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Research paper

Forecast of methane emission from closed underground coal mines exploited by longwall mining – A case study of Anna coal mine

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A R T I C L E I N F O

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A B S T R A C T

Closure and post-closure periods in underground coal mines present specific risks that have to be handled with sound management practices in order to achieve sustainability within the mining sector. These risks may negatively affect the environment and result in hazards on the surface caused by phenomena occurring in the rock mass after mining operations. One of the hazards that has to be considered in the process of coal mine closure is gas, which is caused by methane emission after mining operations cease.

This paper presents a forecast of methane emissions conducted within the framework of the Research Fund for Coal and Steel "MERIDA" project, using a model that was developed by the National Institute for the Environment and Industrial Hazards (INERIS) from France, and the Central Mining Institute (GIG) in Katowice, from Poland. This model enables the estimation of the volume of methane emitted into longwall goafs from relaxed undermined and overmined coal seams in order to assess in a further step the risk of methane emissions into the atmosphere from closed/sealed underground coal mines.

For a critical analysis of the forecasted methane emissions into the longwall goafs, the results obtained with this model were compared with a gas decline curve generated for longwall goafs from closed/sealed underground coal mines in Australia, where long term full range data was available. The results of the analysis allowed the forecasted emissions and, thus, the accuracy of the model to be validated.

The forecast was developed in the "Anna" coal mine, property of the PGG Company, which is located in the southern part of the Upper Silesian region in the south of Poland, near the border with the Czech Republic, and that is undergoing a closure process.

1. Introduction

The closure of an industrial facility brings consequences that are associated with different impacts on the environment. In most situations these problems refer only to land development and the management of industrial waste. The situation is different when an underground coal mine is closed. The hazards associated with past mining operations will affect the environment for many years and, some of them, which were monitored during exploitation, will occur uncontrollably. To prevent negative environmental effects related to the ceasing of mining operations, it is necessary to identify emerging hazards, and to analyse and assess the risks associated with the closure process in order to take steps aimed at minimising these risks. Nevertheless, nowadays limited guidance is available for mining operators (Laurence, 2011).

In some countries several specific guides have been developed, such as: the development of hazard maps in France (Didier, 2009); the implementation and planning of closure strategies in Finland (Heikkinen, Noras, Salminen, 2008); water mining strategies in South Africa (Pulles, 2008); comprehensive closure plans in Australia (Australian Department of Industry Tourism and Resources, 2006); and mine reclamation guidelines in Canada (Cowan, Mackasey, & Robertson, 2010).

In order to develop a full methodology to forecast how underground coal mine closures will affect the environment, an international project funded by the Research Fund for Coal and Steel (RFCS), called MERIDA (Krzemień et al., 2017) is being developed at the Central Mining Institute(GIG) in Katowice, Poland. Results of the research conducted by GIG and project partners from Spain, the United Kingdom, Germany, France, and the Czech Republic, will serve to identify the hazards and to develop environmental risk management procedures at closure and post-closure stages (Krzemień, Sánchez, Fernández, Zimmermann, González Coto, 2016).

To date other projects financed by the European Union have

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developed various tools to assess individual or global environmental impacts: optimising water discharge in MANAGER (Bondaruk, 2013), and in WATERCHERM (Pastor, Klinger, Talbot, 2008); subsidence hazard in PRESIDENCE (Directorate-General for Research and Innovation, European Commission, 2012); flooding management in FLOMINET (Directorate-General for Research and Innovation, European Commission, 2013); and impact assessment in ESIAS (Durucan, 1995).

Taking into consideration the number of environmental incidents, after mine closures, that took place in the United Kingdom (Broughton, 2014), Germany (Heitfeld, Rosner, Mühlenkamp & Sahl, 2004), the Czech Republic (Dvořáček & Slivka, 2004), etc., the need to develop specific guidelines to mitigate environmental risks has become a crucial issue for the European Union. This is stated in the "Strategic Implementation Plan for the European Innovation Partnership on Raw Materials" that includes a specific objective to mitigate environmental, social and health impacts, in order to put Europe at the forefront in raw material sectors (European Commission, 2013).

In Wałbrzych, the Lower Silesian Coal Basin (South-Western part of Poland), hard coal mines were closed between 1994 and 1998. During and after the process, certain phenomena were observed, which had influence on the environment and land development of Wałbrzych and the surrounding area. These phenomena were caused by surface deformation, the migration of gases into the near-surface layer of the rock mass, and aquifer recovery of the Carboniferous water table (Kowalski, 2000). The phenomena of the migration of gases form the mine into the near-surface layer of the rock mass and then to the atmosphere was studied by Szlązak, Obracaj and Borowski (2002). There were also incidents associated with coal mine closures in the Upper Silesian Coal Basin, such as a methane explosion in the Morcinek coal mine during its closure. The explosion was directly associated with the final stage of the coal mine closure process, when the shaft was being backfilled with gangue. Nine people who worked in the mine shaft during the closure were injured.

Research on coal mine closures, conducted within the framework of the MERIDA project (Krzemień et al., 2017), is based on several cases of Polish and Spanish coal mines together with supplementary data from research conducted by other project partners in different European countries. In Poland, the research is based on the ongoing closure of the Anna coal mine, located in the southern part of Upper Silesia, near the border with the Czech Republic. The Anna mine is one of the oldest coal mines in Poland. Its beginnings date back to 1832 when Ferdinand Friedrich August Fritze registered the coal mine together with a licence to build a drift tunnel, and to conduct mining works in a hard coal seam discovered in Pszów. The coal mine also continued its operations during World War II. It reached its peak production of 2,874,378 tonnes (9222 t/day) in 1978, with an average employment of 5591 people.

2. Study area

In 2004, the "Anna" coal mine merged with the "Rydułtowy" coal mine to become one mine: the "Rydułtowy-Anna" coal mine. The coal mines were located next to each other as the mining areas exploited by the mines were adjacent. The boundaries of mining operations in "Rydułtowy" seams 703/1, 706 (707/1–2), and 713/1–2 (exploited when the mines merged), planned due to mining and geological conditions and deposit tectonics, did not match the borders of the mining area, and the "Anna" coal mine continued exploitation of seam 703/1 within the "Rydułtowy" mining area. The mining area of the "Anna" coal mine was 28.66 km^2 (Fig. 1).

At the time of merging, the coal mines mining operations were conducted in the following seams: 703/1, 706 (707/1–2), 713/1–2, 713/1–2, and 712/1–2 in Ruch I ("Rydułtowy" coal mine), and 707/1–2 (706) and 713/1–2 in Ruch II ("Anna" coal mine). Geological characteristics of seams 706 (707/1–2) and 713/1–2 mined in both Ruch units, as well as mining conditions and natural hazards, were very similar.

At the same time, recoverable reserves of "Anna" coal mine were nearly depleted and within a few years the company would face a problem of the significant disproportion between its production capacity (haulage, vertical transport, air volume, etc.) and the size of the mining front.

The essential aim of merging the "Rydułtowy" and "Anna" coal mines was to, firstly, alleviate the process of ceasing production in the "Anna" coal mine and its closure and, secondly, to decrease production in the "Rydułtowy" coal mine. By establishing one mining company it was possible to use the existing mine infrastructure, number and qualifications of the personnel, and technical equipment.

Thanks to the changes in the technical infrastructure, including the connection between the ventilation networks of the mines, it was possible to close a number of mine workings and to improve ventilation conditions. It was particularly important for improving the safety of mining operations in seams with methane hazard. Moreover, it was possible to close the Kościuszko shaft and Głowacki shaft of the "Rydułtowy" coal mine, and access the deposits which had been locked in pillars securing the shafts.

The closure of "Anna" coal mine started in 2006 and was gradually implemented the in newly formed "Rydułtowy-Anna" coal mine. The process involved: closing underground mine workings, the backfilling of shafts, demolishing infrastructure on the surface, and the shutdown of the mine dewatering system. Within the framework of the securing works, a drainage dip heading was driven joining both (Region R in seam 713/1–2): mine water from the natural inflow of the Anna coal mine flows along the mine working to the drainage system of the "Rydułtowy" coal mine.

In 2016, "Anna" coal mine was taken over by Spółka Restrukturyzacji Kopalń Sp. z o.o. (mine restructuring company). Since then, the closure process has been continued. Until 2017, in "Rydułtowy" coal mine, coal was produced in a longwall in seam 713/1–2. In the second half of 2017, Chrobry I shaft and Ryszard II shaft were backfilled and now there is no ventilation connection between underground workings of former Anna coal mine and workings of "Rydułtowy" coal mine. This results in changes in the migration of mine gases, especially methane, and may pose a threat to the infrastructures on the surface.

Addressing geological aspects, the overburden consists of Holocene & Pleistocene clays and sands, as well as Miocene clays, sands and muds that are located deeper. In-between the coal seams there are sandstones layers and/or Carboniferous claystones and mudstones. For the purpose of this analysis, 32 longwalls were identified in four seams within the study area: 702/1–2, 707/1–2, 713/1–2, and 718/1–2. All these seems belong stratigraphically to the seams of Jaklowieckie Beds (700). The type of coal is gas-coking coal in all of them, with an ash content ranging from 2.98% to 22.20%, calorific value of 23,438–3251 kJ/kg, strength of 10–30 MPa, filtration coefficient of 10^{-6}–10^{-8} m/s, and permeability coefficient of 0.1–0.001 darcy. Table 1 presents the characteristics of the seams.

3. Gaseous emissions during the closure and post-closure period

Risk associated with methane occurrence during mining production is the main hazard which influences the safety of both personnel and mining operations. When the hazard increases, the works stop and the area is evacuated. In extreme situations, an increase in methane hazard and its consequences may determine the financial result, and even the future of the whole mine.

Closure of a gassy mine is associated with stopping the primary

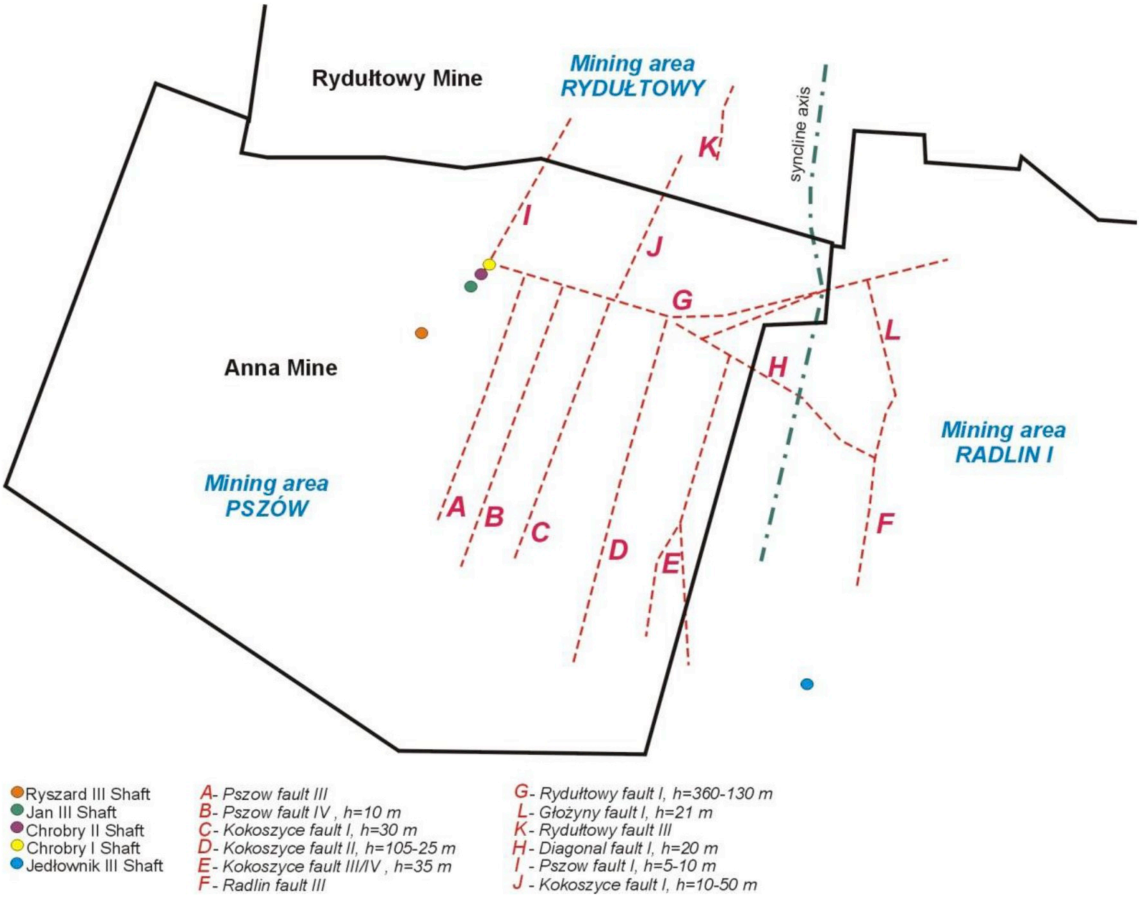

Fig. 1. Mining area of “Anna” coal mine.

ventilation system and creates good conditions for the gas to accumulate in underground mine workings and the surrounding rock mass. The gas can be released due to different mechanisms (Krause & Pokryszka, 2013; Pokryszka & Tauziede, 2000; Tauziede, Pokryszka, Barriere, 2002; Wrona, 2017): water level rising, barometric pressure variations, and ventilation pressure difference. This methane is known as Abandoned Mine Methane (AMM) (U.S. Environmental Protection Agency, 2009a).

According to the U.S. Environmental Protection Agency (2008), the factors that influence abandoned mine emissions are: time since abandonment, gas content, coal adsorption characteristics, CH_4 flow capacity, mine flooding, vent holes, and mine seals.

This gas, together with carbon dioxide (Sechman, Kotarba, Fiszer, Dzieniewicz, 2013), can rise to the surface mainly through former workings that link the mine with the surface, through the covering ground when it is permeable enough, through the sealing of the mine in a percentage that depends on the specific characteristics of the seal (Franklin, Scheehle, Collings, Cote, Pilcher, 2004), and through water release (Pokryszka et al., 2005, pp. 1–15). The gas can lead to accidents like explosions, asphyxia or intoxications (Besnard & Pokryszka, 2005).

Within coal seams saturated with methane, the gas is present in two forms (Kowalski, 2000; Krause & Dziurzyński, 2015):

- Sorbed gas, consisting of adsorbed gas condensed on the coal surface.
- Free gas, contained in pores and cracks of coal mass.

During mining operations in gassy seams, the flow of methane emitted into a longwall area comes from the mined seam as well as from undermined and overmined seams degassing within the stress relaxation zone.

Almost all the volumetric flow of methane emitted during mining operations in a given seam is transported with the return air from the longwall area to the ventilation system, and then through ventilation shafts to the surface. The remaining methane content in the run-of-mine is transported to the surface and emitted into the air. As an effect of the desorption phenomenon, methane released from overmined and undermined seams relaxed by mining operations fills cavities in adjacent mine working goafs. The distance between the overmined and undermined seams and the currently mined seam determines their degree of degassing, i.e. the volume of desorbed methane from a relaxed seam.

Fig. 2 shows the cross-section of the deposit around the longwall area and the estimated degassing of seams and the lowering of methane content in undermined and overmined seams within the stress relaxation zone. The cross-section and the range of the stress relaxation zone were combined with curves of degassing degree for the undermined and overmined seams. Within the zone there are three undermined seams p_1, p_2, and p_3, and two overmined seams n_1 and n_2.

The degassing degree curves combined with the cross-section of the stress relaxation zone enable the estimation of the degassing degree percentage of undermined and overmined seams depending on the distance from the currently mined seam. In given seams the value of the original methane content is divided by the degassing degree curve, into desorbed methane content M_{des} and residual methane content M_{wt}. The value of desorbed methane content M_{des} is emitted from the undermined and overmined seams during mining operations in the seam.

Table 1

Characteristics of the different seams in the study area.

Average absolute methane flow [m^3 CH$_4$/min]	Seam thickness	Seam inclination	Roof of the seam	Floor of the seam
Seam 703/1–2				
Year 2004: 16.09 Year 2005: 20.27 Year 2006: 11.82 Methane bearing capacity [m^3 CH$_4$/t $_{DAF}$] Min: 0.002 Max: 6.140 Average: 2.102	Between 1.60 and 1.90 m (average of 1.75 m), with no gangue intercalation	From 0° along the axis of the Jejkowice tectonic trough to ~15° on its both wings	Approximately a 110 m complex of mudstones intercalated by layers of sandstone and claystone (the immediate roof consists of 4–25 m of mudstone, followed by 4–6 m of sandstone)	1.0–3.5 m of mudstone, then 0.0–3.0 m of sandstone, with approximately 0.6 m of coal (seam 705/1), and 3.5–10 m of mudstone
Seam 707/1–2				
Year 2004: 6.61 Year 2005: 8.59 Year 2006: 9.59 Year 2007: 20.19 Year 2008: 16.21 Year 2009: 7.51 Year 2010: 9.02 Year 2011: 3.43 Methane bearing capacity [m^3 CH$_4$/t $_{DAF}$] Min: 0.006 Max: 5.795 Average: 2.485	Between 1.10 m and 2.40 m (average of 1.88 m), with no gangue intercalation	From 0° along the axis of the Jejkowice tectonic trough to ~15° on its both wings	Up to 9.0 m of mudstone, then approximately 3.5 m of sandstone and 4.0 m of mudstone. Above seam 703/1–2, mudstones, sandstones, and layers of seams 705/1, 705/2 and 705/3 occur alternately	Up to 2.0 m of mudstone and below 2.0–8.0 m of sandstone. Below there is 1.2–1.6 m of coal from seam 708 (vertical distance between seams 707/1–2 and 708 is approximately 10 m). Locally, in a very small area, seams 707/1–2 and 708 are connected
Seam 713/1–2				
Year 2006: 9.21 Year 2007: 7.01 Year 2008: 24.06 Year 2009: 14.54 Year 2010: 12.06 Year 2011: 8.02 Year 2012: 7.65 Year 2013: 15.26 Year 2014: 8.26 Year 2015: 2.07 Year 2016: 3.46 Year 2017: 6.16 Methane bearing capacity [m^3 CH$_4$/t $_{DAF}$] Min: 0.001 Max: 8.840 Average: 2.844	Between 2.3 and 2.5 m (average of 2.4 m) with a 0.2 m layer of interbedded impure coal	From 0° in the axis of the Jejkowice tectonic trough to ~20° on its both wings	3.0–13.0 m of mudstone and then 2.0–6.0 m of sandstone and alternately, layers of mudstone and sandstone. In the northern part of the Rydułtowy section there is the possibility of direct contact between sandstone and the roof of the seam	2.0–5.0 m of mudstone, and below there is sandstone with a thickness between 2.0 and 3.0 m, followed by a 0.2 m layer of imbedded impure coal
718/1–2				

(*continued on next page*)

Table 1 (*continued*)

Average absolute methane flow [m^3 CH_4/min]	Seam thickness	Seam inclination	Roof of the seam	Floor of the seam
Year 2004: 6.46 Year 2005: 12.91 Year 2006: 5.01 Methane bearing capacity [m^3 CH_4/t $_{DAF}$] Min: 0.030 Max: 8.950 Average: 3.817	Between 0.6 and 2.6 m with numerous interbedded inserts with a total thickness of up to 0.5 m	Between 6° and approximately 20° in the eastern wing of the Jejkowice tectonic trough	Approximately a 6.0 m layer of interbedded claystone	4.0 m of claystone with mudstone below

DAF – Dry Ash Free.

During longwall mining operations methane released from the undermined and overmined seams lowers the methane content of the seams to the value of residual methane content. The value of residual methane content M_{wt} of the relaxed seams, after reaching complex equilibrium, partially remains in the coal of the seams and then diffusively (over a long period of time) migrates from the seams relaxed from prior mining operations.

When the closed workings are flooded, the water table rises and gases are ejected towards the surface. It is known as the piston effect (Krause, 2008b). The course of the hydrogeological and gas phenomena in mining areas of gassy coal mines within the closure process may affect the safety of work in adjacent coal mines, and on the surface of mining areas (Krause, 2008a).

4. Methodology

Research conducted in GIG's Barbara experimental mine, based on results of ventilation and methane tests, showed that mine workings adjacent to goafs in gassy mines led to methane emission into goafs for up to 15 years after mining operations cease, according to a model developed by Krause and Pokryszka (2013), presented in Fig. 3. The brown line represents the model, while curves 1, 2, and 3, reflect the methane quantities emitted into the goafs of mined seams, depending on the different contributions of undermined as well as overmined seams. These contributions vary according to the range of induced mining stress relief.

The model assumptions refer to three stages which characterise changes in methane emission into the longwall area during and after mining operations (Krause & Pokryszka, 2013). They are as follows:

1. *Mining period*: absolute methane emission increases up to the value of the maximum methane emission during the mining period for the given conditions. It usually lasts between a few and several months (approximately 1 year).
2. *Post-mining period*: this includes the time necessary to prepare and close a longwall (approximately 3 months). Longwall methane emission decreases to approximately 20% of the average value of the maximum methane emission during the mining period.
3. *Goaf period*: when the absolute methane emission of goafs systematically decreases from the previous value until it completely disappears after 15 years.

Each mined longwall in a gassy seam, depending on its orientation towards relaxed gassy seams, will have a unique course of methane emission during and after mining operations. The model of methane emission from undermined and overmined seams into goafs after mining operations depends on the value of the mean absolute methane-bearing capacity of the production period (Krause & Łukowicz, 2000, pp. 1–36).

Methane emission into a goaf from relaxed overmined and undermined seams during the 15-year period after longwall mining operations cease, for each year separately, can be obtained approximately, with the following formula (Krause & Pokryszka, 2013):

$$V_G = 0.2V_A\left(1 - \frac{u}{15}\right) \tag{1}$$

where:

V_G is the methane emission into a goaf from relaxed overmined and undermined seams during the 15-year period after longwall mining operations cease, calculated for each year separately, in m^3 CH_4/min, V_A is the average absolute methane emission throughout the life of a longwall during the mining operation period in m^3 CH_4/min, and u is the number of years after mining operations ceased.

The assessed volume of methane emitted every year into goafs of n longwalls can be expressed with the following equation in m^3 CH_4/min (Krause, 2008a):

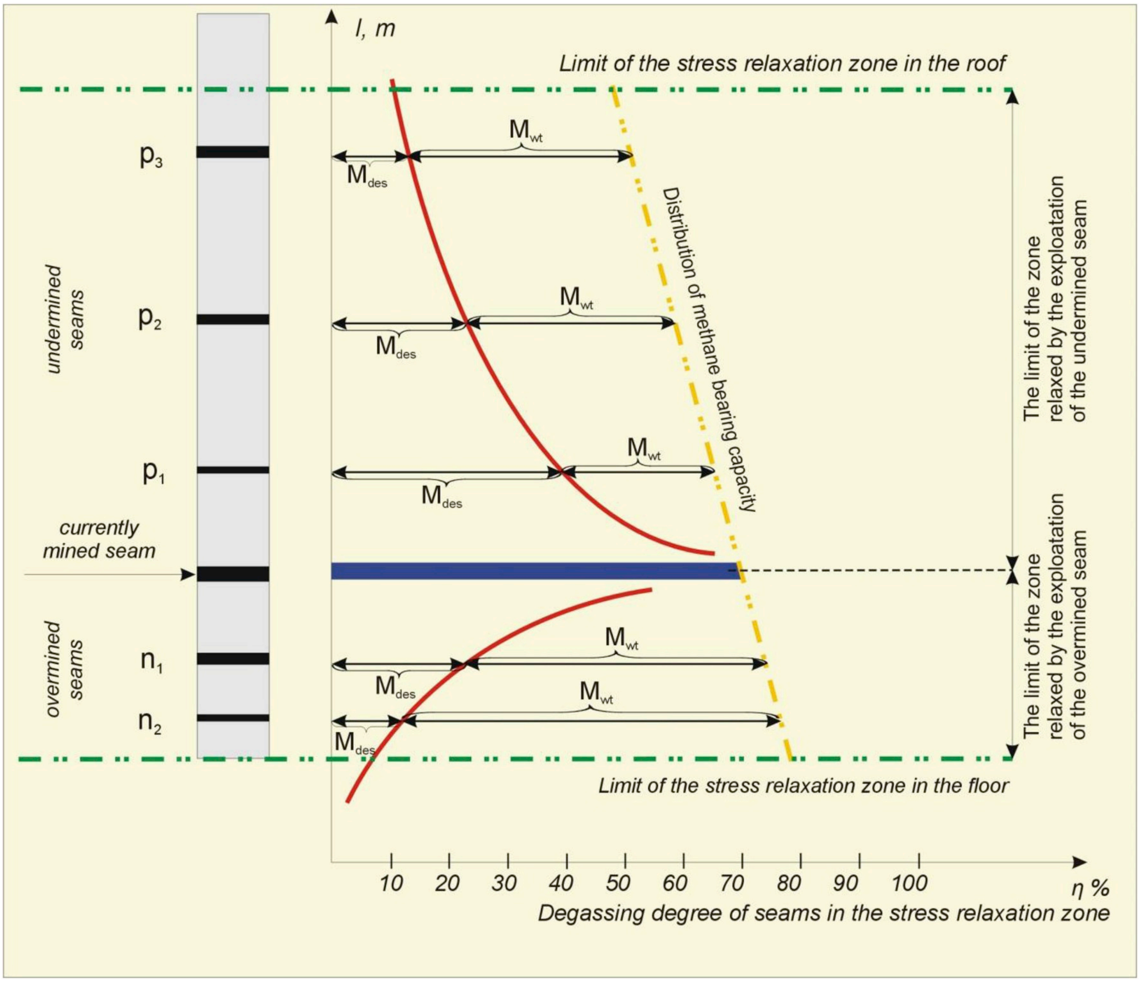

Fig. 2. Degassing degree of undermined and overmined seams within the stress relaxation zone (Krause & Pokryszka, 2013).

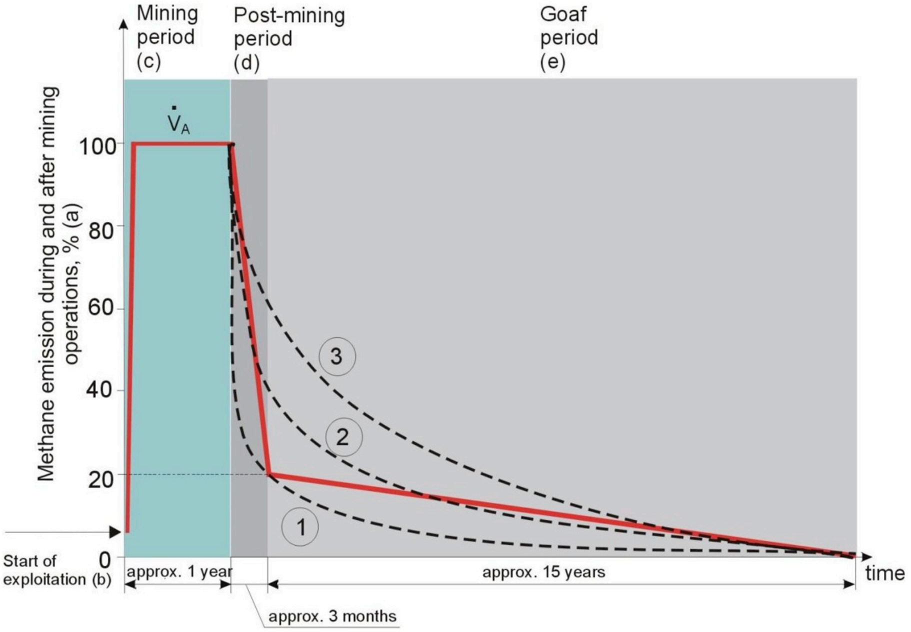

Fig. 3. Model of methane emission from goafs (Krause & Pokryszka, 2013).

$$V_M = \sum_{i=1}^{n} V_{G_i} \tag{2}$$

where:

V_M is the forecasted volume of methane emitted every year into goafs of n longwalls in m^3 CH_4/min, V_{G_i} is the forecasted volume of methane emitted in every single goaf i in m^3 CH_4/min, and n is number of longwalls exploited in the period of the previous 15 years before the closure of the mine.

The total forecasted volume of methane emitted during the 15-year period after longwall mining operations cease, into goafs of n longwalls can be expressed with the following equation in m^3 CH_4/min:

$$V_T = \sum_{i=1}^{15} V_{M_i} \tag{3}$$

where:

V_T is the total forecasted volume of methane emitted during the 15-year period in m^3 CH_4/min, V_{M_i} is the forecasted volume of methane emitted every year into goafs from all the longwalls in m^3 CH_4/min.

For a critical analysis of the forecasted methane emissions into the sealed longwall goafs, the results given by this model were compared with a gas decline curve generated for longwall goafs from closed underground coal mines in Australia, where long-term full range data was available. This decline curve was calculated by means of empirical results as the following equation in litres of CH_4/s (Lunarzewski, 2010):

$$F(x) = ae^{-bx} \tag{4}$$

where:

$F(x)$ is the quantity of gas in litres of CH_4/s, x is the time expressed in months, a is the methane emission intensity, and b is the decline constant. Both a and b were calculated empirically.

5. Results of forecasted methane emissions and discussion

Based on the above dependence and after conducting analyses of seams, longwalls, and absolute methane emissions during the period of mining operations in the “Anna” coal mine, it was possible to forecast methane emissions after sealing off ventilation connections between underground workings of the “Anna” coal mine and “Rydułtowy” coal mine, when mining operations in them cease.

Tables 2–5 present the forecasted methane emissions into the goafs of the different seams according to the model developed by Krause and Pokryszka (2013).

The analysed mining operations in seam 703/1–2, ended with the mining of longwall R-16a in 2006. Between 2004 and 2006, nine longwalls were mined in seam 703/1–2. In 2017, the total forecasted methane emission into goafs was 1.65 m^3 CH_4/min. Methane emission will cease in 2021.

The forecasted methane emission into goafs in seam 707/1–2 included 11 longwalls mined between 2004 and 2011. Methane emission into goafs will cease in 2025 and will include goafs of longwall R-16, where production ended in 2011. The total methane emission into goafs in seam 707/1–2 in 2017–2026 is presented in the last column of Table 2. The volume of methane emission in the aforementioned years will decrease from 3.41 to 0.04 m^3 CH_4/min. In 2017, the forecasted methane emission into the goafs of the 11 longwalls in seam 707/1–2 was 1,792,296 m^3.

In the analysed seam 713/1–2, mining operations were conducted until mid-2017 in longwall R-15. Between 2008 and 2017, mining operations in seam 713/1–2 were conducted in nine longwalls. The seam has the biggest share of methane emission into goafs of the closed “Anna” coal mine. Only in 2017, the methane emission was 4,782,960 m^3. Methane emission will cease in 2032.

The forecasted methane emission into goafs in seam 718/1–2 concerns three longwalls where mining operations stopped between 2004 and 2006. Methane emission into goafs in seam 718/1–2 will cease in 2021, and will have negligible influence on the total methane emission into goafs during closure. In the period 2017 to 2021, it will decrease from 0.75 m^3 CH_4 to zero.

Equations (1) and (2) enable the forecast of methane emission into the goafs of the “Anna” coal mine until it ceases, i.e. until 2031. The forecasted volume of methane emitted into goafs in consecutive years is presented in Fig. 4, and it refers to the goafs of closed longwalls which are not flooded.

The only way to determine the validity of the model and the forecasted methane emissions, without the use of field measures, is to contrast the obtained results with other models that were developed for longwall goafs in closed underground coal mines, where long-term full range data was available.

This is the case of the model developed by Lunarzewski (2010) after extensive studies conducted by Lunagas Pty Limited in Australia, as well as in the United Kingdom, the Czech Republic, Poland, Japan and the USA.

Fig. 5 presents the results obtained with the model of Krause and Pokryszka (2013), and the gas decline curve presented by Lunarzewski (2010).

As can be seen in Fig. 5, both curves are very similar. After the initial decay, Krause and Pokryszka's (2013) model keeps below, although very close to, Lunarzewski's (2010) model. Comparing the total amount of methane emitted, Krause and Pokryszka's (2013) model represents 90.03% of the figure obtained with the Lunarzewski's (2010) model.

Thus, taking into account that the Krause and Pokryszka's (2013) model was specifically developed for Polish coal mines, we can state that it can be considered a valid approximation for the methane emission forecast into longwall goafs in closed underground coal mines.

Following the closure of the “Anna” coal mine, water from the mine workings located near the Chrobry I shaft will build up at the level of 1000 m and then it will flow gravitationally from the parallel crosscut at the level of 1000 m to the drainage dip heading in Region R until it reaches a stopping. The benchmark of the stopping is −840 m. From this point, water will be pumped. Methane emitted into the closed

Table 2

Forecasted methane emission into goafs in seam 703/1-2.

Longwalls	G-4	R-15	G-4a	R-14	G-3a	G-5	R-16	G-5a	R-16a	Total
End of mining operations	2004	2005	2005	2004	2004	2005	2006	2006	2006	
Methane emission into goafs of longwalls in consecutive years [m^3 CH_4/min]										
2017	0.08	0.28	0.14	0.19	0.08	0.14	0.32	0.16	0.27	1.66
2018	0.04	0.19	0.09	0.09	0.04	0.09	0.24	0.12	0.20	1.10
2019	–	0.09	0.05	–	–	0.05	0.16	0.08	0.13	0.56
2020	–	–	–	–	–	–	0.08	0.04	0.07	0.19
2021	End of methane emission into goafs in seam 703/1-2									

Table 3
Forecasted methane emission into goafs in seam 707/1-2.

Longwall	G-2	G-2a	G-3	G-3a	G-4	R-14	G-4a	G-5	G-5a	R-15	R-16	Total
End of mining operations	2004	2004	2005	2006	2007	2008	2007	2007	2008	2010	2011	
Methane emission into goafs of longwalls in consecutive years [m^3 CH_4/min]												
2017	0.10	0.11	0.15	0.22	0.28	0.43	0.43	0.27	0.32	0.71	0.40	3.42
2018	0.05	0.05	0.10	0.16	0.23	0.36	0.34	0.21	0.26	0.62	0.36	2.74
2019	–	–	0.05	0.11	0.17	0.29	0.26	0.16	0.21	0.53	0.31	2.09
2020	–	–	–	0.05	0.11	0.22	0.17	0.11	0.16	0.45	0.27	1.54
2021	–	–	–	–	0.06	0.14	0.09	0.05	0.11	0.36	0.22	1.03
2022	–	–	–	–	–	0.07	–	–	0.05	0.27	0.18	0.57
2023	–	–	–	–	–	–	–	–	–	0.18	0.13	0.31
2024	–	–	–	–	–	–	–	–	–	0.09	0.09	0.18
2025	–	–	–	–	–	–	–	–	–	–	0.04	0.04
2026	End of methane emission into goafs in seam 707/1-2											

"Anna" coal mine will not migrate into the workings and the goafs of the still operating "Rydułtowy-Anna" coal mine.

Table 5
Forecasted methane emission into goafs in seam 718/1-2.

Longwalls	J-1	J-2	J-3	Total
End of mining operations	2004	2005	2006	
Methane emission into goafs of longwalls in consecutive years [m^3 CH_4/min]				
2017	0.20	0.28	0.27	0.75
2018	0.10	0.19	0.20	0.49
2019	–	0.09	0.14	0.23
2020	–	–	0.07	0.07
2021	End of methane emission into goafs in seam 718/1-2			

6. Conclusions

The results of the two models compared in this paper are very similar, as Krause and Pokryszka's (2013) model represents 90.03% of the figures obtained with the Lunarzewski's (2010) model, so Krause and Pokryszka's (2013) model can be considered a good forecast for methane emissions from closed underground coal mines exploited by longwall mining.

Estimation of the volume of methane emitted from a relaxed seam will enable us to assess when cavities of a closed mine will fill with methane and then assess the risk of gas hazard occurring on the surface. As the goafs and workings of the "Anna" coal mine, located around level 1000 m, are partially flooded, it is necessary to estimate methane emission from flooded goafs. Water limits of methane emission will decrease the total volume of methane emitted into the mine. After 2017, the level of water will rise, filling goafs and workings located above. Once the level of water in Ruch "Anna" stabilizes, it will be possible and necessary to conduct methane drainage operations from the surface to avoid methane hazard.

Non-CO_2 gases play an important role in efforts that allow global climate change to be understood and addressed, so these forecasts will also help with the development of emission inventories from abandoned coal mines in order to quantify the anthropogenic sources of greenhouse gases (Cote, Collings, Pilcher, Talkington, & Franklin, 2004). In addition, this will help to fulfil the commitment to the United Nations Framework Convention on Climate Change (UNFCCC) to make available and publish national inventories of greenhouse gas emissions.

Furthermore, these forecasts may also be useful for addressing feasibility studies of methane recovery opportunities. Moreover, degasification systems that drain methane from abandoned mines prevent the gas escaping into other mine working areas, improving mine safety, and reducing methane-related delays and ventilation costs. Degasification systems may include vertical wells, in-mine boreholes,

Table 4
Forecasted methane emission into goafs in seam 713/1-2.

Longwalls	J-12	G-2	R-14	J-11	G-1	R-16	R-17	R-15a	R-15	Total
End of mining operations	2008	2010	2009	2010	2012	2013	2014	2015	2017	
Methane emission into goafs of longwalls in consecutive years [m^3 CH_4/min]										
2017	0.64	0.55	0.71	0.26	0.71	0.72	1.10	0.37	4.04	9.10
2018	0.53	0.48	0.61	0.23	0.64	0.65	1.01	0.34	0.75	5.24
2019	0.43	0.41	0.51	0.19	0.57	0.59	0.92	0.31	0.70	4.63
2020	0.32	0.34	0.41	0.16	0.50	0.52	0.83	0.28	0.65	4.01
2021	0.21	0.27	0.31	0.13	0.43	0.46	0.73	0.25	0.59	3.38
2022	0.11	0.21	0.20	0.10	0.36	0.39	0.64	0.23	0.54	2.78
2023	–	0.14	0.10	0.06	0.29	0.33	0.55	0.20	0.48	2.15
2024	–	0.07	–	0.03	0.21	0.26	0,46	0.17	0.43	1.63
2025	–	–	–	–	0.14	0.20	0.37	0.14	0.38	1.23
2026	–	–	–	–	0.07	0.13	0.28	0.11	0.32	0.91
2027	–	–	–	–	–	0.07	0.18	0.08	0.27	0.60
2028	–	–	–	–	–	–	0.09	0.06	0.22	0.37
2029	–	–	–	–	–	–	–	0.03	0.16	0.19
2030	–	–	–	–	–	–	–	–	0.11	0.11
2031	–	–	–	–	–	–	–	–	0.05	0.05
2032	End of methane emission into goafs in seam 713/1-2									

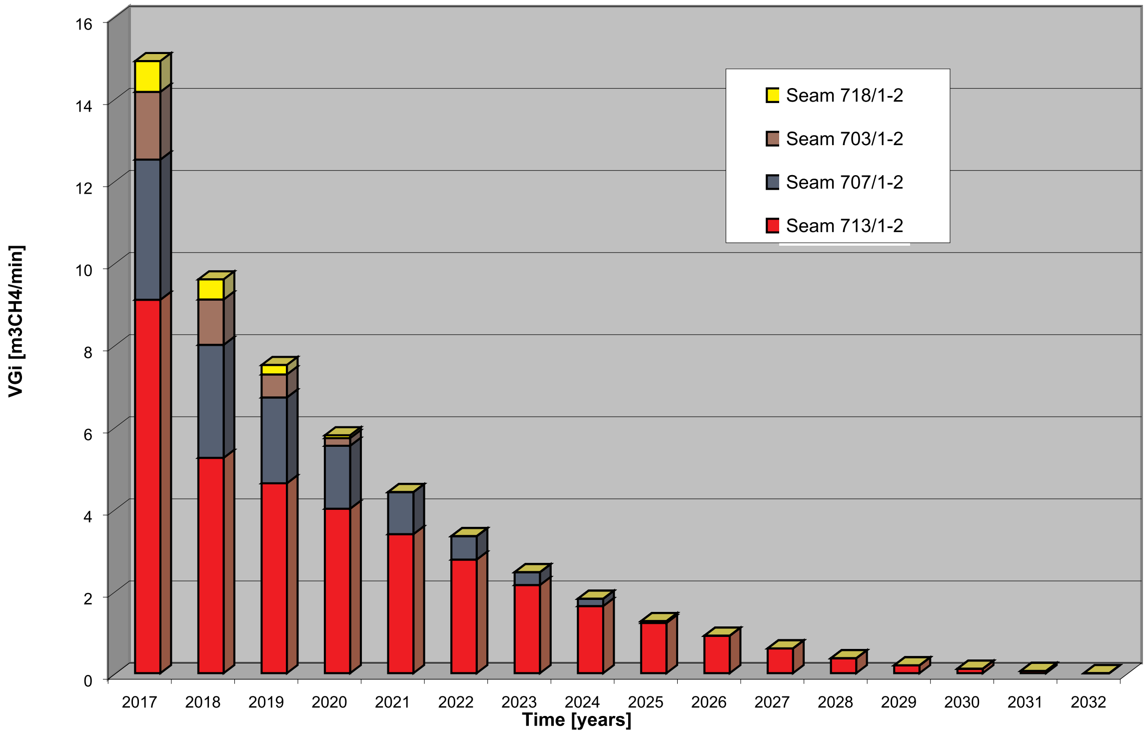

Fig. 4. Forecasted methane emission into the goafs of “Anna” coal mine seams, 2017–2032.

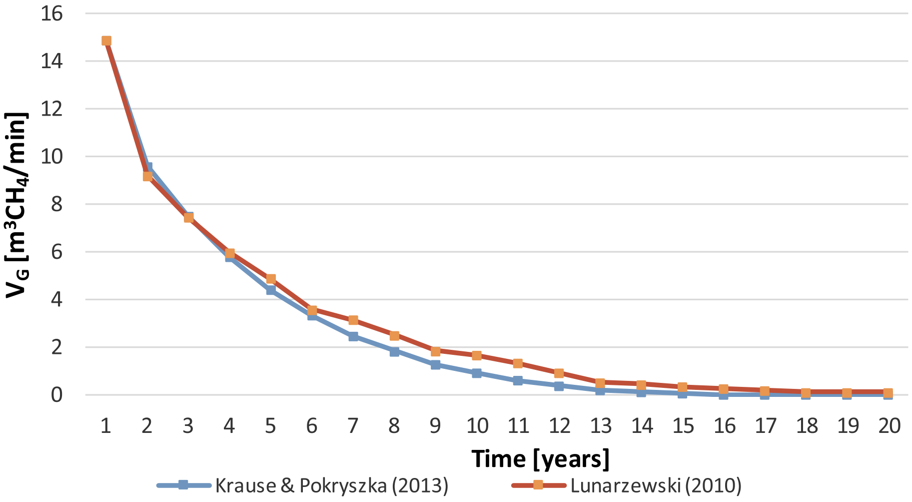

Fig. 5. Comparison of results between the models.

and goaf wells (U.S. Environmental Protection Agency, 2009b).

Finally, following the tendency to target maintenance-free mine closure plans after transitional monitoring (Sawatsky, 2012), these forecasts will help establish a clear limit to achieve this goal, something that is important considering the financial provision statement for the closure cost assessment that coal mines have to develop.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Appendix

Numerical results obtained with the models of Krause and Pokryszka (2013) and Lunarzewski (2010), in m^{3}CH$_4$/min.

Year	Krause and Pokryszka (2013)	Lunarzewski (2010)
1	14.91075554	14.91075554
2	9.592779675	9.194965916
3	7.506359366	7.45537777
4	5.795037495	5.964302216
5	4.411562725	4.887414316
6	3.337906864	3.562013823
7	2.459636284	3.14782617
8	1.812556446	2.485125923
9	1.267538145	1.822425677
10	0.912551991	1.656750616
11	0.602401392	1.325400492
12	0.363584127	0.911212839
13	0.18977037	0.497025185
14	0.107718519	0.414187654
15	0.053859259	0.331350123
16	0	0.248512592
17	0	0.165675062
18	0	0.082837531
19	0	0.082837531
20	0	0.082837531
Total	53.3240182	59.22883451

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jsm.2018.06.004.

References

Australian Department of Industry Tourism and Resources (2006). Mine closure and completion. Queensland government, Australia. Retrieved November 9, 2017, from http://www.minerals.org.au/file_upload/files/resources/enduring_value/mine_closure.pdf.

Besnard, K., & Pokryszka, Z. (2005). Gases emission monitoring in a post-mining content. *Paper presented at the Actes du Colloque international Après-mine 2005, November 16–17, Nancy, France*.

Bondaruk, J. (2013). *Management of mine water discharges to mitigate environmental risks for post-mining period (MANAGER)*. Retrieved November 9, 2017, from http://manager.gig.eu.

Broughton, P. (2014). Developing approaches to the control of risk from abandoned mine entries. *9th safety seminar, safety managing the challenge of change* (pp. 47–61). Sheffield: The Midland Institute of Mining Engineers.

Cote, M., Collings, R., Pilcher, R. C., Talkington, C., & Franklin, P. (2004). *Methane emissions from abandoned coal mines in the United States: Emission inventory methodology and 1990–2002 emissions estimates.* U.S. Environmental Protection Agency. Retrieved November 9, 2017, from http://www.epa.gov/coalbed/docs/amm_final_report.pdf.

Cowan, J., Mackasey, W. R., & Robertson, W. O. (2010). *The policy framework in Canada for mine closure and management of long-term liabilities.* Canada: National Orphaned - Abandoned Mines Initiative. Retrieved November 9, 2017, from http://www.abandonedmines.org/pdfs/PolicyFrameworkCanforMinClosureandMgmtLiabilities.pdf.

Didier, C. (2009). Postmining management in France: Situation and perspectives. *Risk Analysis, 29*(10), 1347–1354. http://doi.org/10.1111/j.1539-6924.2009.01258.x.

Directorate-General for Research and Innovation, European Commission (2012). Prediction and monitoring of subsidence hazards above coal mines (Presidence) (Final report, EUR 25097) http://doi.org/10.2777/3356.

Directorate-General for Research and Innovation, European Commission (2013). Flooding management for underground coal mines considering regional mining networks (Flominet) (Final report, EUR 25905) http://doi.org/10.2777/94695.

Durucan, S. coordinator. (1995). *Environmental simulation and impact assessment system for the mining Industry (ESIAS).* Directorate-General for Research and Innovation. European Commission.

Dvořáček, J., & Slivka, V. (2004). Environmental and safety problems of Ostrava-Karviná district. *Zeszyty Naukowe Politechniki Ślakiej Seria Górnictwo, 260*, 551–558.

European Commission (2013). Strategic implementation plan for the european innovation partnership on raw materials. Retrieved November 9, 2017, from http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/eip-sip-part1_en.pdf.

Franklin, P., Scheehle, E., Collings, R. C., Cote, M. M., & Pilcher, R. C. (2004). Proposed methodology for estimating emission inventories from abandoned coal mines. *2006 IPCC guidelines for national greenhouse gas inventories fourth authors/experts Meeting: Energy (28–30 september 2004): Vol. 2.* (October 2004), 64. Retrieved November 9, 2017, from http://www.epa.gov/coalbed/docs/methodology_abandoned_coalmines.pdf%255Cnhttp://www.ipcc-nggip.iges.or.jp/meeting/meeting.html%255Cnhttp://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/List_of_Participants_Energy.pdf.

Heikkinen, P. M., Noras, P., & Salminen, R. (Eds.). (2008). *Mine closure Handbook: Environmental techniques for the extractive industries. Espoo, Finland*. Retrieved November 9, 2017, from http://arkisto.gtk.fi/ej/ej74.pdf.

Heitfeld, M., Rosner, P., Mühlenkamp, M., & Sahl, H. (2004). Bergschäden im Erkelenzer Steinkohlenrevier. *Altbergbaukolloquium* (pp. 281–295). (Montanuniversität Leoben).

Kowalski, A. (Ed.). (2000). *Eksploatacja górnicza, a ochrona powierzchni. Doświadczenia z wałbrzyskich kopalń. [Mining exploitation versus surface protection. Experiences from the Wałbrzych mines]*. Katowice: Główny Instytut Górnictwa.

Krause, E. (2008a). Prognozowanie wydzielania metanu do rejonów poeksploatacyjnych kopalń czynnych i likwidowanych przez zatopienie. [Forecasting of methane emissions to the gob areas of operating coal mines and those already liquidated by flooding]. *Zeszyty Naukowe Politechniki Śląskiej. Seria Górnictwo, 283*, 129–137.

Krause, E. (2008b). Technologie odmetanowania wpływające na poprawę bezpieczeństwa eksploatacji oraz ograniczenie emisji metanu do atmosfery. [Technologies of degasification affecting safety of coal exploitation and reduction of methane emissions to the atmosphere]. *Zeszyty Naukowe Politechniki Śląskiej. Seria Górnictwo, 283*, 113–128.

Krause, E., & Dziurzyński, W. (2015). *Projektowanie eksploatacji pokładów węgla kamiennego w warunkach skojarzonego zagrożenia metanowo-pożarowego. [Designing the exploitation of coal seams in conditions of combined methane-fire hazard]*. Katowice: Główny Instytut Górnictwa.

Krause, E., & Pokryszka, Z. (2013). Investigations on methane emission from flooded workings of closed coal mines. *Journal of Sustainable Mining, 12*(2), 40–45. http://doi.org/10.7424/jsm130206.

Krause, E., & Łukowicz, K. (2000). *Dynamiczna prognoza metanowości bezwzględnej ścian (poradnik techniczny) [Dynamic prediction of absolute methane bearing capacity of the longwalls (technical guide)]. Vol. 14.* Instrukcja Głównego Instytutu Górnictwa.

Krzemień, A., Krause, E., Wysocka, M., Koteras, A., Więckol-Ryk, A., Wagner, J., ... Helios, M. (2017). *Management of environmental risks during and after mine closure (MERIDA). First annual report. Research Fund for coal and Steel* Contract No. RFCR-CT-2015–20100004.

Krzemień, A., Sánchez, A. S., Fernández, P. R., Zimmermann, K., & González Coto, F. (2016). Towards sustainability in underground coal mine closure contexts: A methodology proposal for environmental risk management. *Journal of Cleaner Production, 139*, 1044–1056. http://doi.org/10.1016/j.jclepro.2016.08.149.

Laurence, D. (2011). Establishing a sustainable mining operation: An overview. *Journal of Cleaner Production, 19*(2–3), 278–284. http://doi.org/10.1016/j.jclepro.2010.08.019.

Lunarzewski, L. (2010). Coal mine goaf gas predictor. In N. Aziz (Vol. Ed.), *10th. Underground coal operators' conference: Vol. 2010*, (pp. 247–256). University of Wollongong & the Australasian Institute of Mining and Metallurgy Retrieved November 9, 2017, from ro.uow.edu.au/cgi/viewcontent.cgi?article=1969&context=coal.

Pastor, J., Klinger, C., & Talbot, C. (2008). *Optimisation of mine water discharge by monitoring and modelling of geochemical processes and development of measures to protect aquifers and active mining areas from mine water contamination (WATERCHEM).* Directorate-General for Research and Innovation. European Commission.

Pokryszka, Z., & Tauziede, C. (2000). Evaluation of gas emission from closed mines surface to atmosphere. *Proceedings of the 6th International Conference on Environmental Issues and Management of Waste in Energy and Mineral Production* (pp. 327–329). Calgary: Balkema.

Pokryszka, Z., Tauziède, C., Lagny, C., Guise, Y., Gobillot, R., Planchenault, J., et al. (2005). *Gas migration from closed coal mines to the surface. Risk assesment methodology and prevention means. Symposium Post-mining 2005, November 16–17, Nancy, France.* Retrieved November 9, 2017, from https://www.researchgate.net/publication/228804171_Gas_migration_from_closed_coal_mines_to_the_surface_risk_assessment_methodology_and_prevention_means.

Pulles, W. (2008). *Best practice guideline G5: Water management aspects for mine closure.* Department of Water Affairs and Forestry, Republic of South Africa Retrieved November 9, 2017, from http://www.bullion.org.za/documents/g5-water-managementaspects-for-mine-closure.pdf.

Sawatsky, L. (2012). Perpetual Maintenance Schemes not a viable option. *CIM Magazine, 3*(7), 48–49.

Sechman, H., Kotarba, M. J., Fiszer, J., & Dzieniewicz, M. (2013). Distribution of methane and carbon dioxide concentrations in the near-surface zone and their genetic characterization at the abandoned "Nowa Ruda" coal mine (Lower Silesian Coal Basin, SW Poland). *International Journal of Coal Geology, 116–117*, 1–16. http://doi.org/10.1016/j.coal.2013.05.005.

Szlązak, N., Obracaj, D., & Borowski, M. (2002). Zagrożenie gazami kopalnianymi w obiektach budowlanych na terenach zlikwidowanych kopalń podziemnych. [Mine gas hazard in buildings in the areas of liquidated underground mines]. *Przegląd Górniczy, 58*(7–8), 42–48.

Tauziede, C., Pokryszka, Z., & Barriere, J. P. (2002). Risk assessment of surface emission of gas from abandoned coal mines in France and techniques of prevention. *Transactions Institution Mining Metallurgy Section A-Mining Technology, 111*, 192–196.

U.S. Environmental Protection Agency (2008). *U.S. Abandoned coal mine methane recovery project opportunities.* EPA430-R-08–002.

U.S. Environmental Protection Agency (2009a). *Coal mine methane recovery: A primer.* EPA-430-R-09–013. Retrieved November 9, 2017, from http://www.epa.gov/cmop/docs/cmm_primer.pdf.

U.S. Environmental Protection Agency (2009b). *Identifying opportunities for methane recovery at U.S. Coal Mines: Underground coal mines profiles of selected gassy underground coal mines.* EPA 430-K-04–003.

Wrona, P. (2017). The influence of climate change on CO2 and CH4 concentration near closed shaft – numerical simulations. *Archives of Mining Sciences, 62*(3), 639–652. http://doi.org/10.1515/amsc-2017-0046.