The assessment of lining structure impact on radon behaviour inside selected underground workings under the cour d'honneur of Książ castle

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Received: 13 June 2020 / Accepted: 13 September 2020 / Published online: 26 September 2020
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Abstract

The results based on 2-year long measurements 01 Jan. 2016–2031 Dec. 2017 have been used for discussing the influence of tunnel lining on the size of ^{222}Rn activity concentration and the impact of the employed rock mass insulation on natural convective air exchange. In April, air movement started when the temperature was at least 7 °C lower than the mean inside. Between May and October, an increase to 9 °C above the underground temperature resulted in an increase of radon concentration. An unconstrained convection process did not start until November and it continued until the end of March. The reinforced concrete lining insulated the fractured and absorptive rock mass. The roof and the sidewall lining had little impact on air movement process.

Keywords Continuous ^{222}Rn measurements · Convective air movement · Transitional periods · Underground corridors · Underground construction · Reinforced concrete lining

Introduction

Being a natural source of ionizing radiation, radon (^{222}Rn) is one of the basic radiation hazards occurring in man's natural life and work environment [1–3].

As demonstrated by statistics, people staying inside enclosed spaces well isolated from the atmosphere and frequently lacking ventilation, such as underground engineering structures including underground tour routes, mine adits, caves, underground laboratories, castle vaults, and mines are at risk of receiving as much as 95% of the effective dose coming from radon [4–26, 85, 86].

The number of such spaces in Poland is growing steadily. A large proportion of the about 200 currently existing ones [5–7, 20–24, 32, 33, 71, 85] are underground workplaces situated at small depths (up to 200 m below ground level) in radon prone areas characterized by increased concentrations of radium ($^{226}\text{Ra} > 30 \text{ Bq/m}^3$), the parent source of radon present in subsoil [27–34]

Due to its gaseous state, radon (^{222}Rn) readily migrates from the structure of rocks building the subsoil into both open and enclosed spaces (especially these situated immediately under the earth's surface). Radon's ability to accumulate, especially in natural cavities within rock masses and their man-made counterparts such as mines, adits, castle vaults or underground laboratories, is due, among other reasons, to its high density—over 7 times as high as the specific weight of the atmospheric air [33–35].

The migration (escape) process, caused mainly by convection and, to a lesser extent, by diffusion and advection, is facilitated by sedimentary, tectonic and erosion structures found in the rock mass, e.g. fissures, fractures and discontinuity planes (faults). Their directional strike and the availability of geofluids (CO_2 or groundwater) quite often increase the speed and extend the route of this radioactive gas transport [8–10, 36–43].

One of the proposed solutions providing protection against the effects of radon migration and its increased exhalation in enclosed spaces is insulating and increasing air tightness by reducing porosity and permeability of building construction and materials [44–57]. In underground facilities both the ground, the roof and side walls of a given space should be insulated. Considering the above observations, the author assessed the effectiveness of such a solution and

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whether reinforced concrete lining, being a structural element of underground workings, can provide insulation and thereby significantly reduce radon concentration inside an underground space.

Study area

The object of research are two underground corridors in adit no. 2, one of the main entrances to the underground system under the cour d'honneur of Książ castle. They were drilled as a part of mining and construction works launched in 1943 within the wider project called *Riese* connected with the Third Reich takeover of Książ castle and its reconstruction and adaptation for a government facility. The work was done by prisoners from the concentration camp Gross-Rosen [58–62]. Since the 1970s, the research site has been a part of an underground geodynamic laboratory [65–70] and as such it is an underground workplace where occupational activity, as defined by Atomic law [63] recently amended in compliance with the EU regulations [64], is conducted in radiation exposure conditions [1, 2, 63, 64].

The system of workings is located 50 m below the level of the cour d'honneur and it is made up of four adits interconnected by numerous underground corridors and chambers. The total length of the underground system of Książ castle is 950 m, its surface area—3.200 m², and the capacity—13.000 m³ [60].

The two sections of the workings selected for investigations are an essential part of the underground system of Książ castle, which is not accessible to visitors (Fig. 1). One section is a concrete-lined corridor being a part of the main passageway. It is located to the left of the fork of the main gallery, a part of the underground tour route since October 2018. In the section chosen for research, the adit roof was inserted in the corridor roof to form one common profile. The corridor cross-section is close to an ellipsis in shape. Its length, starting from the crossing, is c. 35 m, the width—c. 3.7 m, and the height—c. 4.8 m. At the height of about 2.7–3.2 m over the floor, steel reinforcement bars were concreted in the walls. They were meant to facilitate the construction of another roof (inter-roof), dividing the corridor into the main part and the ‘technical’ space. All the walls and the roof of the corridor were made in the reinforced concrete lining, but no concrete floor was executed. The tunnel lining

Fig. 1 Plan of the distribution of measurement points in the undergrounds under the cour d'honneur of Książ castle (C) and view of an underground excavation with reinforced concrete lining (B) where SRDN-3 No. 3 probe (A) was placed (based on 69, 87)

is a structural element. Its role was to enhance the supporting capacity and ensure the stability of the workings. The underground corridors of Książ castle were provided with lining because of their large cross-sections and difficult geological and mining conditions (numerous fractures, faults, and weathered rock). Additionally, it was meant to additionally protect the workings which were intended as a bomb shelter. The layer of concrete directly adhering to the rock mass improved the self-bearing capacity of the workings thus reducing the load on the lining structure. Another function of the chosen lining structure was to prevent the release of gases or water from the ambient rocks into the space. The type of lining was also adjusted to the extent of stress-relief zone and the displacements of rocks surrounding the excavations. When choosing the lining structure parameters, the angle of internal friction and rock cohesion, as well as the humidity of the fractured rock mass were taken into account [59–61, 72–76]. Roughly halfway along the side corridor, there is a drilled entrance to the other studied space. It was left without lining and blind-ended (most likely due to a cave-in resulting from a natural rock fall). Likewise the other corridors, it was executed with a slight dip towards the exit. The mining works carried out in this space were much less advanced (it is not profiled). Major dislocation zones and a lot of outcrops of fault gouge are visible here. In this part of inaccessible tunnels, the tectonic fault is the most conspicuous. The rocks are cut by minor fractures with small depths, large fracture zones with depths reaching dozens of centimetres, as well as systems of fractures occurring next to each other in a small area [60, 77, 78].

The selected research object is characterized by unforced ventilation (based on the principles of convection) and time-varying (subject to seasonal and short-time variation) values of ^{222}Rn activity concentration. The site interior is characterized by stable temperature (averaging 10.2 °C) and humidity (100%) [23, 71].

History and geology

The first measurements of ^{222}Rn activity concentration in the tunnels under Książ castle were launched in 2014. The obtained results indicate that variation in the recorded values of ^{222}Rn activity concentration is influenced chiefly by the process of natural convective air exchange, which is constrained in transitional periods occurring between spring and autumn. Analyses are still being conducted to evaluate the influence of geodynamic phenomena induced by strike-slip movements in the dislocation zone, which can be reflected by changes in the size of radon flux (gas exhalation) from fractured and weathered sedimentary rocks.

So far, no research has been conducted into the assessment of the possible role of lining structures, being the

principal structural element ensuring the stability of underground workings, as a barrier limiting the size of radon exhalation.

The research object is located in the underground part of a castle and palace complex, Poland's third (after Malbork and Wawel) largest architectural monument of this kind. It is situated on a cliff in the Wałbrzych Foothills, in a meander of the river Pełcznica. The underground workings were carved in the slopes of hills cutting the Pełcznica and the Szczawnik valley into two floristic reserves: the Pełcznica Gorge and the Szczawnik Gorge (Fig. 1; [61]).

In geological terms, these workings are situated in the central part of the Świebodzice basin structural unit (ŚU) intersected by a network of numerous faults running along its borders with the neighbouring units: the faults of Struga (to the south) and Szczawienko (to the west), and the Sudetic marginal fault to the east (Fig. 2; [79–82]). The Świebodzice depression is filled with Lower-Carboniferous and, secondarily, Upper Devonian deposits. These are sedimentary rocks classified as parts of the formation of Pogorzała, Pełcznica, Chwaliszów and Książ. Its northern part is made up of overthrusts of the Kaczawa complex metamorphic rocks [70].

Methods

The aim of the paper is the assessment of the role of reinforced concrete lining structure as a barrier insulating the workings from increased radon exhalation, including the assessment of its influence on the character and pattern of changes in ^{222}Rn concentration activity and on the natural convective process of air exchange in the studied space.

The analysis was carried out during two measurement periods lasting uninterruptedly from 1 January 2016 to 31 December 2016 and from 01 January 2017 to 31 December 2017, when continuous measurements of ^{222}Rn activity concentration were conducted.

To equalize the durations of the measurement cycles in 2016 and 2017, 29 February 2016 was excluded from the investigation. The analysis was conducted for two measurement points. One of them was set up in an excavation secured with reinforced concrete lining structure. The other one was regarded as representative of ^{222}Rn activity concentration values recorded in a natural, fractured rock mass visible in one of the selected corridors under Książ.

The convection process and its effect on the size of ^{222}Rn activity concentration is demonstrated by daily changes in ^{222}Rn activity concentration occurring in so-called transitional periods lasting from April to early October. The data on the daily average temperature of the atmospheric air at Książ, recorded from April to October 2017, was obtained from the website of the weather archive of Wałbrzych city [83].

Fig. 2 Location of the undergrounds under the cour d'honneur of Książ castle on a simplified geological map of the Sudetes (based on 88)

The obtained results have been compiled and compared (Figs. 3, 4, 5, 6, 7, 8, Tables 1, 2). The measurement results are also discussed in the context of the currently amended Polish radiological protection regulations [64].

Radon measurements

Measurements of ^{222}Rn activity concentration were conducted by means of two SRDN-3 probes. Each of them was installed in one of the two corridors in the underground

system selected for the research. The probes are Polish-made devices equipped with semiconductor detectors frequently used in long-term measurements conducted in underground spaces [21, 22, 84, 85] including the tunnels under the cour d'honneur of Książ castle [24, 71]. The construction and the operation principle of the SRDN-3 probe have been repeatedly discussed in publications, and its detailed description was included in the work by Przylibski and co-authors [84]. The ^{222}Rn activity concentration detection thresholds for SRDN-3 probes range

Fig. 3 Pattern of ^{222}Rn activity concentration changes with visible seasons registered throughout all the measurement period between 1 January and 31 December 2016 at two measurement points in underground corridors under the cour d'honneur of Książ castle. Graph explanation: straight line—average value of ^{222}Rn activity concentration with moving average fitting

Fig. 4 Pattern of ^{222}Rn activity concentration changes with visible seasons registered throughout all the measurement period between 1 January and 31 December 2017 at two measurement points in underground corridors under the cour d'honneur of Książ castle. Graph explanation: straight line—average value of ^{222}Rn activity concentration with moving average fitting. SRDN-3a the same SRDN-3 device, the letter indicates later production, the designations used in parallel

Fig. 5 Pattern of diurnal ^{222}Rn activity concentration changes in comparison with inside and outside temperature registered in April, June and September 2017 on first measuring point. Graph explanation: dashed line—average value of ^{222}Rn activity concentration with moving average fitting. R—right y axis, L—left y axis. SRDN-3a the same SRDN-3 device, the letter indicates later production, the designations used in parallel

from 90 to 100 Bq/m³. The maximum measurable value of ^{222}Rn activity concentration for a SRDN-3 probe is 157 MBq/m³. The measurement uncertainty depends on the size of the measured ^{222}Rn activity concentration and it may range from 21 to 39%. The higher the value of ^{222}Rn activity concentration, the lower the measurement concentration, starting from 20% for ^{222}Rn values of the

order of 1000 Bq/m³ to even 7% for the value in the range of 5000–10,000 Bq/m³ [23, 84].

The semiconductor SRDN-3 detectors were positioned on tripods at the height of 1 m over the floor of each corridor (Fig. 1).

Fig. 6 Pattern of diurnal ^{222}Rn activity concentration changes in comparison with inside and outside temperature registered in April, June and September 2017 on second measuring point. Graph explanation: dashed line—average value of ^{222}Rn activity concentration with moving average fitting. R—right y axis, L—left y axis

Fig. 7 Pattern of diurnal ^{222}Rn activity concentration changes in comparison with inside and outside temperature registered in May, July, August and October 2017 on first measuring point. Graph explanation: dashed line—average value of ^{222}Rn activity concentration with moving average fitting. R—right y axis, L—left y axis

Fig. 8 Pattern of diurnal ^{222}Rn activity concentration changes in comparison with inside and outside temperature registered in May, July, August and October 2017 on second measuring point. Graph explanation: dashed line—average value of ^{222}Rn activity concentration with moving average fitting. R—right y axis, L—left y axis

Table 1 Basic descriptive statistics for the values of ^{222}Rn activity concentration registered between 2016 and 2017 at two measurement points in underground corridors under the cour d'honneur of Książ castle

Number of SRDN-3 probe	Year of measurements	Number of analysed data	^{222}Rn activity concentration					
			Average	Median	Minimum	Maximum	Interval	Standard deviation (1 σ)
		(–)	(Bq/m ³)					
3	2016	8760	976	950	91	2434	2343	366
3	2017	8760	976	911	91	2434	2343	379
4	2016	8760	2714	2668	1224	4772	3549	521
4	2017	8760	2584	2544	1059	4442	3383	501

Results and discussion

The analysis is based on 35,040 data collected uninterruptedly for 2 years at 2 measurement points (Table 1). One measurement point was set up in an excavation encased in concrete lining (SRDN-3 No. 3), while the other one—in a tunnel drilled in fractured rock mass (SRDN-3 No. 4). Both measurement points were about 100 m apart (Fig. 1). The analysis is supplemented with a discussion of the convection process occurring inside the two selected workings at Książ (Figs. 5, 6, 7, 8).

The collected data has been analysed in the context of seasonal variations, observed in the annual cycle (Figs. 3,

4), and short-term changes observed daily in transitional periods lasting from April to October (Figs. 5, 6, 7, 8). Seasonal changes in underground objects in Poland were first time described by Przylibski [86] in two caves, while the short-period changes were described by Fijałkowska-Lichwa and Przylibski [85].

During the year, ^{222}Rn activity concentrations are subject to almost identical fluctuations at both measurement sites (Figs. 3, 4).

Within the 2-year observation period (2016–2017), the ^{222}Rn activity concentrations recorded at site No. 1 (with reinforced concrete lining) were clearly lower. At the same time, mean annual values of ^{222}Rn activity concentration reached almost 1000 Bq/m³ (Table 1). At measurement site

Table 2 Basic descriptive statistics for ^{222}Rn activity concentration values registered in each month of two years of measurements registered between 2016 and 2017 at two measurement points in underground corridors under the the cour d'honneur of Książ castle

Number of SRDN-3 probe	Month	Year of measure- ments	Number of analysed data	^{222}Rn activity concentration					
				Average	Median	Minimum	Maximum	Interval	Standard deviation (1 δ)
(–)			(–)	(Bq/m ³)					
3	January	2016	744	643	637	91	1262	1172	184
3		2017	744	698	598	130	1145	1016	180
4		2016	744	2332	2338	1513	3370	1857	323
4		2017	744	2134	2111	1100	3122	2022	314
3	February	2016	672	673	676	208	1262	1055	188
3		2017	672	662	637	169	1380	1211	185
4		2016	672	2357	2338	1389	3370	1981	327
4		2017	672	2276	2297	1348	3287	1939	350
3	March	2016	744	766	755	286	1536	1250	199
3		2017	744	704	676	247	1340	1094	186
4		2016	744	2461	2462	1389	3576	2187	352
4		2017	744	2326	2338	1100	3493	2393	334
3	April	2016	720	945	950	286	1848	1562	228
3		2017	720	815	794	169	1926	1758	247
4		2016	720	2798	2792	1554	4236	2682	415
4		2017	720	2454	2462	1389	3988	2600	386
3	May	2016	744	1156	1145	403	2317	1914	290
3		2017	744	1096	1067	364	1926	1562	235
4		2016	744	2986	2998	1760	4360	2600	436
4		2017	744	2799	2792	1760	4112	2352	388
3	June	2016	720	1408	1379	755	2434	1679	248
3		2017	720	1241	1223	481	2004	1523	237
4		2016	720	3251	3246	2132	4772	2641	384
4		2017	720	2898	2874	1678	4401	2723	379
3	July	2016	744	1303	1301	559	2122	1562	249
3		2017	744	1376	1379	637	2161	1523	260
4		2016	744	3128	3122	2214	4442	2228	380
4		2017	744	3039	3039	1884	4442	2558	380
3	August	2016	744	1301	1301	716	2122	1406	242
3		2017	744	1477	1458	755	2434	1679	294
4		2016	744	3111	3122	2049	4277	2228	372
4		2017	744	3117	3101	1760	4401	2641	409
3	September	2016	720	1244	1223	520	2122	1601	273
3		2017	720	1256	1262	403	2200	1797	279
4		2016	720	2986	2998	1967	4195	2228	389
4		2017	720	2888	2874	1719	4195	2476	392
3	October	2016	744	953	911	247	2004	1758	276
3		2017	744	1048	1028	325	2083	1758	270
4		2016	744	2699	2709	1430	4484	3053	408
4		2017	744	2619	2627	1471	3823	2352	424
3	November	2016	720	695	676	208	1527	1319	193
3		2017	720	747	735	208	1458	1250	197
4		2016	720	2271	2297	1306	3411	2104	334
4		2017	720	2266	2255	1059	3452	2393	330

Table 2 (continued)

Number of SRDN-3 probe	Month	Year of measurements	Number of analysed data	²²² Rn activity concentration					
				Average	Median	Minimum	Maximum	Interval	Standard deviation (1 δ)
(–)			(–)	(Bq/m ³)					
3	December	2016	744	615	598	130	1223	1094	170
3		2017	744	657	657	91	1223	1133	179
4		2016	744	2168	2173	1224	3039	1816	310
4		2017	744	2171	2173	1348	3163	1816	315

No. 2, in both 2016 and 2017, mean annual values of ²²²Rn activity concentration were more than twice as high and they exceeded 2500 Bq/m³ (Table 1).

Higher values of ²²²Rn activity concentration were recorded by both probes in late spring and in summer, i.e. from late April to early October (Table 2). Lower ²²²Rn activity concentrations occurred in the cooler part of the year, i.e. from November to March/early April (Table 2).

Daily variations are clearly dependent on the seasonal changes (Figs. 3, 4). Any fluctuations in ²²²Rn activity concentration values correspond to the periods of natural convective air exchange between the space interior and the atmosphere. The temperature inside the underground system under the cour d'honneur of Książ castle is stable regardless of the time of the day or the year, and it averages 10.2 °C. The convection process is triggered suddenly at the moment of change (an increase or a decrease) of the atmospheric air temperature in relation to the mean temperature inside the underground space. The reference point for the occurring changes is the abovementioned constant temperature inside the space, i.e. 10.2 °C. An increase in the external temperature leads to fast accumulation of radon inside the space while its decrease causes rapid outflow of the air, together with the radon it contains, which results in maintaining a possibly constant concentration, until the moment of the next change in the temperature of the atmospheric air. As a result, higher and irregularly time-varying values of ²²²Rn activity concentration are observed daily in the warmer part of the year. In the cooler seasons, much lower and irregularly varying ²²²Rn activity concentration values were recorded on a daily basis (Figs. 5, 6, 7, 8).

The process of natural convective air exchange has been analysed based on daily changes in ²²²Rn activity concentration in transitional periods, when air movement was very slow, hindered or even stopped. These periods occurred between April and early October (Figs. 5, 6, 7, 8).

The process of convective air movement was visible at each measurement site between April and October. Its pattern and character, regardless of the place and the year of measurements was comparable in the same months of

measurements. Radon outflow from the underground space into the atmosphere took place in April. At that time, the temperature of the atmospheric air was 7 °C lower than the temperature inside the underground site (Figs. 5, 6). In May, June, and July, the temperature difference between the site interior and the atmosphere was from 2 °C to even 9 °C. The significantly higher air temperature in relation to the mean temperature inside the underground site resulted in stopping the convection process and radon accumulation in the air stagnating inside the underground workings (Figs. 7, 8). This process demonstrates low permeability, both in the zone of insulated rock mass (site No. 1) and where it is fractured, weathered and intersected by faults (site No. 2), enabling air exchange with the atmosphere only during longer periods favourable to convection (November–March). The obtained measurement results indicate that air exchange with the atmosphere, regardless of the location of the measurement site, be it the zone of fractures (rock loosening) or rock mass insulation (poorly permeable coating) is strongly limited throughout the research site. In August, distinct radon accumulation occurred at both measurement points. This process was triggered instantaneously when the external temperature was 8 °C higher than the temperature inside the studied space (Figs. 7, 8). In September, the air exchange process was first halted and then it slowly restarted. The halt occurred at measurement site No. 1 between the first and the fifteenth day of the month. At that time, the temperature of the atmospheric air was 7 °C lower than the temperature inside the site (Fig. 5, 6). The air exchange did not occur until the second ten days of the month, when the temperature of the atmospheric air dropped to 1–3 °C below the temperature inside the studied space (Fig. 5). At measurement site No. 2, radon was transported outside throughout all the month of the observations. The process of natural convective air exchange was very slow owing to a small temperature difference between the space interior and the atmosphere, which was about 3 °C (Fig. 6). At this time, the recorded values of ²²²Rn activity concentration decreased slightly, from about 3000 Bq/m³ to slightly less than 2800 Bq/m³ (Fig. 6). In October, at both measurement sites (No. 1 and No. 2),

the convection process was halted when the atmospheric air temperature was about 3 °C higher than the temperature inside the underground space. At that time, radon was accumulated inside. A drop in the atmospheric air temperature to at least 2 °C below the temperature inside the underground space (10.2 °C) triggered convective air movement. The air containing accumulated radon was transported outside (Figs. 7, 8).

A distinct area of radon accumulation inside the studied space is the zone of fractured non-insulated rock mass (Figs. 3, 4, 6, 8). The causes of the occurrence of such high radon concentrations are not entirely obvious and require further analyses. Supposedly, it is the pressure change related to strike-slip movements of particular rock blocks in the fault zones of the orogen which is quite significant here. Rock movement, notably in dislocation zones being radon migration paths, may significantly affect the changes in the size of radon flux reaching the workings (Table 1).

Conclusions

Based on long-term measurements of ^{222}Rn activity concentration conducted between 1 January 2016 and 31 December 2017 in the air of two selected underground workings under the cour d'honneur of Książ castle, the author assessed a possibility of applying reinforced concrete lining as a barrier limiting (insulating) radon flux from the surrounding rock into the workings. The assessment was based on analysing the differences in the characteristics of both seasonal and short-term (daily) changes in ^{222}Rn activity concentration at two representative points inside the underground space—one located within weathered rock mass and the other—in an excavation insulated with reinforced concrete lining.

It was found out that ^{222}Rn activity concentrations undergo seasonal changes both in the excavation insulated with a lining structure and in the fractured non-insulated rock mass. The patterns of these changes are almost identical. During the year, distinctly higher values of ^{222}Rn activity concentration occur at both sites from April till early October. Clearly lower values are recorded in the remaining months. The difference between the absolute values of ^{222}Rn activity concentrations recorded in these periods is over twofold.

The ^{222}Rn activity concentrations recorded in the two workings are subject to irregular short-term (daily) changes, particularly apparent in so-called transitional periods. This observation confirms the fact that daily changes are determined by seasonal changes. The observed daily periods when the concentration increases or decreases are very short. Also, differences between the absolute values of ^{222}Rn activity concentrations recorded in these periods are small (at the level of threshold value calculated for SRDN-3 device

measurement uncertainty). As for the excavation insulated from the rock mass directly by reinforced concrete lining, the apparent irregularity may be due to the limited permeability of the rock mass and the restrained possibility of its displacement. Additionally, the lining structure can also significantly insulate the excavation against the impact of external factors such as humidity or temperature. In such a case, air movement triggered (within a short time) by the convection process may be additionally constrained in the transitional period lasting from April to early October, not only because of the too small and short-term daily temperature difference between the underground space interior and the atmosphere, but also owing to the lower permeability of the rock mass. In April, owing to the drop in the atmospheric air temperature below the temperature inside the underground workings, radon is carried out into the atmosphere. In May, June, and July, the outdoor temperature was markedly higher than the temperature inside the workings, which led to a halt in the convection process and accumulation of radon in the stagnating air inside the space. In August, rapid and distinct radon accumulation occurred inside the underground workings at Książ. In the first half of September, convection is stopped and then slowly activated again in the latter half of the month. In October, a small rise or drop in the atmospheric air temperature to 2–3 °C above or below the mean temperature inside the workings results in the respective halt or activation of the convection process. The unconstrained and unlimited flow of air does not start until November and then it continues till early April, when the mean daily temperature of the atmospheric air gets considerably lower than the mean temperature inside the underground workings at Książ (below 10.2 °C). The larger the temperature difference, the more efficient the described process is.

The application of a reinforced concrete lining structure insulating the fractured and absorptive rock mass is relevant for the assessment of the ^{222}Rn activity concentrations recorded inside the workings, but it does not affect the character of changes in ^{222}Rn activity concentration either within a long (at least annual) or a short (a day or an hour) observation cycle. The lining structure is a barrier limiting the radon flux from the surrounding rocks into the workings, and it can also slightly affect the mechanism of radon flow from the rock into the underground space due to factors like reduced porosity of the rock medium. The insulation of the excavation roof and sidewalls has a negligible effect on the course of the convection process, which is determined chiefly by the difference between the temperature of the atmospheric air and the air inside the underground space.

The mean annual values of ^{222}Rn activity concentration are about 1000 Bq/m³ in the tunnel fitted with reinforced concrete lining and slightly more than 2500 Bq/m³ in the fractured rock zone. In the light of radiological protection regulations specified in the EU Council Directive of 5

December 2013 [64] establishing basic security standards for hazards of ionizing radiation exposure, which have been adopted by Polish law, these values are considerably higher than the reference level for radon concentrations in enclosed spaces and workplaces, set at the yearly average of 300 Bq/m³ [64]. In view of exceeding this reference level, precautionary measures should be taken, aimed at lowering the risk through effective ventilation or limiting the exposure by reducing the time spent inside the underground space (especially by employees whose duties require prolonged stays inside the space between spring and early autumn).

Acknowledgements The research was co-financed from funds allocated to scientific research or development and the related projects contributing to the professional development of young scientists and Ph.D. students at the Faculty of Civil Engineering, granted in 2017 (Project No. 0402/0004/17).

Compliance with ethical standards

Conflict of interest The author declares that there is no conflict of interest.

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