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Annual observations of radon activity concentrations in dwellings of Silesian Voivodeship

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Abstract. In the paper, results of year-long measurements of radon levels in dwellings on the premises of Silesian Voivodeship are presented. Track etched detectors with polymer CR-39 foils were used in the investigations. As the studied buildings were located in different regions of Silesian Voivodeship, therefore results of measurements were analysed due to possible influence of geological structure or effect of mining operations in places, where given dwellings were situated. Elevated concentrations of radon were measured mostly in dwellings located in areas, where permeable Triassic limestone and dolomite occur, as it has been predicted. On the other hand, the impact of mining activity such as disintegration of rock-body and activation of faults plays an important role, too, because it enables radon migration and its entry into buildings. Beside the analysis of seasonal variations of radon activity concentration, the impact of temperature and pressure on these fluctuations outdoor and indoor buildings has been analysed.

Key words: radon • apartment buildings • geology • seasonal changeability

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Introduction

Geological structure of the studied area

A factor, which has a decisive impact on the radon concentration in buildings, is geological structure of the studied areas [1, 2, 6–8, 10, 11, 13, 14]. Upper Silesian Coal Basin (USCB), the geological unit, within which the investigations were performed, in large part agrees with the area of Silesian Voivodeship, being an administrative unit of the country (Fig. 1). The mining activity in this region has been carried out for more than 200 years; the oldest coal-mine dating from 1740. Presently, there are 31 underground coal mines which extract approximately 96×10^6 tons of coal per year. About 10 000 miners were employed at the end of 2009.

The Upper Silesia Coal Basin was formed during the Variscan orogeny and rejuvenated during the Alpine [3]. Geological structure of USCB is complicated and differentiated. The Carboniferous rocks are overlain by younger deposits ranging from Permian to Quaternary. Permian, Triassic and Jurassic strata are of erosional character. These deposits form isolated remnants from larger entities, while the younger Tertiary and Quaternary series were deposited under continental conditions [3].

In the area of investigations faults and other features activated by mining operations occur that can give high levels of radon in soil gas, often resulting from the enhanced permeability in fault zones. Unless Triassic limestone with karstic development are involved, the

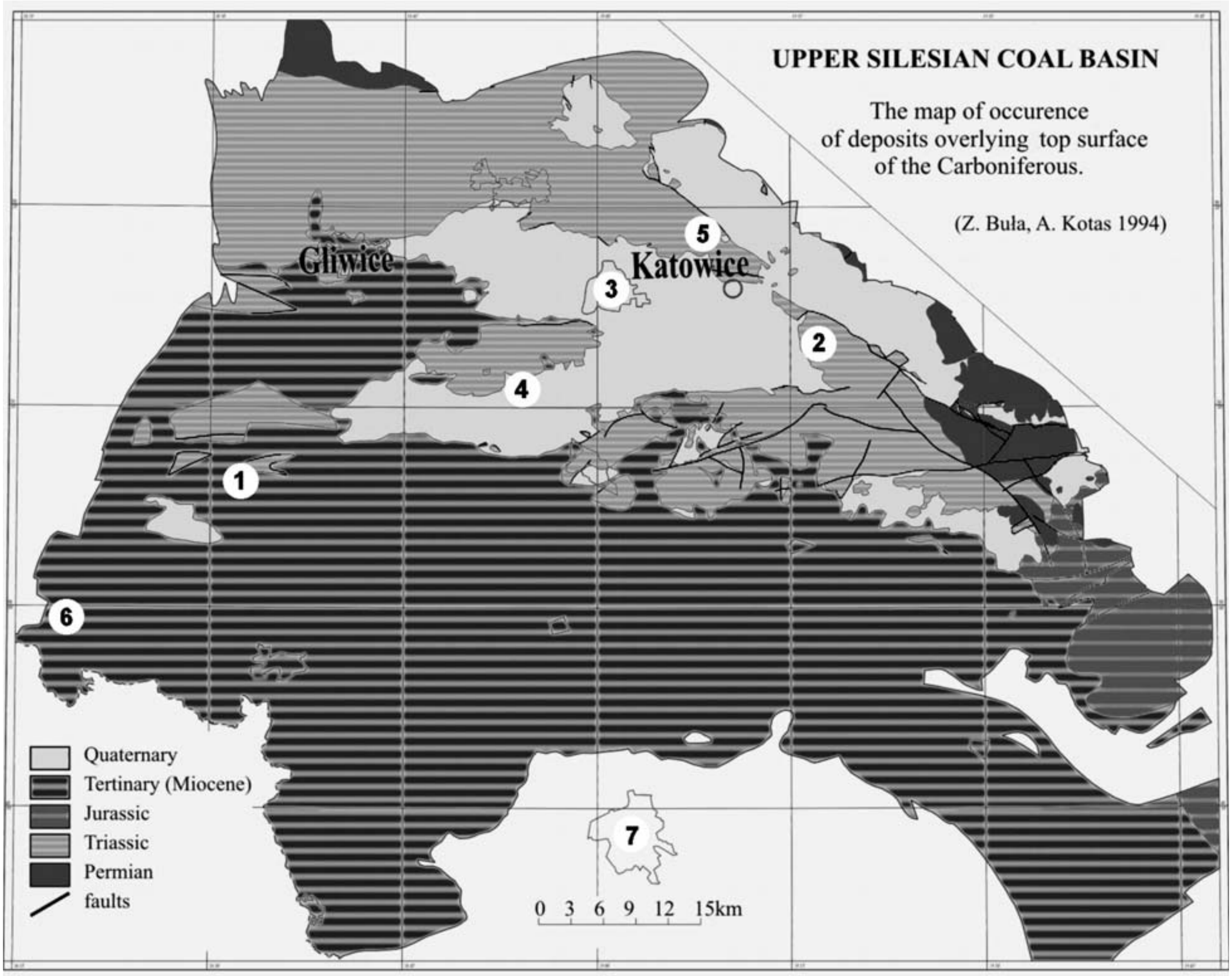

Fig. 1. Location of the investigated dwellings on the structural geological map of USCB.

bulk of the radon in soil gas is a combination of that generated locally in the soil with that generated at shallow regions from the substrate. The depth of generation of recognizable depths is seldom greater than 5 m and at extremes 10 m.

On the tectonic structural map of the Carboniferous [3] the locations of the investigated dwellings are shown (see Fig. 1).

Houses, in which the measurements were performed, are located in different parts of the USCB with diverse geological structures:

1. **Rybnik (Chwałowicka Trough) – 8 buildings, (G2÷G9, G22).** At the Rybnik area, the Carboniferous rocks are overlain by younger deposits ranging from Triassic to Quaternary. Triassic strata are of erosional character. These deposits form isolated remnants from larger entities, often fault bounded [4]. The younger Tertiary and Quaternary series were deposited under continental conditions, and are undisturbed by faults and occur as continuous layers [3]. Unconsolidated Quaternary deposits – boulder clay with interlayer of gravels, stones and sands enable gas emanation and penetration.
2. **Jaworzno (Wilkszyńska Trough) – 12 buildings, (G10÷G21).** At the Jaworzno area, Triassic strata were laid down over the Carboniferous. Triassic limestone and dolomitic limestone occur in the form of outcrops on the surface. The zones of karst process development are very frequently observed that enable gas emanation and migration.
3. **Katowice (Main Saddle) – 4 buildings, (U1÷U4).** Main saddle, within which Katowice is located, is complicated anticline structure, cut with numerous faults, interpenetrating with continuous dislocations. In the area, Carboniferous is overlain by a thin layer of Quaternary sediments: clays, sands and gravels. In some places, Carboniferous series occur in form of outcrops on the surface. Within the saddle, some mines are operating. Results of mining impact, such as disintegration of subsurface layers, activation of fault zones, as well as damages of buildings, ease radon migration and penetration [14]. Studied buildings are situated above the fault zone, in the region of intensive mining exploitation.
4. **Mikołów (Main Trough) – 1 building, (U8).** Main Trough, the biggest structure, located in the central part of the basin. The major faults trend E-W. The Carboniferous rocks are overlain by younger deposits: Neogen and Quaternary. Neogen is represented by Miocene rocks, which are mostly clay rich and are relatively impermeable, thus restricting the flow of ground gases.
5. **Czeladź (Bytomska Trough) – 1 building, (G1).** In the area of Bytomska Trough, Carboniferous strata are overlain by Triassic deposits. The major problems arise from the presence of Triassic limestones

Table 1. Statistical values characterizing concentration of radon activity in 32 studied houses of Silesian Voivodeship for 1 year (calculations for monthly and quarterly concentrations). Calculations were made with the use of the program Statistica <www.StatSoft.com>

Radionuclides/period	Min	Max	Average	Median	I quarter	III quarter	Skewness
^{222}Rn [Bq/m^3]/month (384 results)	5	1100	128	94	57	165	3.5
^{222}Rn [Bq/m^3]/quarter (128 results)	15	711	113	90	53	128	3.2

where buildings often show high radon concentrations. These dolomitic limestones (the equivalent of the ore-bearing Muschelkalk) as well as being karstified, have an induced permeability resulting from lead and zinc mining from within the carbonate rocks, and fracturing from subsidence from the sub-Mesozoic coal mining.

6. **Buków (in south-west part of the Basin) – 3 buildings, (U5÷U7).** In the geologic cross section Carboniferous, Neogene and Quaternary strata are present. The rocks are clay reach and relatively impermeable for fluids.
7. **Two studied buildings are situated outside the Coal Basin, at Bielsko-Biała within the Outer Flysch Carpathian, (U9, U10).** Bielsko-Biała is located within the Polish Outer Flysch Carpathians. This massif is built of typical thick-bedded sandstone underlay by thin-bedded flysch. Numerous cracks, fractures and faults are observed [5].

Measurement methods

Measurements of radon concentration in USCB buildings were performed by means of track detectors. There were three detector types used in the studies: Hungarian type RSFS, British KfK and Swedish SSI. Detailed information about particular type of detector, its traceability and reproducibility can be found in the Ref. [9].

The list below presents studied sites and the detector type used:

1. Katowice – KfK, SSI;
2. Rybnik – RSFS;
3. Jaworzno – RSFS;
4. Czeladź – RSFS;
5. Buków – KfK, SSI;
6. Bielsko-Biała – KfK, SSI;
7. Mikołów – KfK, SSI.

All detectors consisted of the diffusive chamber, in which a CR-39 foil is placed. The detector element uses the CR-39 foil, which registers the alpha particle tracks from the decay of radon and its daughter products. Afterwards, in the laboratory, the detectors were etched in 25% sodium hydroxide in order to enlarge size of tracks left on them by alpha particles. Then, based on number of tracks, radon concentration was calculated. The usage of track detectors comprises of an integrated method, which shows the average value of radon concentration over the exposition period.

Measurements were performed for 12 months, from March 2008 to February 2009. In each building three parallel detectors were exposed monthly and quarterly. The results are presented as an arithmetical average from all single detectors. The uncertainties for each average value are characterized by a standard deviation counted for three parallel measurements.

Results

Table 1 presents the statistical calculations for radon concentration activity in the studied 32 houses of Silesian Voivodeship for over 1 year. Activity concentrations were calculated on the basis of three simultaneously taken measurements in monthly and quarterly time mode. Monthly concentrations of ^{222}Rn varied from 5 ± 11 Bq/m^3 to 1100 ± 110 Bq/m^3 with an average value equal to 128 Bq/m^3, and median (central value, above and below of which there is an equal number of observations) 94 Bq/m^3. Quarterly value of ^{222}Rn concentration varied from 15 ± 4 Bq/m^3 up to 711 ± 85 Bq/m^3, with an average value of 113 Bq/m^3 and median 90 Bq/m^3.

Within term 1998–2008 over 1000 measurements were performed all over USCB, with a mean value equal to 46 Bq/m^3 [14, 15]. In the recent research (March 2008 – February 2009), the obtained averaged outcomes are by far higher than 46 Bq/m^3. It is worth of being emphasized that the average values as well medians for the presented measurements correspond closely to the measurements performed in shorter (monthly) and longer (quarterly) periods, what indicates the correctness of performed measurements, as well as good quality of the detectors (Table 1).

In Table 1, the values of bottom (I) as well as the upper (III) quartile were presented. For these values 25% of observations have values below the bottom quartile, and 25% above the upper quartile. A skewness coefficient was also presented, showing either close relation or not with a given distribution to the normal distribution.

Figures 2a and 2b illustrates the monthly and quarterly average results obtained for seven selected houses laying in an area of Silesian Voivodeship with different geology. As it can be seen from the figure, ^{222}Rn concentrations for all the houses, with exception of the house coded as U4 from the Katowice area, are much the same. Monthly values indicate a rise of concentration during winter months, started from December 2008, what can be clearly noticed on the graph for individual houses. Also results from the last quarter show a gradual increase in concentration, including December 2008, as well as January and February 2009.

The clear seasonal variation in radon concentration in dwellings was noticed here. In most of buildings, maximal radon concentration was measured in winter months, while minimal in summer. This is caused by the intensive ventilation of rooms in summer months. As an example might be a house G11 at Jaworzno, presented in Fig. 3a.

In one case (house U4), a reverse seasonal correlation was observed (Fig. 3b). In the building U4 in Katowice, the highest radon concentrations were measured. It has been noticed, that from May concentration of gas grew, achieving a maximum value in August, then

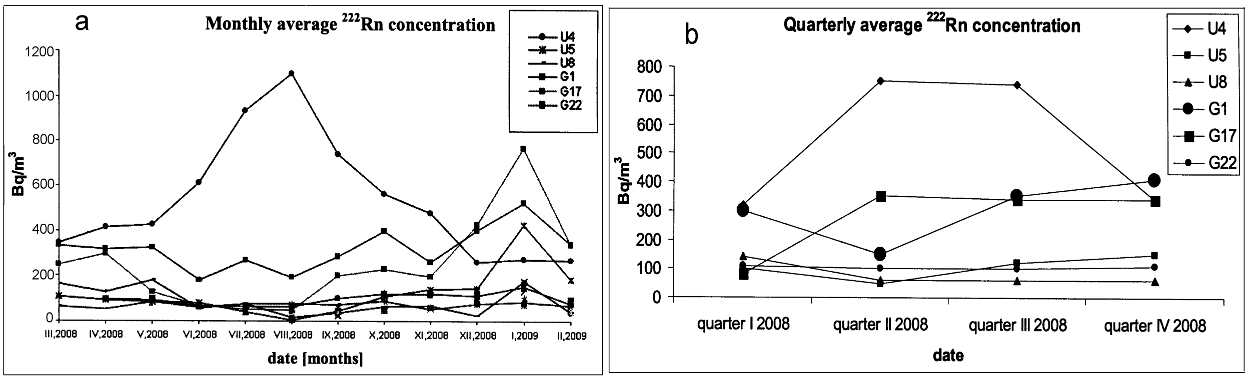

Fig. 2. The average results of ^{222}Rn activity concentration: a – monthly; b – quarterly for seven selected houses in the area of Silesian Voivodeship.

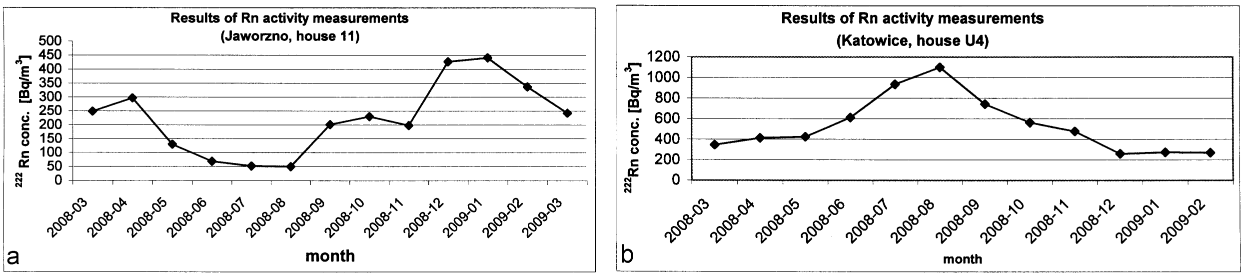

Fig. 3. Results of measurements of radon activity concentration for: a – "typical" residential house; b – house with unnatural behavior of inhabitants.

decreased to December, and became stabilized on the lowest level. One of the reasons why reversal trend of seasonal changes in radon concentration happened there, might be the specific behavior of inhabitants of this particular building. The most probable explanation seems to be connected with the holiday season. Inhabitants left their house without ventilation over a longer time. Insufficient ventilation caused an increase of radon concentration. In nearby houses, such character of seasonal changes in radon concentration was not observed. Therefore, this phenomenon cannot be connected with, for example, particular mining activity as it is observed in this part of town.

Figures 4a and 4b presents the graphs of accumulated probability for normal distribution. The probability was obtained for the value of radon concentration in each house during monthly and quarterly periods. From the graphs, it can be clearly seen that obtained plots do not show the character of normal distribution, and, therefore, they are not symmetrical distributions. The distributions show asymmetrical, a long right-side "tail" indicating, at some numbers, of considerably larger than average value cases. This is confirmed by a coefficient of asymmetry (skewness), which for normal distribution is equal to 0. However, for the obtained data it is equal to 3.5 for monthly distributions and 3.2 for the quarterly ones. The fact that the character of the distribution is not normal is not surprising because results were gathered for all houses through all the year. This can also clearly be seen on different type of "box whiskers graph" (Figs. 5a and 5b). On the right-side of the graphs, a range of not-outstanding results is presented, within "whiskers", however, the values out of them are defined as outstanding or even extreme.

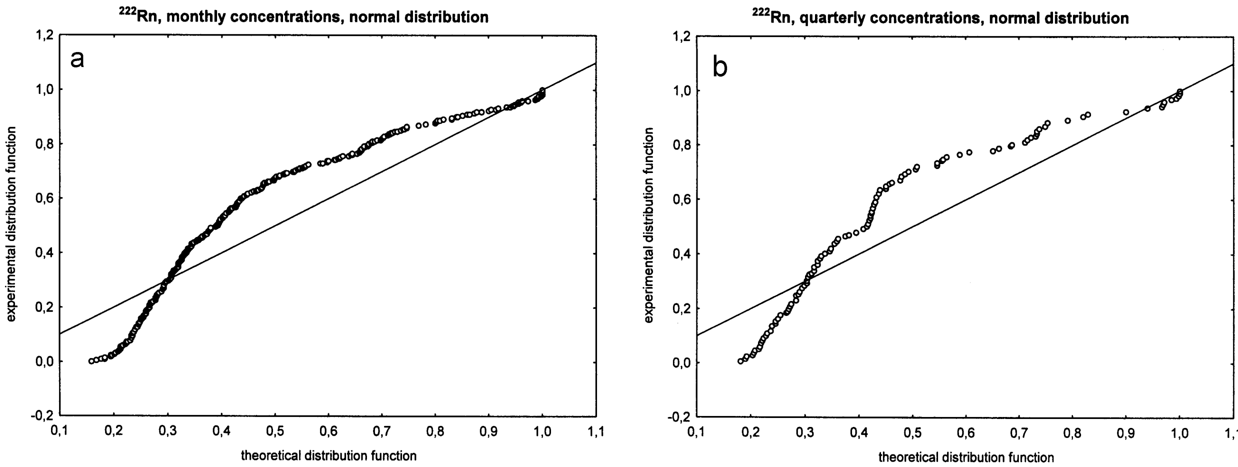

Fig. 4. Graph of accumulated probability for normal distribution, obtained for ^{222}Rn concentrations in all houses. a – monthly; b – quarterly measurement period.

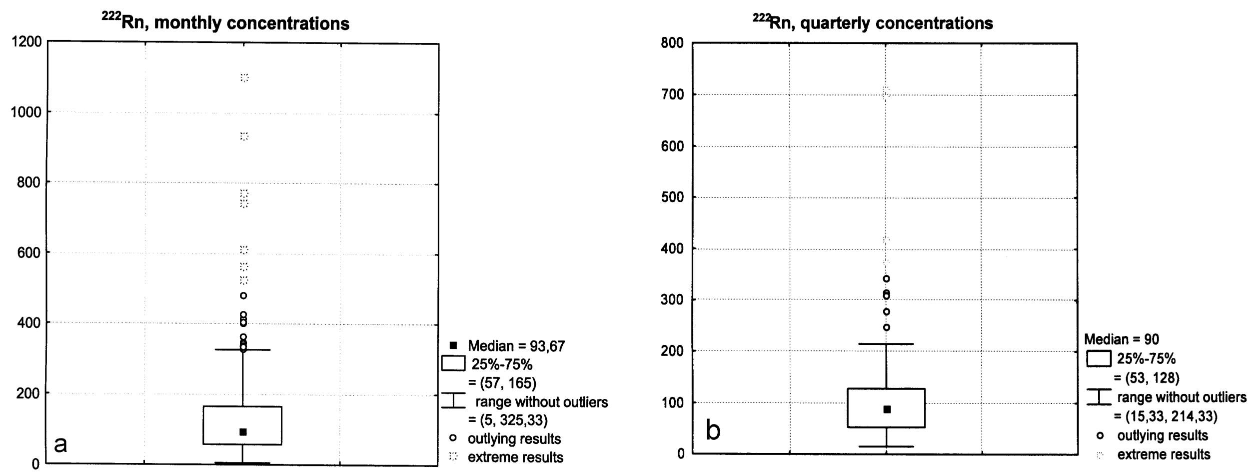

Fig. 5. Box whiskers graph for ^{222}Rn concentration in houses over: a – monthly; b – quarterly measurement period.

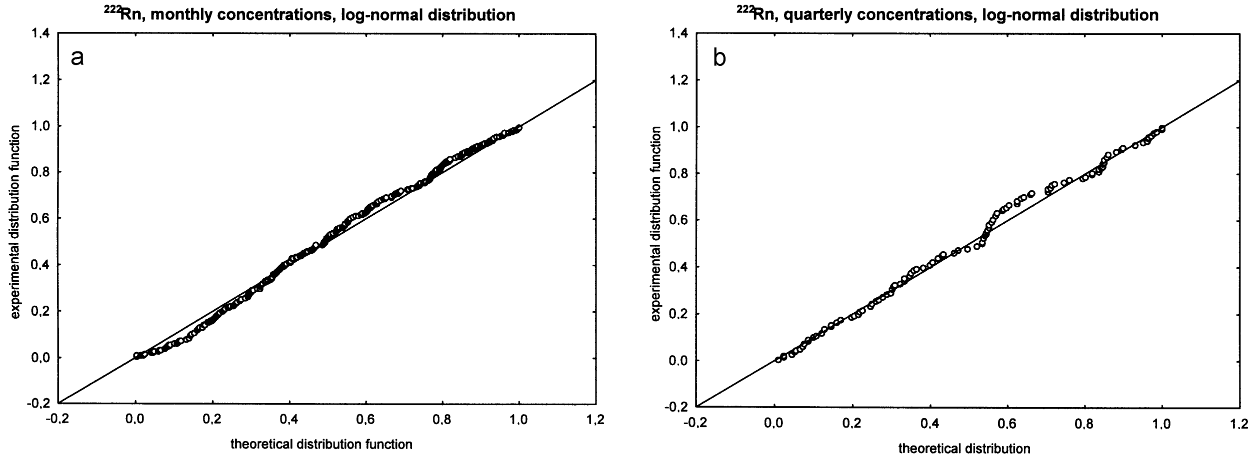

Fig. 6. Graph of accumulated probability for logarithmical normal distribution ^{222}Rn concentrations in all houses during: a – monthly; b – quarterly measurement period.

Table 2. Average arithmetical values and medians for 32 houses in individual months within 1 year of measurements

	January 2009	February 2009	March 2008	April 2008	May 2008	June 2008	July 2008	August 2008	September 2008	October 2008	November 2008	December 2008
Average	172	124	149	138	120	106	110	93	121	141	125	136
Median	128	95	134	116	90	70	69	52	62	94	99	107

The large number of such results shows the lack of normal distribution of the obtained values. Nevertheless, normal distributions have character logarithm values of the above-mentioned activity of ^{222}Rn concentrations (so-called log-normal distributions). Empirical distribution functions for log-normal distributions of ^{222}Rn concentrations, arrange this time themselves into a characteristic way along the line of theoretical distribution function (Figs. 6a and 6b).

Analyzing the average values of ^{222}Rn concentrations, obtained in individual months for a set of 32 houses, it was possible to confirm differences in results of average values and medians (Table 2). Somewhat higher values of the arithmetical average and median obtained for winter months (January 2009, December 2008) as well as considerably lower values of median in comparison to average summer values are noticeable. This shows a lack of normal distributions of the presented seasonal results for individual months. Normal distributions can again be seen for values of logarithms of ^{222}Rn concentrations, where empirical distribution functions arrange themselves along the line of theoretical distribution function. Figs. 7a to 7d depicts the log-normal distributions of accumulated probability for chosen 4 months in 4 different seasons of the year, i.e. January 2009, April 2008, August 2008 and November 2008.

The analyses of individual houses show that the highest values were measured in one building in Katowice (U4). Annual average radon activity concentrations was 535 Bq/m^3 there, with a maximum value of 1100±110 Bq/m^3. In the neighboring buildings considerably lower concentrations were measured, not higher than 200 Bq/m^3.

Relatively high values of concentration, reaching up to 440±57 Bq/m^3, were measured in some buildings at Jaworzno. The average value for this town is 134 Bq/m^3 and this is considerably higher than the average for USCB [15] (see Fig. 8a). In houses at Rybnik, also relatively high values of radon concentration, reaching up to 311±37 Bq/m^3, were measured. The av-

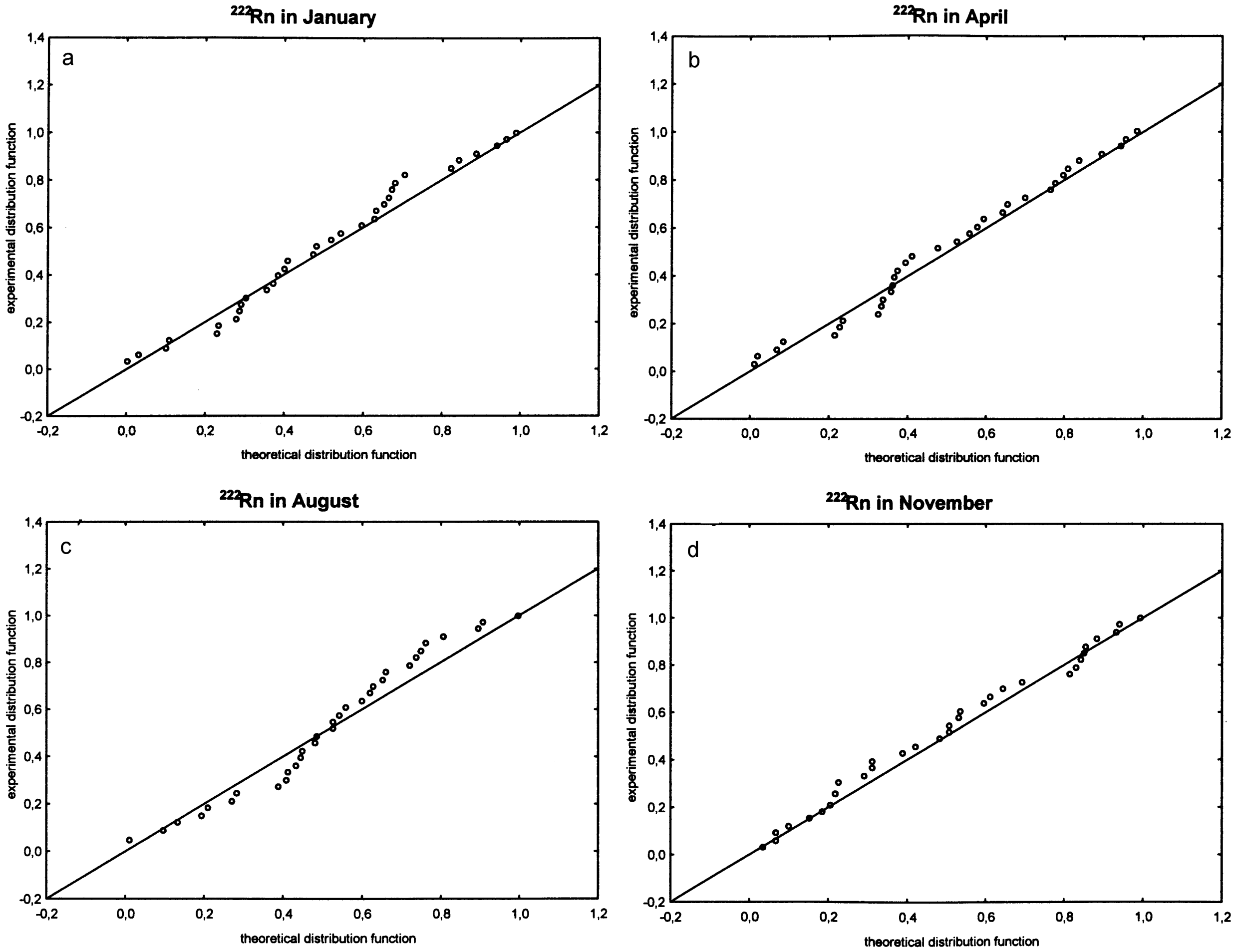

Fig. 7. Log-normal distributions of accumulated probability for ^{222}Rn in selected 4 months: a – January 2009; b – April 2008; c – August 2008; d – November 2008.

erage value for this town is 90 Bq/m^3, and it is also higher than the average for USCB (see Fig. 8b). However, it should me mentioned that the USCB region lies within the borders of Silesian Voivodship which is larger than USCB, so one cannot expect the same radon results.

High concentrations, ranging from 180±34 Bq/m^3 to 524±84 Bq/m^3, were measured at the house without a basement at Czeladź. In the previous years, high values of concentrations of radon were measured in buildings located in the area of similar geological structure [15]. The easy radon migration and its penetration into buildings is caused by the geological structure of the site: strongly cracked and fissured Triassic limestone and dolomite that occur in the form of outcrops on the surface.

Average annual radon concentrations in buildings at Mikołów, Buków and Bielsko-Biała also exceeds average value for USCB, and in individual houses it ranged from 70±15 to 120±19 Bq/m^3. In one building at Buków, measured radon concentration in January exceeded the value 400±54 Bq/m^3.

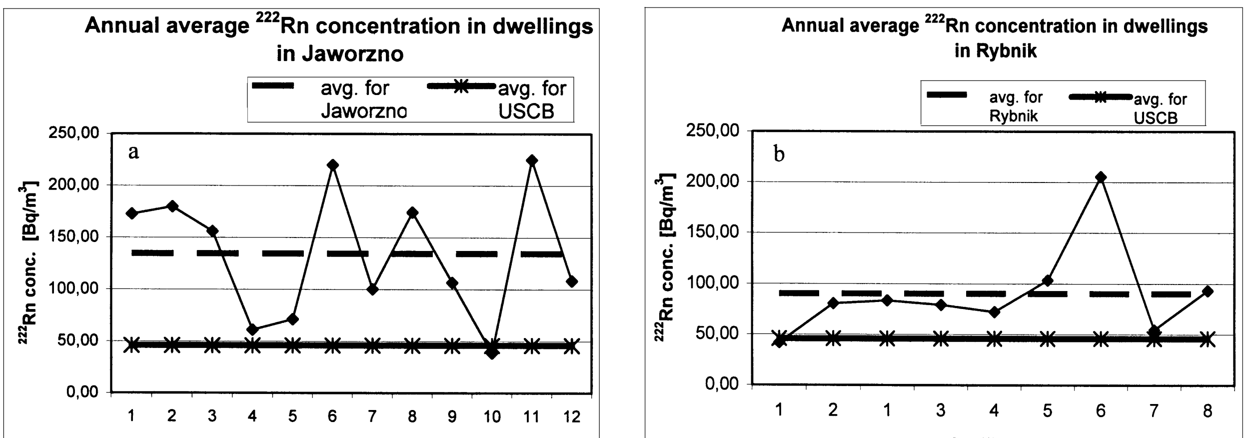

Fig. 8. Average ^{222}Rn activity concentration in buildings in: a – average annual concentration of ^{222}Rn in buildings at Jaworzno; b – average annual concentration of ^{222}Rn in buildings at Rybnik.

Concentration of ^{222}Rn activity in the air in dwellings does not come under any legal standard. In accordance with recommendations of the World Health Organization (WHO), [16], the level of radon in residential buildings should not exceed 100 Bq/m^3. However, if this level cannot be implemented under the prevailing country – specific conditions, the chosen reference level should not exceed 300 Bq/m^3.

To calculate correlation degree between determined values of ^{222}Rn activity concentration and other quantities, such as pressure or air temperature, a coefficient of linear Person correlation was used [12]. This coefficient was applied to calculate the correlation degree between ^{222}Rn concentration and average external monthly air temperature, as well average atmospheric pressure in individual months. The obtained Person correlation coefficients for relationship between ^{222}Rn concentration and temperature vary from –0.06 to +0.32, what shows a faint and weak correlation. For dependence of ^{222}Rn activity concentration on external pressure, the coefficients vary from –0.17 to +0.18, what indicates a weak correlation, negative and positive. However, values of coefficients for pressure and temperature reached from –0.17 up to +0.75 (for summer months). For 26 out of 32 houses, the average monthly temperature in studied rooms was recorded. Therefore, it was possible to determine a coefficient of correlation between its values and measured ^{222}Rn concentration. The obtained values range from –0.71 to +0.3, while positive values were obtained for four houses. In the case of two houses, the correlation was faint (0.02). For remaining houses, the high negative correlation was obtained that indicates the lower temperature in dwellings (winter) and higher radon concentration. During summer, when the temperature in rooms is higher and buildings are often ventilated, concentration of radon decreases. The exception to this rule points out to an unnatural behavior of residents: the observations in this house should be continued.

Conclusions

Radon activity concentration in 32 buildings of the Silesian Voivodeship area in annual measurement campaign varied within 5 ± 11 – 1100 ± 110 Bq/m^3, with an arithmetical average of 128 Bq/m^3, and median 94 Bq/m^3. As it was expected, the authors observed the increased radon hazard in the following areas of the Upper Silesia Coal Basin:

– The fault zones activated by mining operations – Katowice.
– The zones of surface deformation, especially in the vicinity of shallow voids and caverns – Katowice, Jaworzno, Czeladź.
– The zones of karst process development – Jaworzno.
– The zones where permeable sands with gravel, boulder clay occur – Rybnik.

It was concluded, that the local geological structure and the effects of mining operation has a significant impact on radon level concentration in buildings.

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