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Radon problems in mining and post-mining areas in Upper Silesia region, Poland

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Abstract. The new basic safety standards (BSS) Directive 2013/59/Euratom [1] puts EU member states under an obligation to establish, amongst others, national radon action plans. In order to address the issue of long-term risks from radon exposures, it is important to identify areas where elevated levels of radon can be expected. One of the types of areas affected by an increased migration of radon and by the penetration of radon into buildings are areas in which industrial activity, for example, the exploitation of mineral resources, causes changes in the geological environment. The Upper Silesian Coal Basin (USCB) in Poland is one of the examples. The results of studies conducted in the past have shown that the levels of indoor concentration of radon, to a large extent, depend on the geological structure of the subsurface layers. One of the main factors influencing the migratory abilities of radon are the mining-induced changes of a rock body. We estimate that in specific radon-prone zones, the levels of radon may exceed 300 Bq/m^3 in approximately 2% of the dwellings. Another problem that may appear in post-mining areas is linked to the reclamation of radioactively contaminated areas. The complex geology of the strata in USCB, the mining activity that can be observed in the region and, additionally, the discharge of radium-bearing waters into the environment are the most significant factors affecting radon potential and hazard in dwellings in this region. In this paper, problems linked to the detection of radon in the mining area of USCB are presented.

Key words: radon • geology • mining and post-mining areas • mining-induced transformations

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Introduction

The most important determinant of whether there is a radon problem is the presence of uranium and radium in the bedrock and overburden. As the permeability of the ground controls the ease with which radon can be transported, any cavity that exists underground has the potential to accumulate elevated levels of radon. Buildings built upon the ground surface have the potential to draw in ground gas, which may have high concentrations of radon. This phenomenon is usually the result of an under pressure in buildings caused by the so-called chimney effect – hot air rising – and is generally a problem in cold and temperate climates. Whether ground gas with high concentrations of radon accumulates in buildings depends on their construction and the way in which buildings are occupied.

Poland has large reserves of coal and a long mining tradition. The Upper Silesian Coal Basin (USCB) is located in the south-western part of Poland (Fig. 1). The mining activity in this region has been carried out for more than 200 years with the oldest coal mine being erected in 1740. In the 1980s, there were more than 60 mines. Currently, there are 30 underground collieries that extract approximately 72 × 10^6 tons

Fig. 1. Location of Upper Silesian Coal Basin.

of hard coal per year. Approximately 98 000 miners were in employment at the end of 2014.

The USCB with its predominance of sedimentary rocks, which are low in permeability, and its negligibly low concentrations of uranium would at first sight not seem to be at a greater risk of being affected by radon-related problems. It has been indicated, however, that elevated levels of radon observed in such areas can be attributed to the local geology and can be a result of mining subsidence and artificial high permeability. Another possible source of radon potential is the surface contamination resulting from the discharge of radium-bearing coal mine waters.

Despite the fact that the proportion of dwellings with radon levels exceeding the action level threshold may be low in many areas, the total numbers of houses that are affected could be high because of the high density of population.

Applied investigation methods

Within the frame of radon investigation in Upper Silesia, different measurement methods were used. The integrated methods of measurements of the concentration of radon in buildings were performed with the use of Hungarian-type RSFS track detectors. The detector consists of a diffusion chamber in which a CR-39 plastic is placed. The plastic registers alpha particle tracks from the decay of radon and its daughter products. Most of the measurements were carried out in detached houses with basements, on the ground floors. Radon concentrations were calculated based on the number of tracks that showed the average value of radon concentration over the exposition period.

For the measurements of the concentration of radon in soil gas, the following method was applied. A spike was driven into the depth of 80–100 cm. The soil gas that was collected from this depth was pumped into the Lucas cell and, after several hours (at least 3), the activity of radon and decay products inside the cell was measured. The detection limit of the method was 0.2 Bq/l [2].

The measurement of the exhalation rate was done in two stages. First, the accumulation chamber was located at the chosen site for a certain period of time, approximately 3–4 h. At the end of this period, the air from the chamber was sampled into one or two Lucas cells and the radon concentration was measured. Finally, the exhalation rate was calculated by taking into account: accumulation time, the surface of the exhalation and the volume of accumulation chamber [3]. The applied technique of radon exhalation measurements can be considered only as indicator method. For the systematic measurements of radon exhalation rate, methods described in technical reports of the International Atomic Energy Agency (IAEA) [4] and [5] are recommended.

To gain a better understanding of the relationship between the levels of radon emission and the geological structure of the bedrock stratum, geophysical methods such as electrical resistivity profiling (PE) and electrical resistivity sounding (VES) were used in the study [4, 6].

Measurements of radon concentrations in the surface layer related to mining subsidence voids were done by Kies *et al.* [7]. He applied the ground penetrating radar (GPR) method to analyse underground inhomogeneities of rocks. The electrical resistivity methods were used in the analysis of the geological conditions to a depth of up to 50 m [8]. This analysis is focused on the location of strata discontinuities. It was assumed that the anomalies of the electrical properties of rock could be recorded using the electrical resistivity profiling method and could be attributed to the presence of contact zones of lithologically different rocks, zones of cracks and fissures as well as zones of void spaces and caved waste present in the bedrock. The presence of this type of strata discontinuities was identified as a factor that could be potentially conducive to an increase in effective cross-section of gas migration paths. The objective of the electrical resistivity sounding was to determine the lithostratography of bedrock in test sites and to obtain images of discontinuity on vertical cross-sections of strata. The test sites of geophysical investigations were located in zones exhibiting the highest values of indoor concentrations and exhalations of radon.

Factors influencing radon potential in Upper Silesian Coal Basin

The average concentration of radon for the area of the USCB, calculated on the basis of approximately 1000 long-term measurements that were carried out on the ground floors of houses located in the area is 47 Bq/m^3 and is comparable with the values given by other sources [9]. According to the Radiological Atlas of Poland [10], the average concentration of radon in dwellings in Poland is 49 Bq/m^3. The levels of concentration of radon that were measured range between 10 ± 8 and 1600 ± 180 Bq/m^3. The distribution of radon concentrations in dwellings in USCB is approximately log-normal [4, 11].

The most important factors influencing radon potential in Upper Silesia are discussed in the following text.

Local geology

The analysis of the results of measurements conducted in the USCB allowed us to conclude that the distribution of different levels of radon in buildings depends primarily on the local geological structure.

The USCB was formed during the Variscan orogeny and rejuvenated during the Alpine [12]. The coal-bearing Carboniferous, a typical multifacies formation, is composed of clastic rocks and coal seams in the form of a molasse association. The lack of limestone is a characteristic feature of this association. The USCB has Namurian and Lower Westphalian coal measures that are up to 8500-m thick. The Carboniferous strata are overlain by younger deposits ranging from Permian to Quaternary. Permian, Triassic and Jurassic strata are of erosional character. These deposits occur in the form of isolated remnants from larger entities. The younger Tertiary and Quaternary series, deposited under continental conditions, are undisturbed by faults and occur as continuous layers [13].

The average concentration of radon on the ground floors of houses, calculated for the whole area of Upper Silesia, is 47 Bq/m^3. It is indicated, however, that significant variations in different zones of the USCB can be observed [14]. In general, lower radon potential is correlated with the presence of Tertiary Miocene deposits in southern part of Upper Silesia. Elevated concentrations of radon were measured mostly in dwellings located in areas where permeable Triassic limestone and dolomite occur. Figure 2 demonstrates that the average values of radon concentration in buildings can be linked to local geology. We found that the areas with the highest levels of radon concentration in houses exhibit a specific geological structure. The formation enabling easier gas and radon migration are the Middle Triassic rocks represented by diploporita and ore-bearing dolomites and Gogolin limestones. These sediments are characterized by high fracturing with many fissures, small spatial density and porosity higher than that of the surrounding rocks [15]. The highest values of annual average activity concentration measured in that area of the occurrence of Triassic deposits often exceeds the average value for Upper Silesia and amount for 65 Bq/m^3 on the ground floor and 122 Bq/m^3 in the basement [4]. Radon exhalation rates depend on the geological structure of the investigated area. The lowest values varied between 2.4 and 8.6 mBq·m^2·s^{-1} and were measured on the youngest geological formations – Miocene and Quaternary. The range of values measured on the outcrops of Carboniferous deposits was between 6.4 and 26.6 mBq·m^2·s^{-1}. The highest values of radon exhalation rates reaching 79.4 mBq·m^2·s^{-1} were observed in the area with the occurrence of Triassic deposits [16].

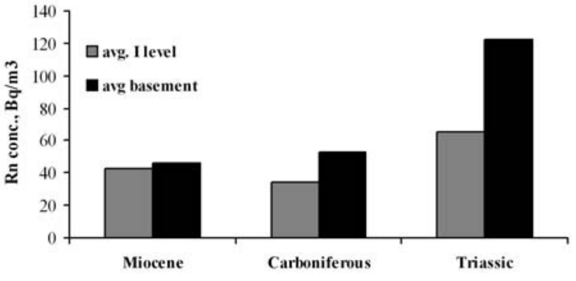

Fig. 2. Results of radon measurements in buildings in relation to local geology.

The most important factors influencing radon migration are rock porosity, pore size distribution and the nature of any fractures and desegregations features [17]. This is why the areas of occurrence of strongly fractured limestone and dolomite strata of the Upper Silesian Triassic formation are also likely to be radon-prone areas.

Tectonics

Local tectonics is another important element influencing radon migration. The area of Upper Silesia is strongly tectonized. The tectonics of the area is connected with the Hercynian orogeny, during which numerous faults and a number of folds, troughs and overthrusts were formed.

In the coal-bearing Upper Carboniferous, three structural zones are distinguished [18]:
- fold tectonics zone in the western part of the Basin,
- block tectonics zone in the central part of the Basin,
- block-folding tectonics zone in the northern and north-eastern parts of the Basin.

One of the largest tectonic dislocations of the region is the Kłodnicki fault zone that throws the strata to the south. The amplitude of the throw ranges from more than 400 m to about 20 m. The Kłodnicki fault is accompanied by a number of minor faults and deformations, the so-called plume faults. The fissures of the Kłodnicki fault are filled with fault breccia of sandstones, mudstones and coaly substance, as well as the blocks of sandstone [19, 20]. As the area of Upper Silesia is densely populated, numerous buildings are built in the area of fault zone. To determine whether the presence of fault influence radon potential, measurements of radon in soil gas concentration along traverses crossing fault zone were performed [21]. Significant changes in radon concentration within the fault zone were found. Concentrations decrease in areas where the fissures are filled with impermeable mudstones and coaly substance. The concentrations increase in areas where the fissures are less sealed with loamy, clay sediment (Figs. 3a and 3b). In Figs. 3 and 4, results of measurements of radon in soil concentration in the Kłodnicki fault zone are presented.

Studies involving geophysical methods such as electrical resistivity profiling (PE) and electrical re-

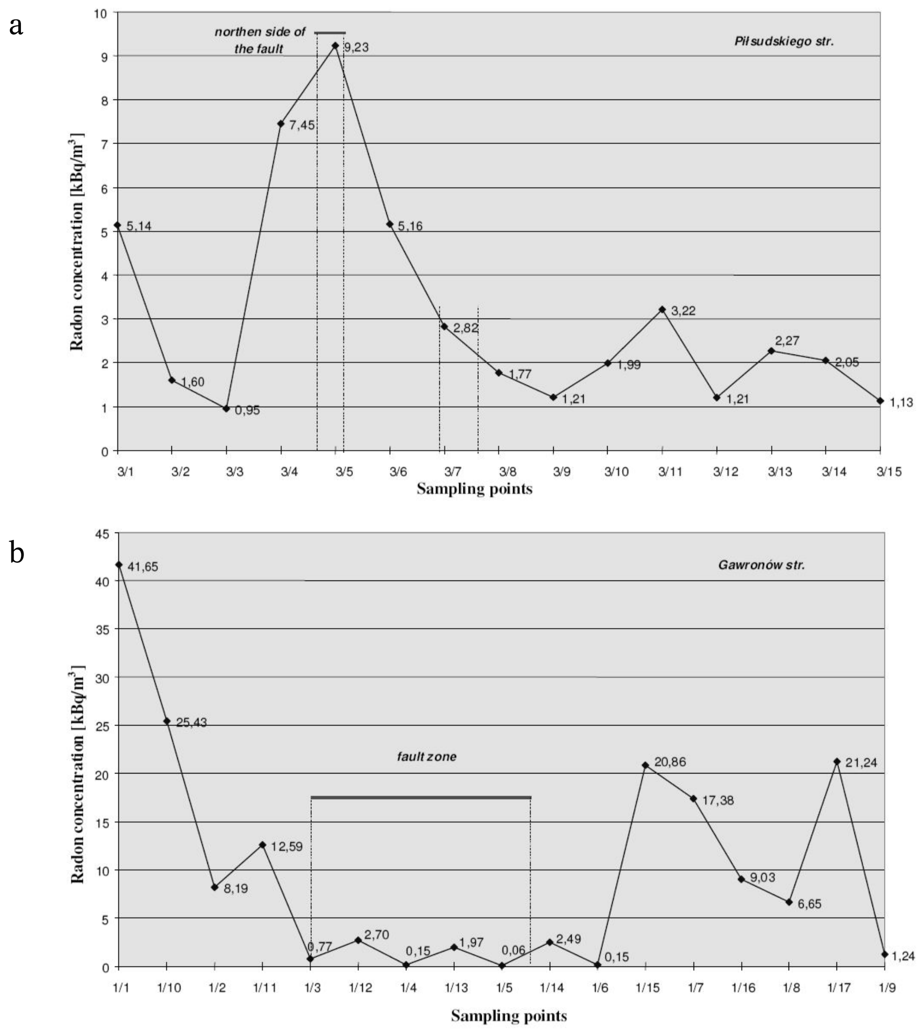

Fig. 3. The examples of the changeability of radon in soil concentrations across fault zone.

sistivity sounding (VES) were used [6, 22] to better understand the structure of the top stratum layer of a bedrock as the main source of radon emission. The results of the geophysical research supporting the analysis of geological data suggest that at sites where the values of radon concentrations are elevated, the tectonic- and mining-induced structural disturbances play a fundamental role in radon migration. The results of the geophysical research supporting the investigation of radon are presented in Fig. 4.

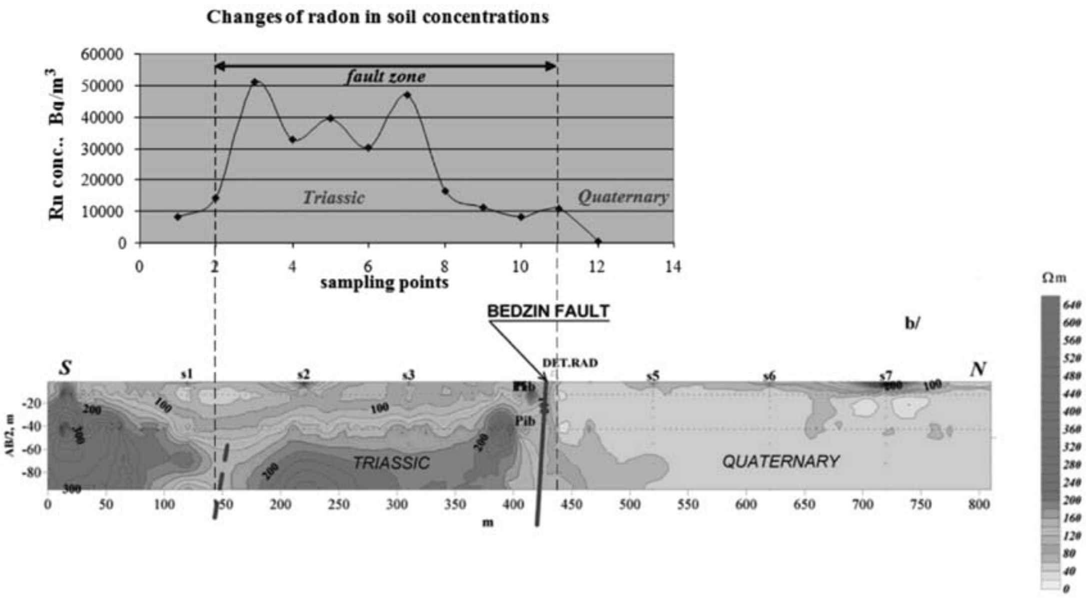

Fig. 4. Geophysical cross-section and results of radon in soil gas measurements in the fault zone.

In the fault zone indicated during the electroresistivity profiling, elevated radon in soil concentration were measured.

The effects of mining activity

In the area of present and past mining activity, the important factor influencing the migratory ability of radon are the mining-induced transformations taking place in a rock mass [4]. In Upper Silesia, coal and ore mining generate considerable changes in rock mass such as surface subsidence [23] and tectonic discontinuities along fault zones generated by mining-induced geodynamic phenomena (underground tremors and bumps). This process leads to recording high levels of radon in soil gas and often results from the enhanced permeability in zones of subsidence. Another phenomenon observed in mining and post-mining areas is the development of zones of karst process causing disintegration of rock body, which eventually enables the migration of gases. Karst processes can be observed in the northern and eastern part of Upper Silesia where the Triassic carbonate deposits occur. The mining-induced dislocations and damages have a strong influence on the foundations of building, creating cracks in floors and walls.

All the mining-induced factors mentioned earlier bring about considerable rock fragmentation of the strata. This can lead to the formation of the increased active surfaces of radon migration pathways in rock masses and can lead to radon exhalation to the atmosphere or to the buildings.

As the mining activity in the region of Upper Silesia has been carried out for more than 200 years, overlapping of effects of shallow exploitation of metal ores and deep coal mining is often observed. In such areas, damages of subsurface strata tend to be even more intense than in other parts of the USCB.

The total concentration of radon in soil gas is a combination of gas generated locally in the soil with that generated at shallow layers from the substrate. The depth at which this gas is generated is seldom greater than 5–10 m [24]. This explains high changeability of values of radon levels measured in sites located at very short distances from each other. In Fig. 5, results of the research carried out in one of the old mining communities in Upper Silesia are

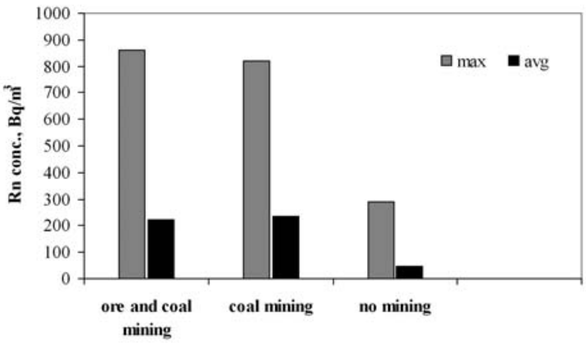

Fig. 5. Radon level in dwellings in relation to the mining activity.

presented. In this city, the following three areas were identified:

1. areas where historical ore mining is overlapped with contemporary hard coal mining,
2. areas where only coal mines are operating,
3. areas without any mining activity. In dwellings located in this zone, average radon concentration is significantly lower than in areas affected by mining.

Figure 5 shows the influence of mining activity on the level of radon in dwellings in a mining community.

Similar problems linked to an elevated radon potential in mining areas have been reported in Germany in zones where mining operations were carried out at shallow depth [25].

Presence of settling ponds and piles of wastes contaminated by radium isotopes

The USCB mine waters have extremely high concentrations of salts, much higher than oceanic levels. The total dissolved concentration is usually about 100 kg/m^3 but may be as high as 220 kg/m^3 [26]. Importantly, Silesian mining brines contain elevated concentrations of radium isotopes, ^{226}Ra and ^{228}Ra [27]. Considerable concentrations of radium are found at the surface, especially in settling ponds. Radium-bearing waters are discharged to settling ponds. Later on, after the suspended matter settles, these are discharged to brooks and rivers [28]. Sometimes enhanced levels of radium concentration in river waters, bottom sediments and vegetation are observed. As a result of the restructuring of the Polish coal industry, more than half of the operating collieries were closed during the past two to three decades. The dewatering of closed mines, however, still has to be continued. Many of the mines are connected by a complex system of galleries and cessation and dewatering of closed ones is not possible. Because of the continuing dewatering of closed collieries, the several tens of megabecquerel of ^{226}Ra and even higher activity of ^{228}Ra are still released daily into the settling ponds and rivers [27]. In Upper Silesia, there are currently more than 20 settling ponds in use, numerous of them containing waters and bottom sediments with enhanced concentration of radium isotopes. Some of the ponds are excluded from use, dried and reclaimed because of the fact that the former mining areas are transferred to local communities. Results of measurements of radon exhalation rates carried out within the borders of abandoned settling ponds and in their close vicinity varied from 2.0 mBq·m^2·s^{-1} up to more than 400 mBq·m^2·s^{-1}, which was the highest value measured in the USCB [27].

The methods of reclamation of the abandoned coal mine settling ponds have been selected in such a way as to reduce the risk of the spread of radioactive plum outside the objects. The sealing should be planned so as to avoid migration and penetration of that gas into buildings that might be built in the future in the areas of former and currently existing settling ponds. The investigation and observations carried out within the borders of the reclaimed pond, however, indicate that potential dwellers of buildings constructed in this area would be put at risk of being exposed to high doses of radon and its decay products. This is due to the fact that any damages and cracks in the insulation layers covering the bottom sediments of the liquidated pond can open pathways for radon migration.

Sites reclaimed with the use of waste material from the mining industry and coal combustion can also be problematic. Grounds contaminated by waste containing elevated radium concentration may be a source of an enhanced radon emission. In the past, waste material from coal mines stored on the surface was not monitored in terms of its content of natural isotopes because of the lack of general knowledge about Naturally Occurring Radioactive Materials (NORM) and Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). Boards of collieries do not have data concerning distribution of sites potentially contaminated by enhanced natural radioactivity. Preparing a map of radon potential of post-mining areas and the high changeability of factors influencing its migration should thus be considered.

Discussion and conclusions

The results of studies of radon performed in Upper Silesia have shown that the indoor concentration level of radon depends not only on the geological structure of the subsurface layers but also on factors divided into the following three groups:

1. Local geology:
   - deposits that overlie the surface of the Carboniferous,
   - tectonics.
2. The effects of mining activity:
   - disintegration of rock body,
   - the development of zones of karst process,
   - geodynamic phenomena,
   - fault zones activation – this may additionally increase radon risk activated by mining operations,
   - particularly intense damages of strata in areas of overlapping of historical shallow mining and current deep exploitation of hard coal,
   - damages of constructions caused by the surface subsidence, creating pathways for easier radon migration into buildings.
3. Coal mines closure operations that may have a severe impact on the surrounding environment:
   - presence of settling ponds and piles of wastes contaminated by radium isotopes,
   - reclamations of abandoned ponds,
   - sites not recorded in databases, which are potentially contaminated by enhanced natural radioactivity.

Radon monitoring in mining and post-mining areas should be done in as many buildings as possible because of the fact that factors enabling radon migration may occur simultaneously. Moreover, industrial areas are usually also highly inhabited and many of the people potentially exposed to elevated doses of radon and radon progeny live there.

The work was performed in Upper Silesia region, Poland.

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