.0 | + | ± | + |
| | | 06:00 | 1.0 | 3.0 | 1.0 | + | ± | + |
| | | 07:00 | 1.0 | 3.0 | 1.0 | + | ± | + |
| | | 08:00 | 2.0 | 3.0 | 1.0 | + | ± | + |
| | | 09:00 | 2.0 | 3.0 | 1.0 | + | ± | + |
| | | 10:00 | 2.0 | 3.0 | 1.0 | + | ± | + |
| | | 11:00 | 2.0 | 3.0 | 2.0 | + | ± | + |
| | | 12:00 | 2.0 | 3.0 | 2.0 | + | ± | + |
| | | 13:00 | 2.0 | 2.0 | 1.0 | + | + | + |
| | | 14:00 | 1.0 | 2.0 | 2.0 | + | + | + |
| | | 15:00 | 2.0 | 3.0 | 2.0 | + | ± | + |
| | | 16:00 | 2.0 | 4.0 | 2.0 | + | − | + |
| | | 17:00 | 2.0 | 2.0 | 2.0 | + | + | + |
| | | 18:00 | 2.0 | 2.0 | 2.0 | + | + | + |
| | | 19:00 | 1.0 | 3.0 | 1.0 | + | ± | + |
| | | 20:00 | 2.0 | 3.0 | 2.0 | + | ± | + |
| | | 21:00 | 2.0 | 3.0 | 1.0 | + | ± | + |
| | | 22:00 | 2.0 | 3.0 | 2.0 | + | ± | + |
| | | 23:00 | 3.0 | 3.0 | 2.0 | ± | ± | + |
| | | 00:00 | 2.0 | 3.0 | 1.0 | + | ± | + |

reference AlphaGUARD device and its expanded uncertainty (k = 2) respectively.

The assessment results are comparable and explicitly point to the absence of discrepancies between $^{222}$Rn activity concentrations recorded by the AlphaE detector and the reference values. The results for the SRDN-3a probe are somewhat worse, as the obtained values of $z$ index lie in the region "uncertain but acceptable" (Tables 4, 5). An unsatisfactory value of |z| index as compared to the reference value was recorded for the three CR-39 track detectors during the first exposure. Among the three results from the second exposure, one was unsatisfactory and two—satisfactory (Table 4). The large result variation for track detectors with comparable exposure periods may be due to various numbers of readings of tracks registered on the detector, as well as to mechanical contamination of the detector. It this case the differences should be also related to the seasonal variability of radon activity concentrations observed in residential buildings (basement and ground floor) worldwide [26–28]. However, the most frequently observed regularity is the occurrence of higher radon concentrations in rooms during the colder seasons (related to the first exposure period), while the minimum values are recorded in the warmer periods (related to the second exposure period). This phenomenon is mainly due to the thermal chimney effect. The warm air inside rises towards the upper floors, simultaneously sucking radon from cracks in the concrete screed, foundations, walls damage, and various leaks. It is possible that the occurrence of seasonal variability of radon activity concentration in buildings [26, 29] may also cause differences in the results of measurements performed using passive detectors during this study. The second, this effect could be associated with the so-called transitional periods occur mainly in April and October. The consequence of a noticeable difference between the internal and ambient temperature is intensive ventilation of facility. When the temperatures of the atmospheric air and the air inside an space are similar, natural air movement is impeded, and ventilation less efficient. Equally important is considerable natural or man-made insulation of these spaces from the influence of the atmosphere and external conditions. This translates into a virtually constant annual temperature: 7–8 °C in technical corridor. As a consequence of variable thermal conditions, air exchange between the space interior and the atmosphere decreases in the summer, and increases in the colder seasons. This process is very well known in underground objects in Poland [25, 30].

To assess the measurement accuracy of devices in relation to each other 2 components A and B were determined. The A component was described using data from Eq. (1) and B with the value of formula (2): The result of the z-test assessment is considered acceptable (satisfactory) when the value of A is less than or equal to the value of B.

$$\left| x_i - x_{ref} \right| \tag{2}$$

where $x_i$—mean result from a single detector; [Bq/m$^3$], $x_{ref}$—mean reference value of $^{222}$Rn radioactive activity concentration registered by the AlphaGUARD reference detector; [Bq/m$^3$], $U_{ref}$—expanded uncertainty of the reference $^{222}$Rn radioactive activity concentration for the AlphaGUARD (coverage factor k = 2 corresponding to confidence level 0.05α); $U_{eq}$—expanded uncertainty of the reference $^{222}$Rn radioactive activity concentration for the AlphaGUARD detector (coverage factor k = 2 corresponding to confidence level 0.05α); [Bq/m$^3$], and B with the value of formula (3):

$$2.58\sqrt{U_{ref^2} + U_{eq^2}} \tag{3}$$

The obtained results are satisfactory for the AlphaE detector and the SRDN-3a radon probe (the value of A < B) in relation to the values from the reference device for both exposures, as well as to those from the CR-39 track detectors in the second exposure. Results closest to the reference values were obtained from the second exposure measurements by the AlphaE detector. The results from the third exposure of the reference device were compared with the results of measurements by the AlphaE from both measurement campaigns. The obtained results produced the same result consistency. Such a result of the comparison could have been expected as AlphaGUARD devices are very well calibrated and the AlphaE device had been calibrated using the AlphaGUARD as the reference instrument.

## Conclusions

The first test checking the usefulness and operation correctness of devices used to measure $^{222}$Rn activity concentration in workplaces produced concordant results for two measurement methods and techniques. The reference level used for both comparisons was obtained from measurements with an AlphaGUARD radon monitor in successive exposures. The place selected for the experiment was a hydrotechnical structure well isolated from the impact of weather conditions by reinforced concrete casing and with known character of service staff work—average activity of 2 h a week.

A parallel measurement campaign using devices for short-time measurements enabled identifying the similarities and differences between currently used measurement methods and techniques. Routine measurements aimed only at producing the result necessary to define the mean annual level of radon activity concentration can be carried out for a period of at least 1–3 days in every data recording cycle using screening measurement detectors, or a quarter of a year using a passive measurement technique. Track detectors, unlike semiconductor detectors, do not provide a full picture of temporal distribution of $^{222}$Rn activity concentration in a facility. Their application for presenting changes in a seasonal cycle is possible when 3-month-long measurements are conducted for at least a year. The conducted tests showed that due to a possibility of obtaining a large spread of results in two different measurement periods (2 months, 3 months), it would be best to set the time of one measurement to a minimum of 3 months in a mode with at least 1 repetition or, to verify the result, conduct parallel measurements using another CR-39 detector.

The obtained comparable numbers of outliers prove the stability of the measurement process for each detector. Their share in the result set was over 13.0% for 1344 data and 13.5% for 2808 data from the AlphaE detector, and nearly 10% for the SRDN-3a radon probe. The reference AlphaGUARD device recorded 15.8% outliers both in the 1st and the 3rd exposure, and only 10.5% in exposure no. 2.

The measurements performed in two cycles for a total duration of 4152 h demonstrate that the AlphaE device combines the advantages of devices dedicated to short-time and monitoring measurements at a moderate cost. It also enables detection of relatively low (from 20 Bq/m$^3$) values of $^{222}$Rn activity concentration. It can be an interesting alternative to all the other tested detectors, providing that it operates for a minimum of 1–3 days during screening measurements, and preferably for at least 3 months during long-term measurements.

According to the manufacturer, measurement error of the AlphaE detector is 10%. In the authors' opinion, the significant comparability of results from the AlphaE detector and those from the SRDN-3a radon probe confirms its underestimation. Both devices using semiconductor detectors register a small number of pulses for low values of $^{222}$Rn activity concentration. The authors believe that when operating in concentrations lower than 100 Bq/m$^3$, measurement error of a minimum of 20% should be considered appropriate. In order to determine the real uncertainty, the AlphaE device should be calibrated at radon concentrations changing within the whole range of values to which the instrument is dedicated, i.e. from c. 10 to 10$^6$ Bq/m$^3$.

Considering the high reliability (accuracy) of measurements in the conducted exposures, all the tested detectors can be widely used in both routine and scientific measurements. If, apart from providing the average result, measurements are also aimed at indicating the detailed range and character of changes in the registered concentration, it is best to choose active measurement techniques. From the user (company manager / client) perspective, measurement using screening detectors is simpler, enables continuous monitoring of $^{222}$Rn activity concentration, but it is also more expensive. On the other hand, although measurement using track detectors does not allow previewing the results while the measurements continues, it does not entail such big costs connected with purchasing the equipment. Therefore it is much cheaper and hence it will be better-suited for commercial measurements.

## Contributions

Lidia Fijałkowska-Lichwa is the leader of a research project including the conducted research. She is the author of the idea and in order to implement it, she gathered and collated the suitable data obtained from the conducted measurements. She performed the statistical analyses of these data and interpreted their results. She also created the material illustrating the performed calculations and analyses. Tadeusz A. Przylibski and Piotr Maciejewski were responsible for preparing the contents of AlphaGUARD monitor - the reference instrument. Piotr Maciejewski conducted measurements using the AlphaGUARD device and processed them to enable their comparison with the results from the remaining detectors. Maciej Norenberg was responsible for CR-39 track detectors. He also etched the track detectors and read the measurement results obtained by using them. The authors edited the text, and read and approved the final manuscript.

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**Data availability** All relevant data and materials are presented in the paper.

## Declarations

**Conflict of interest** The authors state that there are no conflicts of interest regarding the publication of this article and that there are no financial ties to disclose.

**Ethical approval** Not applicable.

**Informed consent** Consent for publication was obtained.



## References

1. EU Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation and repealing. Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/ Euratom. Official Journal of The European Union. 17.1.2014, L 13/1–L 13/73
2. Atomic Law of 29 November 2000 R. Atomic Law–Journal of Laws (2021) item 1941 [in Polish]
3. Chief Sanitary Inspector (GIS) Report (2021) Good practices for methods of measuring radon activity concentration in workplaces, buildings, rooms and spaces intended for human residence 1–33 Warszawa [in Polish]

4. Minister of Health Announcement of 22 January 2021 concerning the National action plan in case of long-term hazards arising from exposure to radon in buildings intended for human residence and in workplaces. Monitor Polski. (2021) item 169 [in Polish]
5. IAEA - International Atomic Energy Agency (2007) Report on the IAEA-CU-2006–03 World-wide open proficiency test on the determination of gamma emitting radionuclides Vienna
6. IAEA - International Atomic Energy Agency (2014) Radiation protection and safety of radiation sources: International Basic Safety Standards General Safety Requirements Part 3 No. GSR Part 3 Vienna
7. ICRP - International Commission On Radiation Protection (2011) Lung Cancer Risk from Radon and Progeny ICRP Publication 115 Ann
8. ICRP - International Commission On Radiation Protection (2014) Radiological protection against radon exposure ICRP Publication 126 Ann ICRP 43(3)
9. ICRP - International Commission On Radiation Protection (2017) Occupational Intakes of Radionuclides: Part 3 ICRP Publication 137 Volume 46 No. 3/4
10. Regulation of the Minister of Health of 18 June 2020 concerning areas where mean annual radioactive radon concentration in the air inside a large number of buildings may exceed the reference level. Journal of Laws 2020 item 1139 [in Polish]
11. Chałupnik S, Skubacz K, Wysocka M, Mazur J, Bonczyk M, Kozak K, Grządziel D, Urban P, Tchorz-Trzeciakiewicz D, Kozłowska B, Walencik-Łata A, Podstawczyńska A, Olszewski J, Bartak J, Karpińska M, Wołoszczuk K, Dohojda M, Nowak J, Długosz-Lisiecka M, Foerster E, Przylibski TA (2020) Radon intercomparison tests–Katowice 2016. Nukleonika 65(2):127–132. https://doi.org/10.2478/nuka-2020-0020
12. Mamont-Cieśla K, Stawarz O, Karpińska M, Kapała J, Kozak K, Grządziel D, Chałupnik S, Chmielewska I, Olszewski J, Przylibski TA, Żebrowski A (2010) Intercomparison of radon CR-39 detector systems conducted in CLOR's calibration chamber. Nukleonika 55(4):589–593
13. Podgórska Z, Wołoszczuk K (2018) Report on comparative measurements of atmospheric radon concentration with passive detector method. Central Laboratory for Radiological Protection Warszawa [in Polish]
14. Wołoszczuk K, Norenberg M (2022) Report on interlaboratory comparison measurements of atmospheric radon concentration. 1–10 Warszawa [in Polish]
15. www.gov.pl/web/gis 19.10.2022
16. Błachuta J, Jelonek M, Panasiuk D, Roggenbuck A, Udolf J, Wawręty R, Zając K, Żelaziński J (2006) Dams and floods. A report by the Society for the Earth and the Polish Green Network. Published as part of "Monitoring of selected dams and regulation of rivers and streams" project ISBN 83–60106–04–5 [in Polish]
17. Kowal A (1991) Treatment of water from Dobromierz reservoir. Environment protection 1(42):35–38 (**[in Polish]**)
18. https://www.bertin-technologies.com/product/radon-professional-monitoring/radon-alphaguard/ 25.01.2023
19. Calibration certificate of AlphaE detector S/N AE001330 (2021) Frankfurt
20. AlphaE Producer's manual Bertin Technologies (2020) 1–40 [in German]
21. Hadler NJC, Iunes PJ, Osorio AAM, Paulo SR (1991) Relationship between track size and energy for alpha particles in CR-39. International Journal of Radiation Applications and Instrumentation Part D Nuclear Tracks and Radiation Measurements 19:313–318
22. Olszewski J (2019) Assessment of occupational hazard due to exposure to radon in underground tour routes and spas. Habilitation monograph. Institute of Occupational Medicine in Łódź. Radiological Protection Department 1–61 Łódź [in Polish]
23. http://www.ichtj.waw.pl/drupal/?q=node/13 25.01.2023
24. Przylibski TA, Bartak J, Kochowska E, Fijałkowska-Lichwa L, Kozak K, Mazur J (2010) New SRDN–3 probes with a semiconductor detector for measuring radon activity concentration in underground spaces. J Radioanal Nucl Chem 289:599–609
25. Fijałkowska-Lichwa L, Przylibski TA (2011) Short-term $^{222}Rn$ activity concentration changes in underground spaces with limited air exchange with the atmosphere. Nat Hazard 11:1179–1188
26. Karpińska M, Mnich Z, Kapała J (2004) Seasonal changes in radon concentrations in buildings in the region of northeastern Poland. J Environ Radioact 77(2):101–109. https://doi.org/10.1016/j.jenvrad.2004.02.005
27. Kellenbenz KR, Shakya KM (2021) Spatial and temporal variations in indoor radon concentrations in Pennsylvania, USA from 1988 to 2018. J Environ Radioact. https://doi.org/10.1016/j.jenvrad.2021.106594
28. Baltrenas P, Grubliauskas R, Danila V (2020) Seasonal variation of indoor radon concentration levels in different premises of a university building. Sustaiability 12:61–74. https://doi.org/10.3390/su12156174
29. Al-Ghamdi SS (2014) Seasonal and location dependence of indoor and soil radon concentrations in two villages, Najran region Saudi Arabia. Radiat Meas 69:12–17. https://doi.org/10.1016/j.radmeas.2014.07.020
30. Fijałkowska-Lichwa L, Przylibski TA (2022) Monthly and quarterly correction factors for determining the mean annual radon concentration in the atmosphere of underground workplaces in Poland. Environ Geochem Health. https://doi.org/10.1007/s10653-022-01280-2