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Short-term ^{222}Rn activity concentration changes in underground spaces with limited air exchange with the atmosphere

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Abstract. The authors investigated short-time changes in ^{222}Rn activity concentration occurring yearly in two underground tourist facilities with limited air exchange with the atmosphere. One of them is Niedźwiedzia (Bear) Cave in Kletno, Poland – a natural space equipped with locks ensuring isolation from the atmosphere. The other site is Fluorite Adit in Kletno, a section of a disused uranium mine. This adit is equipped with a mechanical ventilation system, operated periodically outside the opening times (at night). Both sites are situated within the same metamorphic rock complex, at similar altitudes, about 2 km apart.

The measurements conducted revealed spring and autumn occurrence of convective air movements. In Bear Cave, this process causes a reduction in ^{222}Rn activity concentration in the daytime, i.e. when tourists, guides and other staff are present in the cave. From the point of view of radiation protection, this is the best situation. For the rest of the year, daily concentrations of ^{222}Rn activity in the cave are very stable. In Fluorite Adit, on the other hand, significant variations in daily ^{222}Rn activity concentrations are recorded almost all year round. These changes are determined by the periods of activity and inactivity of mechanical ventilation. Unfortunately this is inactive in the daytime, which results in the highest values of ^{222}Rn activity concentration at the times when tourists and staff are present in the adit. Slightly lower concentrations of radon in Fluorite Adit are recorded in the winter season, when convective air movements carry a substantial amount of radon out into the atmosphere.

The incorrect usage of mechanical ventilation in Fluorite Adit results in the most unfavourable conditions in terms of radiation protection. The staff working in that facility are exposed practically throughout the year to the highest ^{222}Rn activity concentrations, both at work (in the adit) and at home (outside their working hours). Therefore, not very well considered solution for the ventilation system not only does not prevent radioactive exposure of the staff, but can even increase it.

The authors have also observed comparable characteristics of the annual patterns of ^{222}Rn activity concentration changes in underground spaces and residential buildings situated in the same or similar climatic zones.

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1 Introduction

Radon is a radioactive noble gas. The longest-lived of its isotopes is ^{222}Rn with a half-life of $T_{1/2} = 3.8224$ days (Collé, 1995a, b). Due to its radioactive properties, long half-life and low chemical reactivity, ^{222}Rn plays an important role in the environment. It migrates easily to the atmosphere from rocks and soils, where it is formed as a result of natural alpha transformation of ^{226}Ra in the uranium-radium series (Mogro-Campero and Fleischer, 1977; Miliszkiewicz, 1978; Cothern and Smith, 1987; Cotton et al., 1995; Ciba et al., 1996; Emsley, 1997; Martinelli, 1998; Daintith, 2000). While migrating, the gas accumulates in all spaces, particularly those with impeded air exchange with the atmosphere (Tanner, 1964, 1980; Mogro-Campero and Fleischer, 1977; Martinelli, 1998). Its concentrations can subsequently reach values of tens or even hundreds of thousand $\mathrm{Bq\,m^{-3}}$ (Fernàndez et al., 1984; Kobal et al., 1987; Eheman et al., 1991; Ciężkowski et al., 1993; Kies and Massen, 1995; Szerbin, 1996; Peńsko et al., 1998; Przylibski, 1999, 2001; Field, 2007; Fijałkowska-Lichwa, 2010).

Radon, together with its radioactive progeny, is responsible for about 40–50% of the effective dose (1–2.5 $\mathrm{mSv\,year^{-1}}$) which a typical person receives from all natural and man-made sources of ionising radiation within a year (Commission Recommendation, 1990; UNSCEAR, 2000; Waligórski, 2010). Due to this fact, underground

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Table 1. Mean and extreme values of mean monthly radon (^{222}Rn) concentration in the air of selected underground tourist facilities in Poland (according to Chruścielewski and Olszewski, 2000; Chibowski and Komosa, 2001; Przylibski, 2002).

Underground space name	^{222}Rn activity concentration in the air (Bq m^{-3})		
	Min.	Mean	Max.
Sudetes			
Jaskinia Niedźwiedzia (Bear Cave)	100	1260	4180
Jaskinia Radochowska (Radochowska Cave)	60	450	1370
Podziemne muzeum "Kopalnia złota" w Złotym Stoku (Underground museum "Gold Mine" in Złoty Stok)	70	1880	18 500
Podziemna trasa turystyczna im. 1000-lecia Państwa Polskiego w Kłodzku (Underground tourist route of the Millenium of the Polish State in Kłodzko)	70	290	2210
Podziemne Fabryki Walimia (Underground Factories of Walim)	40	90	330
Sztolnia nr 9 i 9 a w Kowarach (Adit no. 9 and 9a in Kowary)	340	580	690
Remaining part of Poland			
Podziemna trasa turystyczna w Chełmie (Underground tourist route in Chełm)	2	166	622
Podziemna trasa turystyczna w Sandomierzu (Underground tourist route in Sandomierz)	15	44	77

spaces where people do various kinds of jobs (tourist facilities, mines, car parks, tunnels, stores, etc.) must be subject to monitoring of ^{222}Rn activity concentration level. It is a particularly important task, regulated by law in many countries as well as by a variety of guidelines and recommendations from international organizations (ICRP, 1993; Åkerblom, 1999; IAEA, 2003).

Seasonal changes in radon concentration in the air of underground spaces have been discussed and analysed by many authors (i.e. Przylibski, 1996, 1998, 1999, 2000, 2001; Przylibski and Piasecki, 1998; Przylibski and Ciężkowski, 1999; Przylibski and Fijałkowska-Lichwa, 2010; Gillmore et al., 2001, 2002; Chibowski and Komosa, 2001; Kullab et al., 2001; Kávási et al., 2003; Papachristodoulou et al., 2004; Perrier et al., 2004a, b; Olszewski et al., 2005; Lario et al., 2005, 2006; Gervino et al., 2007; Bahtijari et al., 2008; Vaupotič, 2008; Lu et al., 2009; Fijałkowska-Lichwa, 2010). Their findings have turned out to be comparable, and the most recent studies only extend the previously known regularities to next underground spaces.

Recently, more and more findings concerning short-term changes in ^{222}Rn activity concentrations have been published. The purpose of these analyses is to understand the mechanisms of these changes and identify their causes (i.e. Li et al., 2006; Perrier et al., 2007; Perrier and Richon, 2010). Having this in mind, the authors of this paper have also decided to investigate changes in radon activity concentration in underground tourist facilities in much smaller time ranges. This decision was due to the fact that these changes have paramount importance for radiation protection of employees, and also, but to a much lesser extent, of visitors. The knowledge of changes in radon activity concentrations both during the year and during the day will help develop guidelines for optimal scheduling of daily and yearly working time in underground spaces. Work should be planned in such a way that employees receive the lowest possible dose of ionising radiation from radon and its progeny.

2 Choice of research objects

In view of the accessibility of measuring equipment and the possibility of its constant supervision, the authors chose underground spaces accessible to visitors, where guided tours are offered, as their research objects. The sites are inaccessible outside the opening times.

In Poland there are over 70 underground tourist routes in five categories of spaces. They include caves, mines, strategic-military spaces, cellar systems and other underground tourist attractions. Most of them are situated in areas with high radon potential, predominantly in the Sudetes, a fragment of the European Variscan orogenic belt. Because of this, these sites are prone to the occurrence of high radon concentrations (Table 1).

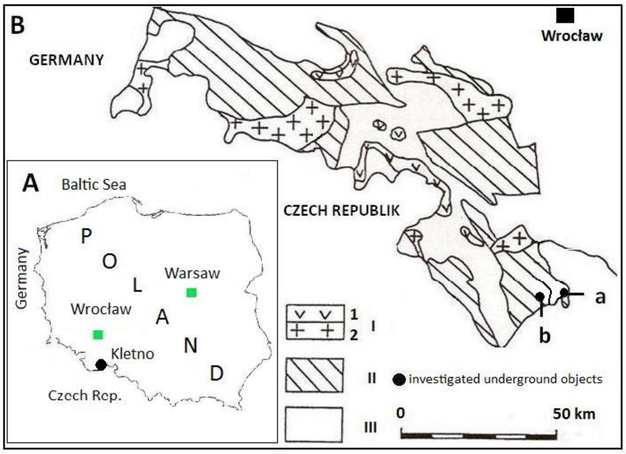

Fig. 1. Location of Bear Cave (a) and Fluorite Adit (b) in Kletno on a map of Poland (A) and a geological sketch of the Polish part of the Sudetes (B). I: igneous rocks: 1: intrusive rocks, 2: extrusive rocks, II: metamorphic rocks, III: sedimentary rocks.

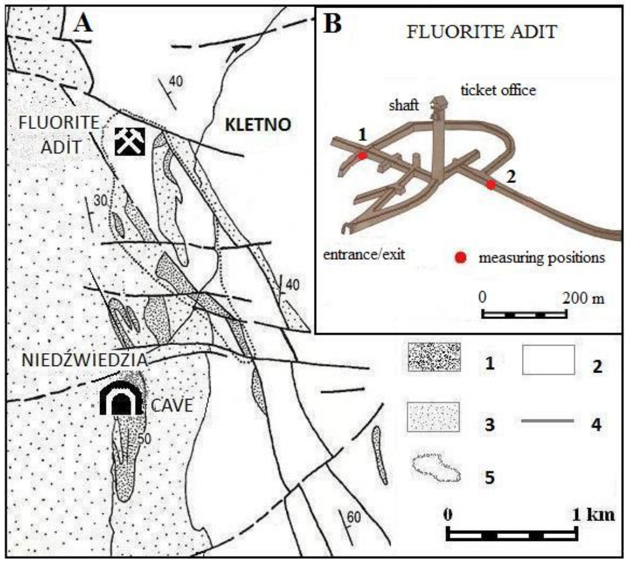

Fig. 2. Geological sketch of Kletno area with plotted sites of Bear Cave and Fluorite Adit (A) and a plan of Fluorite Adit with plotted sites of ^{222}Rn activity concentration measurements (B). 1: lenses of marbles and erlans, 2: gneisses, 3: metamorphic schists, 4: faults, 5: area of disused uranium mine in Kletno.

Due to high radon concentrations making the measurements easier, two sites situated in the Sudetes, the SE part of the Bohemian Massif, were chosen. They lie in SW part of Poland, within the crystalline Śnieżnik Massif (Fig. 1). The source of radon in these spaces are U and Ra-rich orthogneisses (Banaś, 1965; Borucki et al., 1967; Przeniosło, 1970; Przylibski, 2004). In the area of Kletno, these rocks are cut with numerous faults facilitating radon migration. Two sites were chosen, lying close to each other – at a straight-line distance of about 2 km (Fig. 2), differing in origin, the lithology of surrounding rocks and the effectiveness of ventilation. These are: "Jaskinia Niedźwiedzia" (Bear Cave) nature reserve in Kletno, and the underground tourist-educational route "Sztolnia Fluorytowa" (Fluorite Adit) located in a part of a disused uranium mine in Kletno.

Bear Cave is a natural site, formed in a marble lens contained within mica schists and gneisses (Fig. 2a). Fluorite Adit is situated within the same gneisses and mica schists. It lies in a tectonic zone where rocks were shattered and the resultant fissures were filled hydrothermally with Fe and U ore minerals. These minerals were successively extracted in mines (Fig. 2a). A fragment of an underground mining system developed from the Middle Ages (extraction of Fe ores; hematite) up to the mid-20th century (U ore mining; uraninite) has been opened to visitors and named Fluorite Adit. The name is derived from mineralisation of hydrothermal veins, with a predominance of fluorite accompanied by quartz, hematite and uraninite.

Fluorite Adit is fitted with a periodically operated mechanical ventilation system, as its natural air exchange with the atmosphere is not efficient enough. A fan is placed at the shaft mouth near the ticket office (Fig. 2b). Bear Cave, on the other hand, has locks preventing air exchange with the atmosphere with the aim of protecting its microclimate and preserving its beautiful speleothems. These locks are installed at the entrance and exit from the middle level of the Cave, which is accessible to visitors (Fig. 3b).

3 Measurement method

When choosing the appropriate measurement equipment, the authors paid particular attention to four basic aspects: detector type, measurement method and data storage capacity, resistance to hard operating conditions (including relative humidity reaching 100%) and the type of power supply. The type of the detector used determined the lower limit of detection (LLD), the size of the whole appliance and its resistance to hard operating conditions. This is why a semi-conductor detector turned out to be the most appropriate, as its relatively high LLD was not critical for high ^{222}Rn activity concentration values recorded in the chosen spaces. What is more, it ensured high resistance of the structure to the hard operating conditions and possibly the small dimensions of the whole appliance. The authors decided to use Polish probes, type SRDN-3, fitted with a semi-conductor detector, which ensured a suitably long (up to 12 months) period of unmanned operation; besides, the diffusion sampling it used did not disturb the poor air circulation inside the studied spaces. These probes are additionally equipped with temperature and relative humidity sensors. The structure and operation of these probes have been described by Przylibski et al. (2010). The calibration of these probes

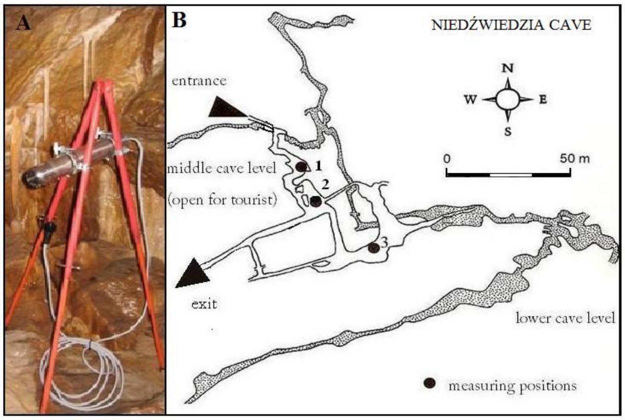

Fig. 3. Plan of Bear Cave in Kletno with plotted sites of ^{222}Rn activity concentration measurements (B) and a photo of SRDN-3 probe operating at measurement site No. 3 (A).

was performed at the Laboratory of Radiometric Expertise (Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland). The measurements were performed using a radon calibration facility. The main part of the post is a radon chamber and another important component is a certified radon source (PYLON Electronic Development Co., Canada) (Kozak et al., 2003). Measurement results from SRDN-3 probes are frequently checked by AlphaGUARD radon monitor during short measurements in the cave and adit where the probes are installed. The AlphaGUARD was used as a reference device.

In order to monitor the influence of external atmospheric conditions on the level of radon activity concentrations in both studied spaces, a weather station, Vantage Pro2, was installed at the entrance to Bear Cave. It collected, also in 1-h mode, data concerning the temperature of atmospheric air, its relative humidity, as well as atmospheric pressure, wind speed and direction. Measurement results from this station are representative of the area of both studied sites, which are situated at similar altitudes (the cave at 800 m a.s.l., the adit – at 773 m a.s.l.), about 2 km apart.

4 Results and discussion

Due to the seasonal character of long-term changes in radon activity concentration in the chosen spaces (Fig. 4), 24-h changes were analysed in relation to seasonal changes, which, to a large extent, coincide with changes in the intensity of tourism. One can distinguish three periods varying in tourism intensity, which are characteristic of the cave and the adit: early season – winter/spring (February–April), high season – summer (May–August), late season – autumn/winter (October–January) – facility closing.

Seasonal changes in ^{222}Rn activity concentration presented in Fig. 4a, also observed in Bear Cave as early as

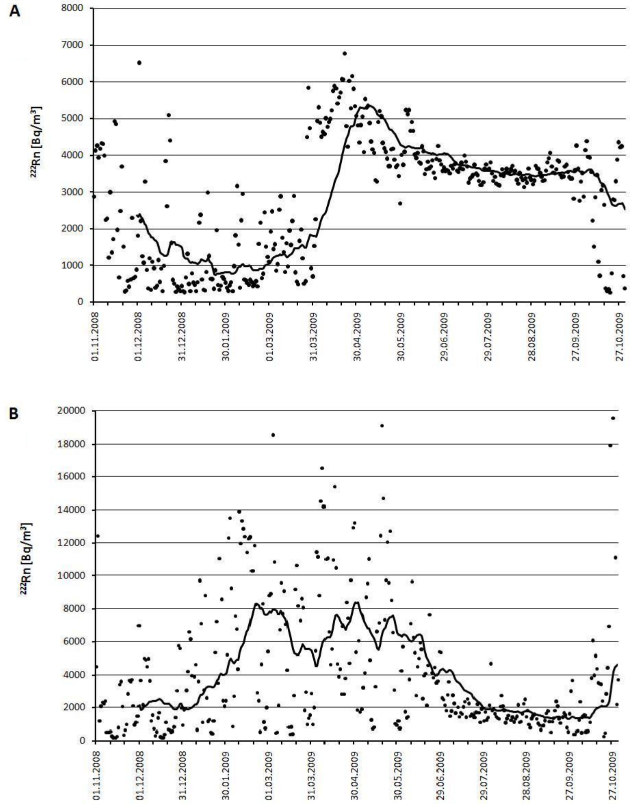

Fig. 4. Changes in ^{222}Rn activity concentration during the year-long monitoring measurements in Bear Cave in Kletno **(A)** and Fluorite Adit in Kletno **(B)**. Points represent mean daily values of radon concentration, and the line – the moving average with period of 30 days.

in the late 20th century (Przylibski, 1999), reveal the occurrence of high concentration values from May to September and low values between November and March. The transitional periods, when radon concentration inside the cave changes significantly, are April and October. At these times, convection currents are triggered, which leads to a ceasing (in April) and restarting (in October) of a more intensive air exchange between the cave and the atmosphere. These movements occur when atmospheric air temperature rises or falls above or below the temperature inside the cave, which is almost constant throughout the year and amounts to 6.5 °C (Przylibski, 1999).

Daily changes in ^{222}Rn activity concentration are presented in the example of three selected 24-h periods representing the above-mentioned characteristic periods distinguishable in each space in a year. February 12th 2009 was chosen for Bear Cave, as characteristic of the winter period, when the facility opens to visitors. This day is typical of a period with low and quite stable values of ^{222}Rn activity concentration. 2 August 2009 represents the peak of tourist season and simultaneously the summer season, when high

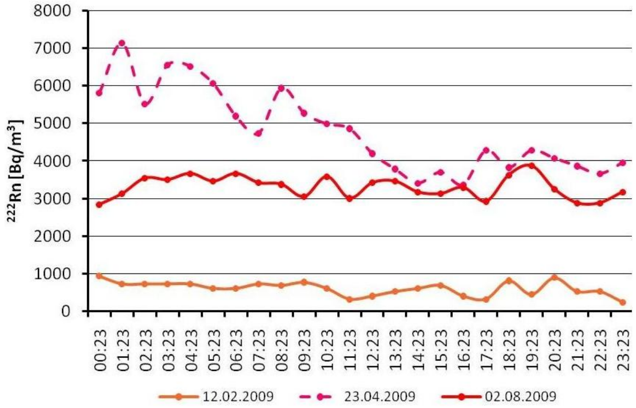

Fig. 5. Daily pattern of ^{222}Rn activity concentration changes for three chosen characteristic days, representing three seasons of the year, differing in values and variation in radon concentration in Bear Cave in Kletno.

and fairly stable values of ^{222}Rn activity concentration are recorded. 23 April 2009 represents the spring season, when ^{222}Rn activity concentration increases due to the termination of convection and the gas accumulates in the cave.

The pattern of seasonal changes in ^{222}Rn activity concentration in Fluorite Adit (Fig. 4b) is markedly different from that in Bear Cave (Fig. 4a). In the period from February to July, high and changeable values of radon activity concentration are observed. From August to October, low and quite stable values of activity concentration of this gas were recorded. Finally, radon concentration between late October and January was small but changeable (Fig. 4b). Days characteristic of these periods were chosen to illustrate the pattern of ^{222}Rn activity concentration changes in Fluorite Adit. These were 8 May 2009, 22 October 2009 and 2 January 2009.

In Bear Cave, similar patterns of 24-h changes in ^{222}Rn activity concentration were recorded on 12 February 2009 and 2 August 2009. They only differed in the absolute values (Fig. 5). The variations had irregular character and were quite small, which fully confirms the conclusions from the observation of seasonal changes (Fig. 4a). Therefore, one cannot distinguish any periods within a day when radon activity concentration is clearly higher or lower. This fact points to the poor permeability of the cracking zone in the orogene, which makes air exchange with the atmosphere possible only in long-term periods favourable to convection. This observation also confirms the good tightness of the locks. Consequently, the cracking zone in rocks above the cave roof enables air exchange with the atmosphere particularly in the spring season. This is when significant variations in ^{222}Rn activity concentration are recorded inside the cave. They are shown in Fig. 5 for 23 April 2009. What is conspicuous here are higher concentrations of this gas at night, and only half as high in daytime. The decline in ^{222}Rn activity concentration starts at about 05:00–07:00 a.m., when temperature difference between the warmer cave interior and the minimum 24-h temperature of atmospheric air is the biggest. This is probably when convection is triggered. This process does not end until early afternoon, at around 02:00 p.m. From that moment on, gradual accumulation of radon inside the cave begins, and it lasts until night hours, reaching its maximum at about 03:00 a.m. Such a pattern of daily changes in ^{222}Rn activity concentration is very favourable from the point of view of radiation protection of guides and other employees working inside the cave, as well as visitors. Most work inside, as well as sightseeing, takes place when radon activity concentration is the lowest in a day.

The above interpretation is also verified by the fact that it is only in spring when ^{222}Rn activity concentration is correlated with the atmospheric air temperature. The linear correlation coefficient between the values of these parameters is -0.43. This value is statistically significant at the 0.05 level for 24 data pairs. Such a value of linear correlation coefficient indicates that radon activity concentration inside the cave decreases with the increase in outdoor temperature.

The graph in Fig. 6 depicts three characteristic daily patterns of ^{222}Rn activity concentration changes in Fluorite Adit. 22 October 2009 is characteristic of the period of low and quite stable values. Changes in radon concentration during the day are quite small, as the air inside the adit, warmer in this part of the year (autumn) carries radon out and into the atmosphere. Tourist traffic in this season is quite small, so guides do not stay long inside the adit either. The remaining two days (Fig. 6) are characterised by similar patterns of ^{222}Rn activity concentration changes in relation to each other. The former one (2 January 2009) represents the beginning of tourist season with large changes in radon activity concentration, although at the level of its smaller absolute concentrations. On the other hand, higher absolute values are characteristic of 8 May 2009, representing the spring season and also high tourist season. Low concentration values on these days are recorded in the evening and at night, i.e. from about 06:00 p.m. or 10:00 p.m. to 09:00 a.m. Starting at 09:00 a.m., fast growth in ^{222}Rn activity concentration is observed, lasting until 04:00–05:00 p.m., followed by another period of quick fall. Superimposing the patterns of radon activity concentration changes on two days – 2 January 2009 and 8 May 2009, enables identifying two processes responsible for such a change pattern. The decisive factor is obviously the mechanical ventilation running at night, i.e. from 05:00 p.m. till 09:00 a.m. At these hours, initially a decrease and then (between 07:00 and 10:00 p.m.) stable low values of radon activity concentration are recorded inside the adit. A rapid rise in ^{222}Rn activity concentration is recorded after disconnecting the mechanical ventilation at 09:00 a.m., continuing practically until its re-connecting at 05:00 p.m. However, on the two selected days, radon concentrations increased to reach significantly different values – about 7500 Bq m^{-3} (on 2 January 2009) and about 23 000 Bq m^{-3} (on

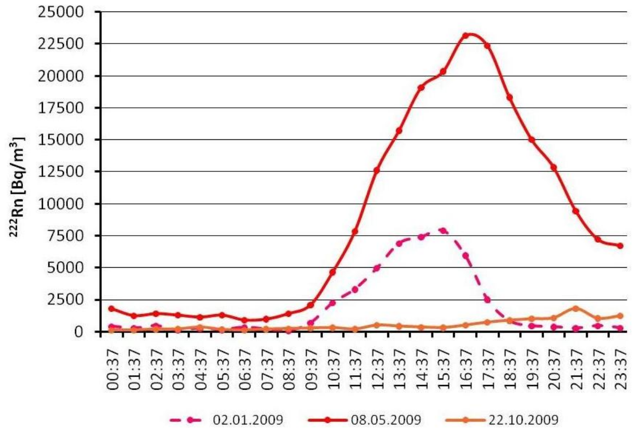

Fig. 6. Daily pattern of ^{222}Rn activity concentration for three selected characteristic days, representing three seasons in a year, differing in values and variation in radon concentration in Fluorite Adit in Kletno.

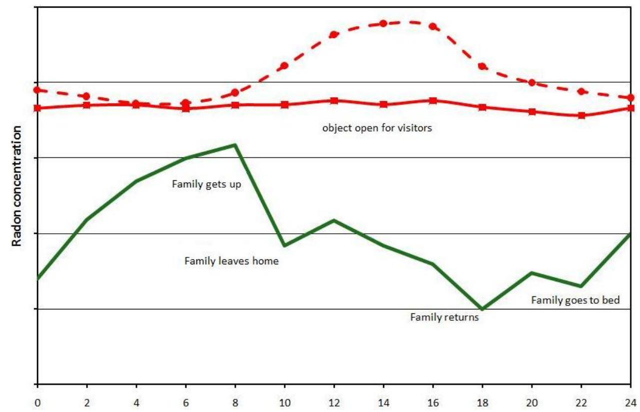

Fig. 7. Daily pattern of ^{222}Rn activity concentration changes in Fluorite Adit (dashed line, red) and Bear Cave (continuous line, red) registered in April 2009 in relation to a typical daily pattern of radon concentration changes in residential buildings (continuous line, green). Daily pattern of ^{222}Rn activity concentration changes in a residential building was taken from website www.hpa.org.uk, 2010.

8 May 2009). This means that in daytime (09:00 a.m. to 05:00 p.m.) in the cold season (winter – 2 January 2009) warmer air flows naturally (advection) out of the adit, carrying radon into the atmosphere. This results in a significant decrease in the activity concentration of this gas inside the adit, compared to the spring season, when radon-rich air, cooler than the atmospheric air, stagnates inside the adit.

Measurements conducted in Fluorite Adit demonstrate that the least favourable conditions in terms of radiation protection coincide with the heaviest tourist traffic, both in a day (Fig. 6), and in a year (Fig. 4b). This is caused by natural factors (advection), but particularly by disconnecting the mechanical ventilation disturbing the visitors. Switching off the fan results in a fast rise in ^{222}Rn activity concentration in the adit.

The recorded values of basic atmospheric parameters in Kletno enabled the authors to analyse correlations between radon activity concentration inside Fluorite Adit and these parameters. The data from 8 May 2009 were analysed, as the highest radon concentration changes in the adit occurring on that day facilitated the interpretation. The analysis of simultaneous changes in atmospheric air temperature and ^{222}Rn activity concentration inside the adit proved that radon concentration in the adit increases with a rise in outdoor temperature. This is due to cool air stagnating inside the adit, additionally helped by disconnecting the mechanical ventilation. Radon released from the orogene is held up inside the adit with this cool air. On 8 May 2009, the linear correlation coefficient between the temperature outside the adit and ^{222}Rn activity concentration inside reached 0.86. This value is statistically significant at the 0.05 level, showing strong positive correlation between these parameters.

Figure 7 shows 24-h changes in ^{222}Rn activity concentration inside Bear Cave and Fluorite Adit compared to a typical pattern of radon concentration changes in a residential building. The authors chose the spring season, when changes in radon activity concentration in underground spaces are the largest. These changes follow a different pattern from that in residential buildings. In underground spaces the highest values are recorded in daytime (the adit) or at night (the cave), while in residential buildings the highest values are observed in the morning. Comparing these two facts leads to a conclusion that people employed to serve visitors in Fluorite Adit are exposed to maximum, or close to maximum values of radon activity concentration 24 h a day, since the highest values in the adit are recorded in daytime (during working time), and in residential buildings – before and after the working hours (Fig. 7). This is highly unfavourable from the point of view of radiation protection. In the case of this tourist facility, mechanical ventilation, switched on at the wrong time, does not fulfil its function at all. It does not cause the lowering of radon concentration inside the space at the time when visitors, and especially the staff employed to serve them and perform other jobs inside the facility, stay there. A much better situation in terms of radiation protection can be observed in Bear Cave. The pattern of daily changes in radon concentration there is similar to changes observed in residential buildings. Therefore, staff exposure to the influence of ionising radiation coming from radon and its progeny is far smaller there than in Fluorite Adit, despite the fact that forced ventilation cannot be used in the cave due to speleothem protection. It should be emphasized, however, that such a situation occurs only in spring, when the convection process of air exchange with the atmosphere starts in underground spaces.

The analyses of annual changes in ^{222}Rn activity concentrations inside the studied underground spaces in Kletno demonstrate that the charateristics of these changes are a bit similar (Fig. 8). The pattern of these changes in the studied underground spaces was also compared to annual changes in radon activity concentration inside residential buildings in northern Poland, as well as with data from buildings presented by the UK Health Protection Agency (Karpińska et al., 2004; www.hpa.org.uk, 2010). Due to the lack of data from residential buildings in the Kletno area, the authors used available data published for northern Poland. Analyses of these change patterns, shown in Fig. 8, proved their character in underground spaces to be similar to that in buildings located in northern Poland, and completely different from that in buildings analysed by the Health Protection Agency. The observed patterns of annual radon concentration changes shown in Fig. 8 are most likely to be determined by climatic similarities and differences between buildings situated in the areas of Poland and the UK. It is interesting that seasonal changes in ^{222}Rn activity concentration in residential buildings and underground spaces situated in areas with similar climatic conditions have similar patterns.

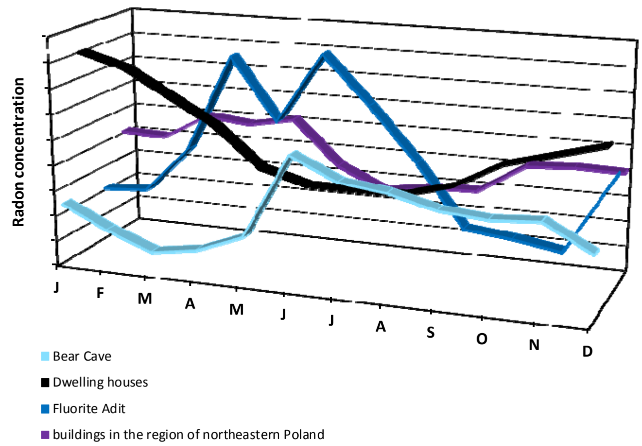

Fig. 8. Annual pattern of ^{222}Rn activity concentration changes in two studied underground spaces in Kletno in relation to annual pattern of radon concentration changes in residential buildings. The pattern of ^{222}Rn activity concentration changes in residential buildings is based on data from the website www.hpa.org.uk, 2010 (residential buildings) and data from residential buildings in the Northeast of Poland, according to (Karpińska et al., 2004).

5 Conclusions

The study of underground tourist facilities in Kletno (Sudety, SW Poland) confirmed the occurrence of convection air movements. So far, convection has been documented for autumn and, in particular, for spring. Thanks to using new SRDN-3 probes with a semi-conductor detector, the authors could investigate changes in ^{222}Rn activity concentration hour after hour throughout the entire calendar year. It enables precise investigation of the process causing retention of radon inside the space or removing it to the atmosphere.

In Bear Cave, a space very well isolated from the atmosphere, convection movements causing transport of radon to the atmosphere were observed. Those movements, occurring in autumn and spring, started early in the morning (between 05:00 and 07:00 a.m.), and declined in the early afternoon at about 02:00 p.m. This process resulted in the lowest values of ^{222}Rn activity concentration in daytime, i.e. when tourists visit the cave and the staff are present there. In the remaining seasons, daily variations in ^{222}Rn activity concentration were very small.

In Fluorite Adit, equipped with ventilation devices, the pattern of 24-h changes in ^{222}Rn activity concentration looks completely different. Large 24-h variations in ^{222}Rn activity concentration are recorded virtually throughout the entire year, except the season between late July and and late September. 24-h radon concentration changes inside the adit depend on the time of activating the mechanical ventilation. From the moment when it is switched on after closing the facility to visitors, at about 05:00 p.m., ^{222}Rn activity concentration decreases steadily to an almost stable minimum value. Depending on the initial maximum concentration, this value is reached at about 07:00 p.m. in winter, or as late as at 01:00 a.m. in spring and summer, when daytime ^{222}Rn activity concentration reaches the maximum values for the calendar year. In spite of similar patterns of 24-h changes in winter, as well as in spring and summer, there are distinct differences in absolute radon concentration values. This means that in winter, when the temperature inside the adit is higher than that of the atmospheric air, convection occurs. Because of this, even at the time when the mechanical ventilation is disconnected, i.e. in daytime (from 09:00 a.m. to 05:00 p.m.), convection air movements result in transportation of large amounts of radon out into the atmosphere. Because of this, its concentration in the adit in winter is almost a third of that in late spring and summer, when convection does not occur. Such a characteristic of ^{222}Rn activity concentration changes inside Fluorite Adit results in the fact that the least favourable conditions in terms of radiation protection in this space occur at the time of the heaviest tourist traffic, both in a year and a day. Thus, improperly used mechanical ventilation does not prevent radiation exposure of visitors and the staff. The authors have also observed an interesting regularity in the annual pattern of ^{222}Rn activity concentration. The characteristics of these changes are similar in residential buildings and underground spaces situated in the same or similar climatic zones.

When comparing daily changes in ^{222}Rn activity concentration in both studied underground spaces with those in a typical residential building, one notices a difference in the character of these changes. Remembering that the employees serving visitors in the Fluorite Adit live in typical buildings in terms of daily ^{222}Rn activity concentration, we could not overlook the fact that they live in extremely unfavourable conditions from the point of view of radiation protection.

For 24 h a day, they stay both at home and at work (in the adit) at the times when the values of radon concentration are the highest.

Therefore, one can say that inadequately considered and tested usage of mechanical ventilation not only does not prevent radiation exposure of employees in underground spaces, but it can even increase it. For this reason, it is essential to continue research into natural variations in ^{222}Rn activity concentration in underground spaces and, based on its results, develop appropriate methods and procedures aimed at reducing the exposure of people employed in these spaces to ionising radiation from radon and its progeny.

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References

Åkerblom, G.: Radon legislation and national guidelines, European Research into Radon in Construction Concerted Action (ERRICCA) Report F14P-CT96-0064(DG12-WSMN), 1999.

Bahtijari, M., Vaupotič, J., Grogeorič, A., Stegnar, P., and Kobal, I.: Exposure to radon in the Gadime cave, Kosovo, J. Environ. Radioactiv., 99, 343–348, 2008.

Banaś M.: Symptoms of mineralization in Śnieżnik Kłodzki metamorphic, Prace Geologiczne Komisji Nauk PAN, Kraków, 27, 1965 (in Polish).

Borucki J., Głowacki, Z., Masłowski, W., Sałdan, M., Uberna, J., and Zajączkowski W.: Estimation of prospection perspectives of uranium ore deposits in Poland, Prace Instytutu Geologicznego, Wydawnictwa Geologiczne, Warszawa, 1967 (in Polish).

Chibowski, S. and Komosa, A.: Radon concentration in basements of Old Town buildings in the Lublin region, Poland, J. Radioanal. Nucl. Ch., 247(1), 53–56, 2001.

Chruścielewski, W. and Olszewski, J.: Natural radiation in the tourist facility of underground adits No 9 and 9a in Kowary, (w) Zdulski M. (red.) – Człowiek, Środowisko, Zagrożenia, PAA w Warszawie, Biuro Obsługi Roszczeń Byłych Pracowników ZPR-1 w Jeleniej Górze, Wyższa Szkoła Pedagogiczna im. T. Kotarbińskiego w Zielonej Górze, Instytut Socjologii, Jelenia Góra, 125–131, 2000 (in Polish).

Ciba, J., Trojanowska, J., and Zołotajkin, M.: Little encyclopedia of chemical elements, Wydawnictwa Naukowo-Techniczne, Warszawa, 1996 (in Polish).

Ciężkowski, W., Marszałek, H., and Solecki, A.: Radon in the groundwaters and soil air of the Karkonosze granite area. Mat. Konf. Geoekologiczne Problemy Karkonoszy, Uniwersytet Wrocławski, Wrocław, 119–124, 1993 (in Polish).

Collé, R.: A precise determination of the ^{222}Rn half-life by 4-liquid scintillation measurements, Radioactivity & Radiochemistry, 6(1), 16–29, 1995a.

Collé, R.: Critically evaluated half-life for ^{222}Rn radioactive decay and associated uncertainties, Radioactivity & Radiochemistry, 6(1), 30–40, 1995b.

Cothern, C. R. and Smith Jr., J. E. (eds.): Environmental Radon, Plenum Press, New York, USA, 1987.

Cotton, F. A., Wilkinson, G., and Gaus, P. L.: Basics of Inorganic Chemistry, Wydawnictwo Naukowe PWN, Warszawa, 1995 (in Polish).

Daintith, J. (Ed.): Dictionary of Chemistry. Prószyński i S-ka, Warszawa, 2000 (in Polish).

Eheman, C., Carson, B., Rifenburg, J., and Hoffman, D.: Occupational exposure to radon daughters in Mammoth Cave National Park, Health Phys., 60(6), 831–835, 1991.

Emsley J.: Chemistry, a guide to elements, Wydawnictwo Naukowe PWN, Warszawa, 1997 (in Polish).

Fernàndez, P. L., Quindòs, L. S., Soto, J., and Villarm E.: Radiation exposure levels in Altamira Cave, Health Phys., 46(2), 445–447, 1984.

Field, M. S.: Risks to cavers and cave workers from exposures to low-level ionizing α radiation from ^{222}Rn decay in caves, J. Cave Karst. Stud., 69(1), 207–228, 2007.

Fijałkowska-Lichwa, L.: Occurrence of increased values of ^{222}Rn concentration in the air of underground tourist facilities in Lower Silesia – monitoring as a tool for assisting the determination of its causes, X Konferencja Naukowa Doktorantów i Młodych Uczonych, Interdyscyplinarne zagadnienia w górnictwie i geologii" pod redakcja Jana Drzymały i Wojciecha Ciężkowskiego, Szklarska Poręba 19–22 maja 2010, Prace Naukowe Instytutu Górnictwa PWr, 127, 131–140, 2010 (in Polish).

Gervino, G., Barca, D., Bruno, S., Bonetti, R., and Manzoni A.: Annual average and seasonal variations of indoor radon concentrations in Piedmont (Italy) using three different detection techniques, Nucl. Instrum. Methods., 572, 254–256, 2007.

Gillmore, G. K., Phillips, P., Denman, A., Sperrin, M., and Pearce, G.: Radon levels in abandoned metalliferous mines, Devon, Southwest England, Ecotoxicology and Environmental Safety, 49, 281–292, 2001.

Gillmore, G. K., Phillips, P. S., Denman, A. R., and Gilbertson, D. D.: Radon in the Creswell Crags Permian limestone caves, J. Environ. Radioactiv., 62, 165–179, 2002.

International Atomic Energy Agency (IAEA): Radiation Protection against Radon in Workplaces other than Mines, Safety Reports Series, 33, Vienna, 2003.

International Commission on Radiation Protection (ICRP): Protection against Radon-222 at home and at work, Publication No. 65, Pergamon Press, Oxford, UK, 1993.

Karpińska, M., Mnich, Z., and Kapała, J.: Seasonal changes in radon concentrations in buildings in the region of northeastern Poland, J. Environ. Radioactiv., 77, 101–109, 2004.

Kávási, N., Somlai, J., Kovács, T., Szabó, T., Várhegyi, A., and Hakl J.: Occupational and patient doses in the therapeutic cave, Tapolca (Hungary), Radiation Protecion Dosimetry, 106(3), 263–266, 2003.

Kies, A. and Massen, F.: Radon and underground climate in the Moestroff Cave, in: Gas geochemistry, edited by: Dubois, C., Alvarez Calleja, A., Bassot, S., and Chambaudet, A., University of Franche-Comtè, Besançon, France, Science Reviews, Nortwood, 63–70, 1995.

Kobal, I., Smodiš, B., Burger, J., and Škofljanec, M.: Atmospheric ^{222}Rn in tourist caves of Slovenia, Yugoslavia, Health Phys., 52(4), 473–479, 1987.

Kozak, K., Janik, M., Mazur, J., Kochowska, E., and Bogacz, J., Łoskiewicz, J., Swakoń, J., Zdziarski, T., and Haber, R.: Radon Calibration Chambers at the H. Niewodniczański Institute of Nuclear Physics, Report IFJ No. 1920/AP, 2003 (in Polish).

Kullab, M. K., Al-Bataina, B. A., Ismail, A. M., and Abumurad, K. M.: Seasonal variation of radon-222 concentrations in specific locations in Jordan, Radiat. Meas., 34, 361–364, 2001.

Lario, J., Sanchez-Moral, S., Cañaveras, J. C., Cuezva, S., and Soler, V.: Radon continuous monitoring in Altamira Cave (northern Spain) to assess user's annual effective dose, J. Environ. Radioactiv., 80, 161–174, 2005.

Lario, J., Sanchez-Moral, S., Cuezva, S., Taborda, M., and Soler, V.: High ^{222}Rn levels in a show cave (Castañar de Ibor, Spain): proposal and application of management measures to minimize the effects on guides and visitors, Atmos. Environ., 40, 7395–7400, 2006.

Li, X., Zheng, B., Wang, Y., and Wang, X.: A study of daily and seasonal variations of radon concentrations in underground buildings, J. Environ. Radioactiv., 87, 101–106, 2006.

Lu, X., Li, L. Y., and Zhang X.: An environmental risk assessment of radon in Lantian karst cave of Shaanxi, China. Water, Air Soil Poll., 198, 307–316, 2006.

Martinelli, G.: Gas geochemistry and ^{222}Rn migration processes. Radiation Protection Dosimetry, 78(1), 77–82, 1998.

Miliszkiewicz, A.: Radon, PWN, Warszawa, 1978 (in Polish).

Mogro-Campero, A. and Fleischer, R. L.: Subterrestrial fluid convection: a hypothesis for long-distance migration of radon within the earth, Earth Planet. Sc. Lett., 34, 321–325, 1977.

Olszewski, J. and Chruścielewski, W., and Jankowski, J.: Radon on underground tourist routes in Poland, International Congres Series, 1276, Elsevier, 360–361, 2005.

Papachristodoulou, C. A., Ioannides, K. G., Stamoulis, K. C., Patiris, D. L., and Pavlides, S. B.: Radon activity levels and effective doses in the Perama Cave, Greece, Health Phys., 86, 619–624, 2004.

Peńsko, J., Pachocki, K., Różycki, Z., Majle, T., Gorzkowski, B., and Wilejczyk E.: Radon therapy – radon inhalatorium in Kowary, Rocznik PZH, 49, 189–198, 1998 (in Polish).

Perrier, F. and Richon, P.: Spatiotemporal variation of radon and carbon dioxide concentrations in an underground quarry: coupled processes of natural ventilation, barometric pumping and internal mixing, J. Environ. Radioactiv., 101, 279–296, 2010.

Perrier, F., Richon, P., Crouzeix, C., Morat, P., and Le Mouël, J.-L.: Radon-222 signatures of natural ventilation regimes in an underground quarry, J. Environ. Radioactiv., 71, 17–32, 2004a.

Perrier, F., Richon, P., Crouzeix, C., Morat, P., and Le Mouël, J.-L.: Corrigendum to radon-222 signatures of natural ventilation regimes in an underground quarry, J. Environ. Radioactiv., 72, 369–370, 2004b.

Perrier, F., Richon, P., Gautam, U., Tiwari, D. R., Shrestha, P., and Sapkota, S. N.: Seasonal variations of natural ventilation and radon-222 exhalation in a slightly rising dead-end tunnel, J. Environ. Radioactiv., 97, 220–235, 2007.

Przeniosło, S.: Geochemistry of uranium in alluviums of eastern part of Lądek and Śnieżnik Kłodzki metamorphic, Biuletyn Instytutu Geologicznego, 224, Z badań petrograficzno-mineralogicznych i geochemicznych w Polsce, T. IV, 205–298, 1970 (in Polish).

Przylibski, T. A.: Changes in radon concentration in the air of Bear Cave in Kletno (Sudety), Przegląd Geologiczny, 44(9), 942–944, 1996 (in Polish).

Przylibski, T. A.: Radon in the air in the Millenium of the Polish State underground tourist route in Kłodzko (Lower Silesia), Arch. Environ. Prot., 24(2), 33–41, 1998.

Przylibski, T. A.: Radon concentration changes in the air of two caves in Poland, J. Environ. Radioactiv., 45(1), 81–94, 1999.

Przylibski, T. A.: Changes in the concentration of radon-222 and its daughter products in the air of the underground tourist route in Walim (Lower Silesia), Arch. Environ. Prot., 26(3), 13–27, 2000.

Przylibski, T. A.: Radon and its daughter products behaviour in the air of an underground tourist route in the former arsenic and gold mine in Złoty Stok (Sudety Mountains, SW Poland), J. Environ. Radioactiv., 57, 87–103, 2001.

Przylibski, T. A.: Radon in the air of caves and other underground tourist facilities. Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej, Nr 102, Studia i Materiały Nr 29, Górnictwo i Geologia VI, 167–179, 2002 (in Polish).

Przylibski, T. A.: Concentration of ^{226}Ra in rocks of the southern part of Lower Silesia (SW Poland), J. Environ. Radioactiv., 75(2), 171–191, 2004.

Przylibski, T. A. and Ciężkowski, W.: Seasonal changes of radon concentration in the Niedźwiedzia Cave (SW Poland), Il Nuovo Cimento, 22C(3–4), 463–469, 1999.

Przylibski, T. A. and Fijałkowska-Lichwa, L.: Radon occurrence in underground spaces with impeded ventilation, in: Dzieje górnictwa – element europejskiego dziedzictwa kultury, Tom 3, edited by: Zagożdżon, P. P., Madziarz, M., Ofic. Wyd. PWr., 380–394, 2010 (in Polish).

Przylibski, T. A. and Piasecki, J.: Radon as natural radioactive tracer of permanent air movements in the Niedźwiedzia Cave (Śnieżnik Kłodzki, Sudety Mts.), Kras i Speleologia, 28, 725–728, 1998.

Przylibski, T. A., Bartak, J., Kochowska, E., Fijałkowska-Lichwa, L., Kozak, K., and Mazur, J.: New SRDN-3 probes with a semiconductor detector for measuring radon activity concentration in underground spaces, J. Radioanal. Nucl. Ch., 285, 599–609, 2010.

Szerbin, P.: Radon concentrations and exposure levels in Hungarian caves, Health Phys., 71(3), 362–369, 1996.

Tanner, A. B.: Radon migration in the ground: a review, in: The Natural Radiation Environment, Chapter 9, edited by: Adams, J. A. S. and Lowder, W. M., University of Chicago Press, Chicago, USA, 253–276, 1964.

The Commission of the Recommendation of 21 February 1990 on the protection of the public against indoor exposure to radon: European Communities, 90/143/, 1–2, Euratom, 1990.

UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation: Sources and effects of ionizing radiation, Report to the General Assembly, with Scientific Annexes, New York, United Nations, 2000.

Vaupotič, J.: Nanosize radon short-lived decay products in the air of the Postojna Cave, Sci. Total Environ., 393(1), 27–38, 2008.

Waligórski M.: Information from National Atomic Energy Agency about the state of nuclear security and radiological protection in Poland in 2009, Bezpieczeństwo Jądrowe i Ochrona Radiologiczna, 2(80), 3–52, 2010 (in Polish).

The Health Protection Agency (UK), large network with the Centre of Radiation, Chemical and Environmental Hazards: www.hpa.org.uk/webw/HPAweb\&HPAwebstandard/HPAweb_C/1197636998945?p=1158934607683, last access: 4 April 2010, 2010.