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AN ANALYSIS OF THE METHANE EXPLOSION IN THE AREA OF THE RETURN SHAFT BOTTOM AT MINE

Methane explosions are one of the greatest hazards in the coal mining industry and have caused many accidents. On 27 July 2016 at approximately 11:01 a.m., an explosion of methane occurred at the bottom of Zygmunt return shaft at the depth of 411 metres. The explosion resulted in one casualty.

The article presents the results of, and the conclusions from, an in-depth analysis of the changes in the parameters of mine air, especially methane concentration, air flow and the operation of mine fans, recorded by sensors installed in the workings and in Zygmunt ventilation shaft around the time of the accident. The analysis was based on signals recorded by the monitoring system, related to the evolution of methane and fire hazards prior to and after the accident occurred. An attempt was made to identify the cause and the circumstances of the methane explosion at the bottom of the return shaft.

Keywords: mine ventilation; methane explosion; recording of air parameters

1. Introduction

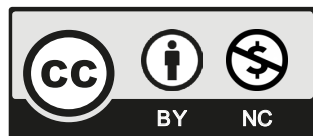
Methane explosions are among the most serious hazards in the coal mining industry in Poland and worldwide, and unfortunately continue to cause many accidents [1-3].

The first accident on record caused by a methane explosion occurred in a coal mine in the United States and resulted in the death and injuries to the personnel and the destruction of workings. This first reported explosion occurred in 1810. Such explosions happen when explosive gas and/or dust accumulated in a mine is ignited by a flame or spark. Occasionally, unanticipated and unusually high emissions occur, which, despite normal ventilation controls, result in an explosive mixture

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that a spark from a cutting bit, or electrical equipment, can easily ignite. Investigations [4] have shown that such emissions are often associated with anomalous geologic features or conditions.

The history of mining accidents worldwide reveals that the largest and most tragic events are caused by methane explosions [5,6]. The worst mining disaster ever occurred in the Benxi coal mine in China during the Second World War. On 26 April 1942, an explosion of gases mixed with coal dust killed 1,549 people. In Europe, the worst mining disaster happened in a French coal mine in Courrières on 10 March 1906. In the wake of the accident, 1,099 miners died, and its primary cause was an explosion of coal dust. In 1960, there was a methane explosion in a coal mine in Datong, China, which claimed the lives of 682 miners. In 1963, a series of gas explosions in a Japanese coal mine killed 458 miners. In this case, a coal-filled wagon broke off and fell down, and the resulting sparks caused an ignition. The most tragic mining disaster in Britain occurred in Senghenydd on 14 October 1913, when a methane explosion caused 440 casualties. The explosion and the fire that followed were so enormous that the miners who suffocated from lack of oxygen also died. A coal mine in Zimbabwe claimed 426 people in June 1972. According to some reports, the disaster was followed by a series of underground explosions that created fireballs and the release of poisonous gases, choking the trapped miners. On 31 January 1923, 145 miners died as a result of a gas and coal dust explosion in the then German Heinitz coal mine (from 1945 to 2004 operating as the Rozbark mine) in Bytom. It was one of the most tragic mining disasters that occurred in Polish territories.

On March 19, 2007, a methane explosion occurred in the longwall Ulyanovskaya mine in the Kemerovo Oblast. As reported by BBC News on March 21, 2007, at least 108 people were killed by the methane blast, which occurred at a depth of about 270 metres. Preliminary findings from the Ulyanovskaya investigation found that safety equipment had been tampered with deliberately to decrease the readings of methane levels in the mine. According to Governor Tulayev, this was done “consciously in order to increase coal production.” It was a typical example of irresponsible human actions causing a deadly threat to miners.

The above accidents prove that explosions of methane in deep mines are extremely dangerous to miners working underground. Recent years have shown that methane explosions are most frequent in the extraction areas of the mines and are connected with the formation of an explosive gas mixture in the circulating mine air or in the gob of a longwall [7]. Kurlenya & Skritsky [8], investigating the causes of a methane explosion in the longwall area, indicated that the most probable cause of the explosion was the ignition of the methane-air mixture and subsequent explosions initiated by coal spontaneous combustion fires in the excavated space. It appears that the formation of an explosive gas mixture can also be caused by an accumulation of methane in an area where air supply is limited [9,10] and the occurrence of an initial in the form of sparking during coal winning by a shearer or a fire source. The mechanism of coal self-ignition in the edge parts of pillars between longwalls, affected by rock pressure, is also known. An interesting development is the research into and tests of detection of methane accumulation and circulation sites by means of seismic sounding [11] and with the use of tomographic methods [12].

Explosion hazards in sealed coal mines are an issue of utmost importance, which, according to Cheng [13], requires a comprehensive understanding of explosion dynamics, mining operations, and mining safety. To ensure safety, a systematic monitoring of activities at a hazardous coal mine is required, using automated means of control [14].

A methane explosion in proximity to a ventilation shaft, where the volumetric air flow rate is very high and admixtures of methane are very well diluted, seems unlikely, and yet in practice such events have happened many times.

The worst mining disaster of this type occurred on December 6, 1907, when an explosion killed 362 of the 367 miners working in two shafts owned by the Fairmont Coal Company outside Monongah in West Virginia, USA. The explosion was attributed to concentrations of coal dust and methane gas that were ignited when a train of coal cars broke away and crashed in the mine, severing electrical cables. According to the Minerals Council South Africa, a methane gas explosion that occurred at the Tafelkop Shaft at Ermelo Mines, east of Johannesburg in South Africa on April 9, 1987, claimed the lives of 34 mine workers and injured 17. The gas exploded about 350 metres below the ground in the old section of the Gencor-owned mine, resulting in an inrush of carbon monoxide into the working places of the 9 West 1 South panel.

Several methane explosions in shafts have also been recorded in the Polish hard coal mining industry. The most tragic event took place in the area of the Sister Shaft (Schwesterschachte) of the Victoria mine in Wałbrzych [15] on July 29, 1929, killing 33 employees. The cause of the explosion was a leak in a mining gasoline lamp. In the Moszczenica mine, during the sinking of the shaft on April 8, 1959, there was a methane explosion [16]. As a result of the incident, nine miners were killed. A special commission investigating the causes and effects of the incident concluded that the cause of the methane explosion was the ignition of a cigarette in a window. On June 24, 1999, in the Morcinek mine, as shaft III was being closed by backfilling, methane exploded and then exploded [17]. The accident caused injuries to nine employees in the area of the shaft and damage to the shaft outlet, the headroom building and the building of the fan station.

The methane explosion discussed in this paper, which occurred in a shaft on 27 July 2016, was a complex occurrence, and its aftermath could affect the safety of the workforce even in remote areas of the mine. Hence, this event required a detailed analysis of the evolution of methane and fire hazards and the parameters of ventilation in the period before the incident [18]. The analysis was based on signals recorded by the automatic gasometry system and the recorded operation time of machines. The devices were installed in the workings from which the ventilation air is withdrawn, located in the F panel in seam 364/1-2 and in the Zygmunt ventilation shaft.

Due to the unusual location of the accident, the main objective of the analysis was to identify a potential source of methane and the reasons for its outflow into ventilation-active workings, as well as to identify factors facilitating the accumulation of methane with explosive concentrations in these workings. As a result of this analysis, the most probable sources of open fire occurrence were identified. An attempt was also made to formulate conclusions regarding ventilation [19], focusing on appropriate gasometry protection through draining air from the area of sealed-off longwalls with high absolute gas-bearing capacity. These measures were aimed at controlling methane concentrations in the currents of return air flowing to the shaft.

2. Distribution of airflow in the workings in the sub-network of the Zygmunt shaft

A diagram of workings in the sub-network of the Zygmunt shaft, together with the airflow distribution, is shown in Fig. 1. An amount of 7310 m³/min of air was exhausted from the level of 411 m to the Zygmunt shaft. Of this amount, approximately 1570 m³/min was removed from the area of gate F-1103 and incline F-24, i.e. from the area of completed exploitation of longwall 65 in seam 364/1-2. On the other hand, about 1000 m³/min of air was exhausted from the level 326 m. In total, 8310 m³/min of air was flowing through the Zygmunt shaft between the level of

326 m and the ventilation duct. Since the external losses were 700 m³/min, 9010 m³/min of air was flowing through the fan installed in the Zygmunt shaft.

In front of the inlet to the ventilation duct, a methane sensor MM1001 was installed in the Zygmunt shaft, and at the level of 326 m, another methane sensor MM1002, a CO1033 carbon monoxide sensor and an anemometer AN1031 were installed. On the other hand, at the level of 411 m, a carbon monoxide sensor DCO1010 was present, and in the shaft below the level of 411 m, a methane sensor MM1003 was located. Zygmunt shaft below the level of 411 m was ventilated using air duct ventilation, and pumping water was removed from the shaft sump using a P3cc pump powered from the level of 411 m.

3. The extraction of seam 364/1-2 at longwall 65 and the occurring methane hazard

During its exploitation, longwall 65 in seam 364/1-2 was ventilated with the Y ventilation system with the fresh air supply along the coal body and the air exhaust along a one-sided gob, and with the additional fresh air supplied to the flow returning from the longwall to the gate F-1106. The air from longwall 65, during its exploitation, was removed to the Zygmunt shaft. A section of a map of seam 364/1-2, including longwall 65, is shown in Fig. 2.

The longwall 65 was mined under conditions of high methane hazard. TABLE 1 presents the absolute and ventilation methane-bearing capacity of longwall 65 and the obtained methane drainage efficiency.

TABLE 1

Methane-bearing capacity in the area of longwall 65

Month in 2015.	Methane drainage at longwall 65 (underground station)		Ventilation methane bearing capacity at longwall 65	Absolute methane bearing capacity at longwall 65	Methane drainage efficiency at longwall 65
	m ³ CH ₄ /min	Thousand cubic meters CH ₄ /m-c	m ³ CH ₄ /min	m ³ CH ₄ /min	%
January	17,65	787,90	16,32	33,97	51,96
February	21,66	873,33	20,27	41,93	51,74
March	23,55	1 051,27	20,73	44,28	53,41
April	24,43	1 055,38	21,81	46,24	52,87
May	20,02	893,69	17,36	37,38	53,53
June	19,13	826,42	18,77	37,90	50,50
July	19,13	853,96	17,54	36,67	52,17
August	19,42	866,91	16,39	35,81	54,27
Sept	17,16	741,31	14,56	31,72	53,79
October	10,60	473,18	8,20	18,80	56,38
November	9,30	401,76	6,43	15,73	59,12
December	7,20	321,41	5,82	13,02	55,30
Σ	17,44	9 146,52	15,35	32,79	53,75

During September, the absolute methane-bearing capacity fluctuated between $31.7 \text{ m}^3 \text{ CH}_4/\text{min}$ and $46.2 \text{ m}^3 \text{ CH}_4/\text{min}$ as longwall 65 advanced. When the exploitation at the longwall was terminated, absolute methane-bearing capacity dropped to approximately $13.0 \text{ m}^3 \text{ CH}_4/\text{min}$. Extraction at longwall 65 was terminated on 31 January 2016.

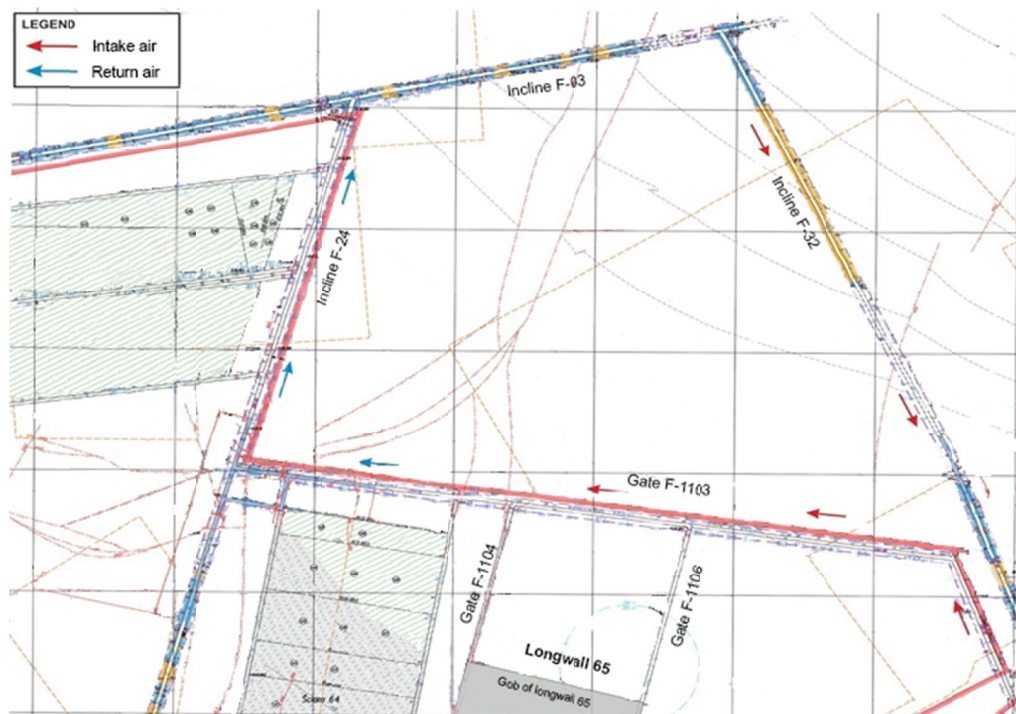


Fig. 1. A section of a map of seam 364/1-2 with highlighted longwall 65

The forecasted inflow of methane to the area of longwall 65 during the months following the end of exploitation was estimated at $6.1 \text{ m}^3 \text{ CH}_4/\text{min}$. It means that despite sealing off the area of longwall 65 with air stoppings, an amount of $6.1 \text{ m}^3 \text{ CH}_4/\text{min}$ still penetrated the excavated spaces of the longwall at the end of July 2016.

Therefore, the sealed-off space of longwall 65 was a source of methane release into the workings at the level of 411 m situated at the bottom of the Zygmunt shaft.

4. An analysis of the parameters of mine air recorded by the gasometry system during and after the explosion in the Zygmunt shaft

A list of sensors which were linked to the methane explosion in Zygmunt shaft on 27 July 2016 is presented in TABLE 2.

The devices selected for the analysis included the barometer installed on the surface in a room adjacent to Zygmont shaft, seven anemometers, 10 methane sensors and 13 carbon monoxide sensors, which recorded the moment of the explosion or its consequences in the area of Zygmont shaft and in the workings along the routes of airflow in the mine. The location of these sensors is shown in mine diagrams in Area A (Fig. 2) and Area B (Fig. 3).

The analysis of the evolution of air parameters recorded by the monitoring system after the accident revealed when exactly and how the parameters changed and the delays that occurred after the explosion in the Zygmont shaft, which were compiled in TABLE 2.

TABLE 2

Exact times and delays in the occurrence of changes in parameters

Sensor	Location	Time of change	Remarks
BA 2002	Room MTA-1 – Zygmont shaft	11:01:11	air pressure pulse
W48	Sump Zygmont shaft	10:56:55	enable
W47	Sump Zygmont shaft	10:56:57	enable
WenGł.2	Main fan Zygmont shaft	11:01:27	disable
WenGł.1	Main fan Zygmont shaft	11:02:19	enable
Pressure drop	Pressure drop across the fan Zygmont shaft	11:01:11	1 ↘ 0
MM1001	Zygmont shaft 10 m below main fan draft	11:01:09	10:50:40 ↗ 4.7%
MM1002	Bypass Zygmont shaft – boundary point at 326 m level	11:01:09	↑ 3.7%
MM1003	Zygmont shaft 10 m below 411 m level	11:01:09	10:58:47 ↗ 1.4%
MM1(398)	NW cross-cut, 10-15 m to the south of B-419 gate	11:01:17	↑ 5.0%
AN1031	Bypass Zygmont shaft – boundary point at 326 m level	11:01:19	↓ no data available
MC1010	Shaft bottom Zygmont shaft 411 level	11:01:09	↓ no data available
CO1033	Bypass Zygmont shaft – boundary point at 326 m level	11:01:21	↓ no data available
AN1014	Incline B-06, 50-100 m from the 334/2 cross-cut	11:01:38	↑ 1.9 m/s

* ↘ means decrease but ↗ means growth.

The consequences of the explosion were recorded as an air pressure pulse after the explosion (TABLE 2) by the barometer denoted as BA2002, installed in the room MTA-1 – Zygmont shaft. The air pressure pulse after the explosion is shown in the diagrams presented in Fig. 4. Following the explosion, some of the sensors installed in the area of the Zygmont shaft were damaged (TABLE 2). The carbon monoxide sensor MC1010 ceased to record due to its damage at 11:01:09. (No data available). The anemometer AN1031 stopped recording at 11:01:19 and was followed by carbon monoxide sensor CO1033 two seconds later, i.e. at 11:01:21, probably due to a failure (no data available).

The analysis also included the recording of the operating parameters of WG1 and WG2 main fans at the Zygmont shaft and W47 and W48 fans in the sump. The times at which the operating status of the fans changed are shown in TABLE 2.

The fans installed in the sump of the Zygmont shaft were activated about 5 minutes before the accident and could influence the distribution of methane in the area of the shaft.

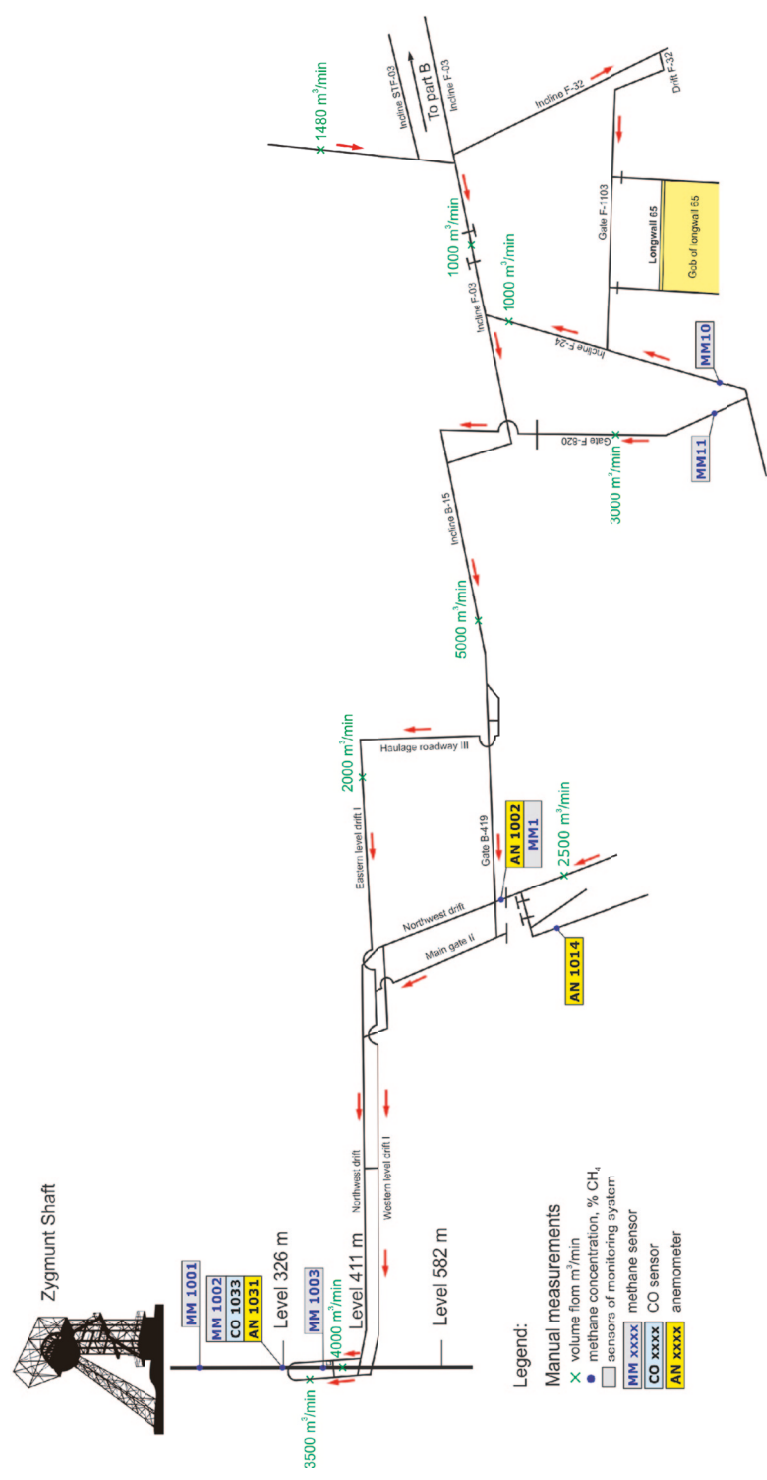


Fig. 2. Diagram of air flow with location of sensors in the area A of the mine

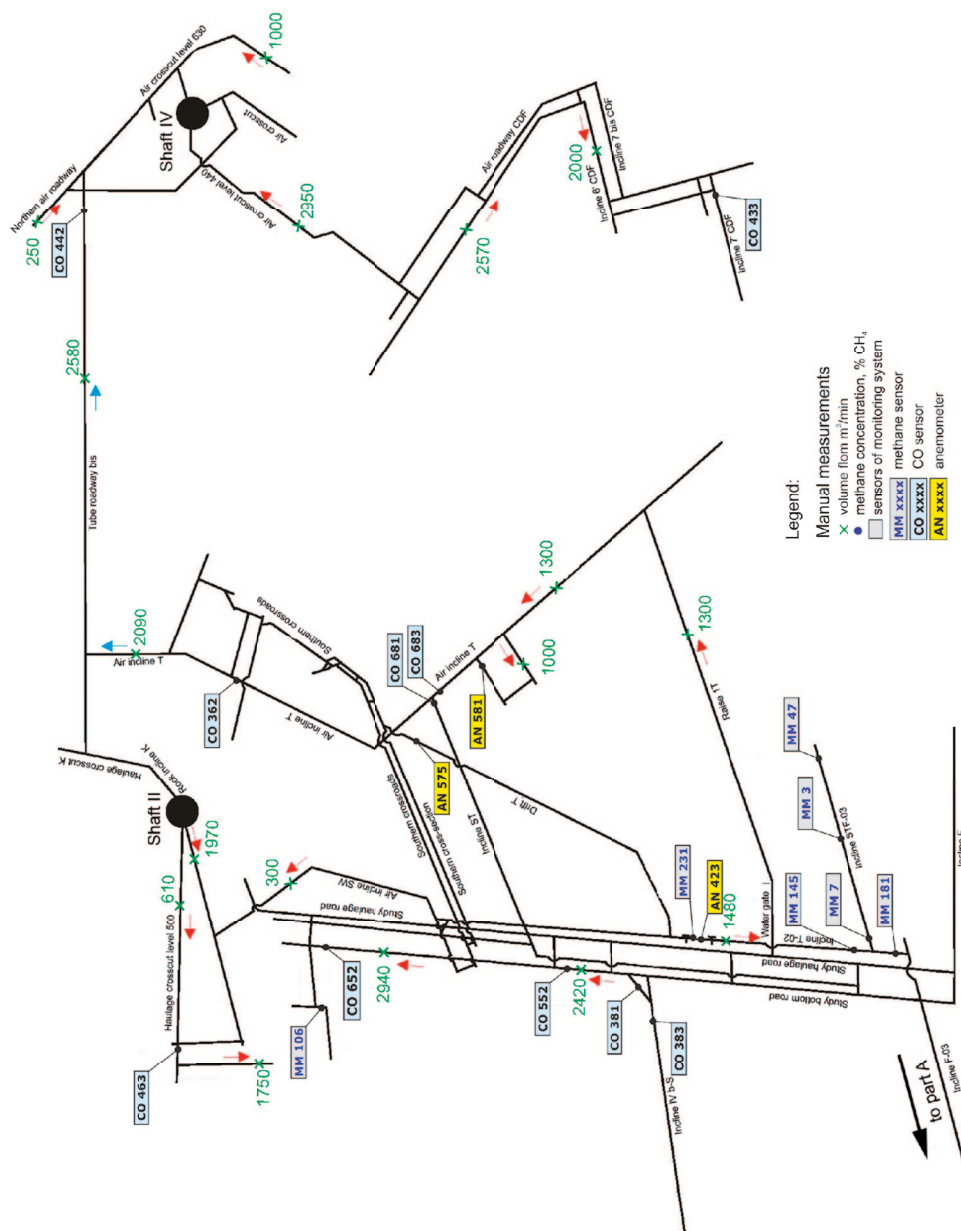
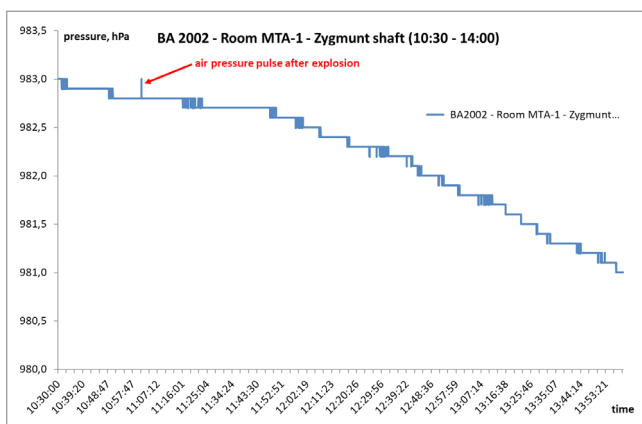
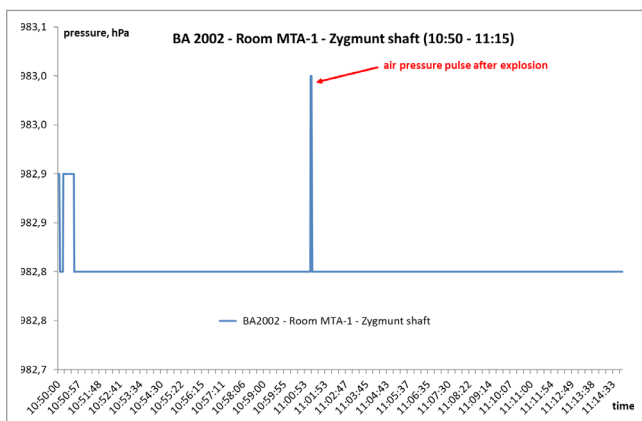


Fig. 3. Diagram of air flow with location of sensors in the area B of the mine



4a) Air pressure recorded from 10:30 am to 2:00 pm



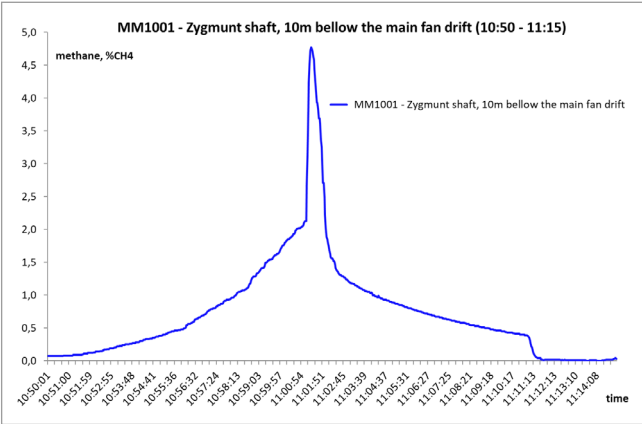
4b) Air pressure pulses recorded at 11:01:11

Fig. 4. Air pressure recorded from 10:30 am to 2:00 pm by BA2002, in Zygmunt shaft

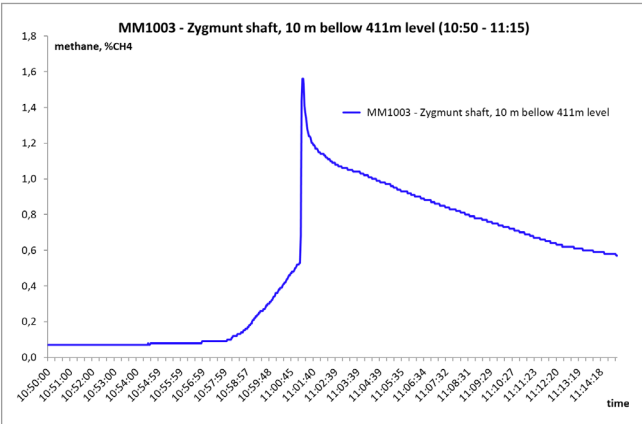
In subsequent graphs, we see a sharp increase in methane concentration before the accident in the Zygmunt shaft, recorded 10 m below the main fan drift by the methane sensor MM1001 (Fig. 5a). An increase in methane concentration was also detected by the methane sensor MM1003 located in the Zygmunt shaft, 10 m below level 411 m, before the accident (Fig. 5b).

The moment of the explosion was recorded simultaneously at 11:01:09 (TABLE 2) by all the methane sensors MM1001, MM1002 and MM1003 in the form of a dramatic rise in methane concentration. The methane sensor MM1002 (TABLE 2) situated in this area did not record any changes in concentration prior to the moment of the explosion (Fig. 5c).

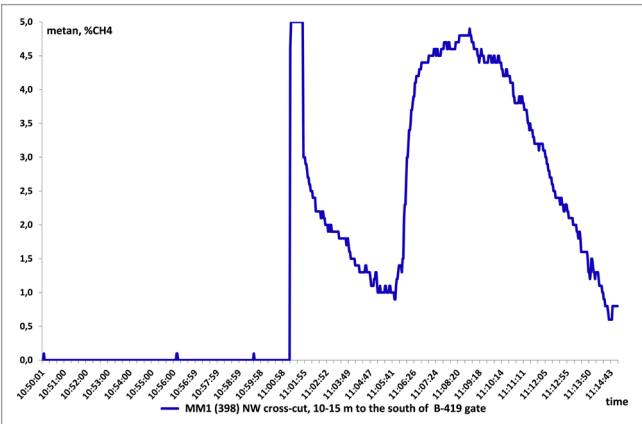
An interesting evolution of methane concentration was recorded by the methane sensor MM1 (398) installed in the north-western cross-cut about 10-15 m to the south of the B-419 gate (Fig. 5d). This sensor was not recording changes in methane concentration, but 8 seconds after the explosion, previously recorded by sensors in the shaft region, i.e. at 11:01:17 (TABLE 2), it showed a rapid increase in methane concentration to 5.0% CH₄. Given that this sensor was



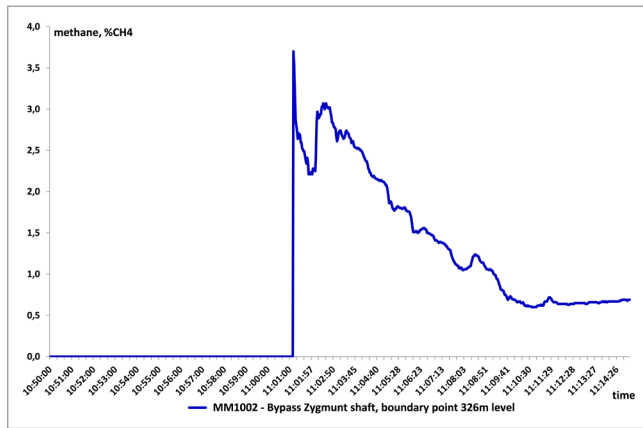
5a) Methane concentration (MM1001)



5b) Methane concentration (MM1003)



5c) Methane concentration (MM1002)



5d) Methane concentration (MM1)

Fig. 5. Methane concentration recorded in the area of Zygmunt shaft

in the current of fresh air, it can be assumed that as a result of the explosion, the pressure wave caused a rapid pushing of highly concentrated methane from the north-western cross-cut, which embraced the methane sensor located in this cross-cut 10-15 m to the south of the B-419 gate.

A comparison of the values of methane concentrations registered by the MM 1001, MM 1002, MM 1003 and MM-1 (398) sensors is shown in Fig. 6.

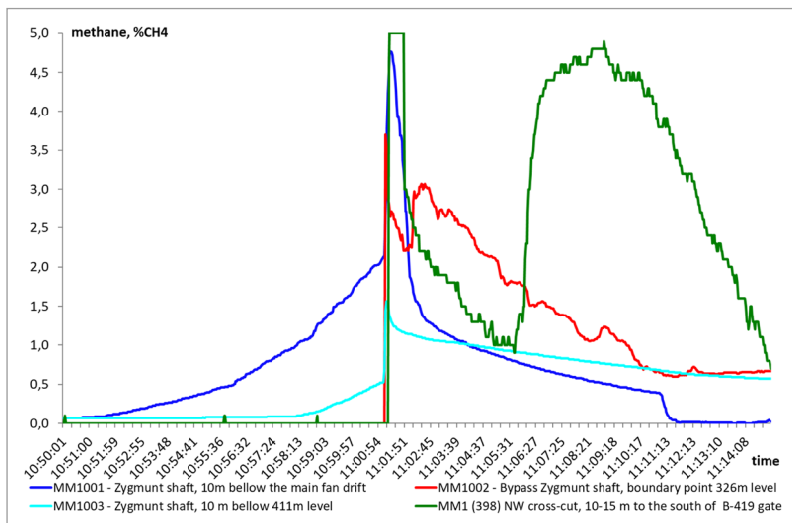


Fig. 6. A comparison of the values of methane concentration recorded after the explosion

According to Figs. 7 and 8, records of methane concentration in mine area B show a systematic increase in methane concentration in incline T-02, with a delay of about an hour. The value

recorded by the methane sensor MM181 amounted to over 4% CH₄, while the sensor MM145 recorded over 3.5% CH₄, and these readings were undoubtedly related to the explosion in the Zygmont shaft in the mine area A. The explosion that occurred in the Zygmont shaft area of the mine caused a significant disturbance in methane concentration. This disturbance was caused by a reversal of the airflow direction in area B, specifically in incline T-02, located 50 metres

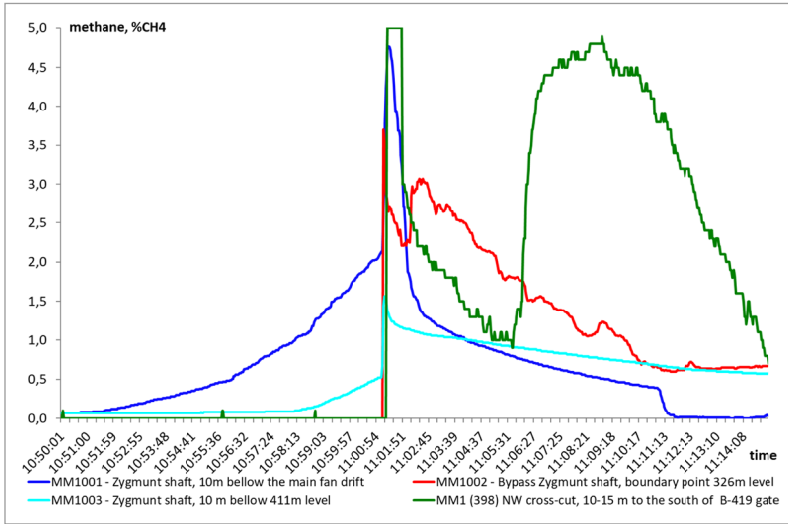


Fig. 7. Methane concentration recorded after the explosion in the Zygmont shaft in the mine area A and in incline T-02 in the mine area B

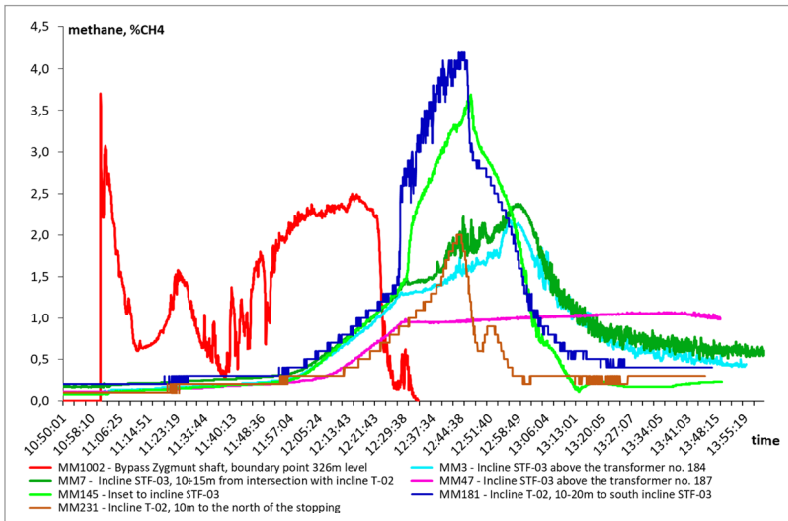


Fig. 8. Methane concentration recorded after the explosion in the Zygmont shaft in the mine area A and in incline STF-03 in the mine area B

south of the intersection with the belt incline in stone. The reversal lasted almost 2 hours, as shown by anemometer AN423 (Fig. 9). After the explosion in the area of the Zygmunt shaft, the direction of airflow also reversed in drift T at the end of the slide wire, which also lasted almost 2 hours, as shown by the anemometer AN575 (Fig. 10).

Fig. 11 shows cumulative air velocity recordings that confirm significant airflow disturbances, including a reversal of airflow direction in area B of the mine long after the accident.

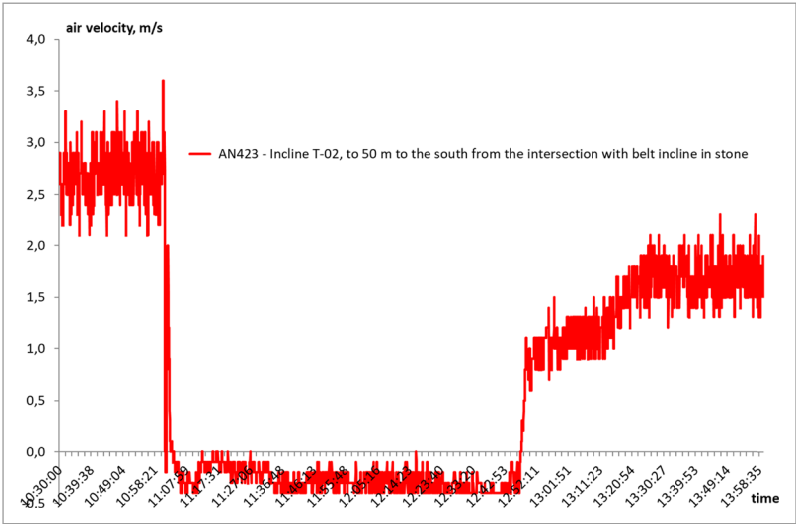


Fig. 9. Air flow rate recorded in incline T-02 to 50 m to the south of the intersection with belt incline in stone

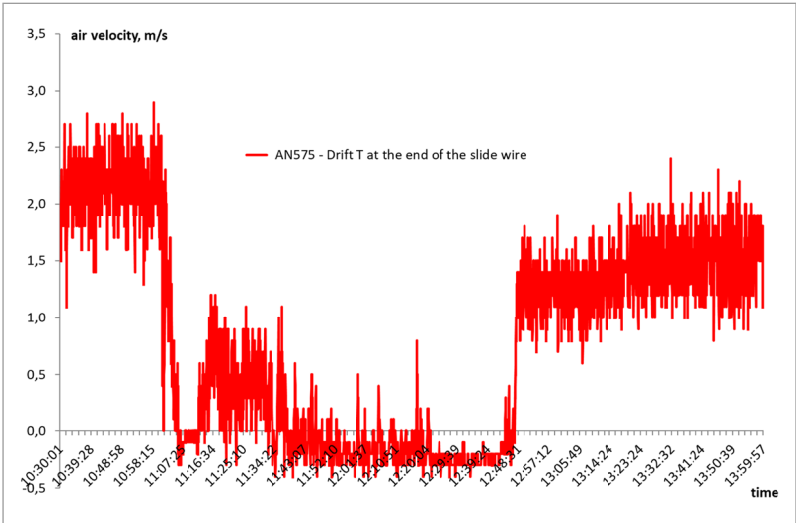


Fig. 10. Air flow rate recorded in drift T at the end of the slide wire

Such a significant increase in the concentration of methane in the workings in the area of B of the mine called for the identification of the source from which methane inflow was so significant. It should also be emphasized that the reversal of the airflow direction in incline T-02 caused the appearance of a near-explosive mixture, moving towards active workings, which posed a high risk of methane explosion in this section of the mine and escaped detection by the protective devices.

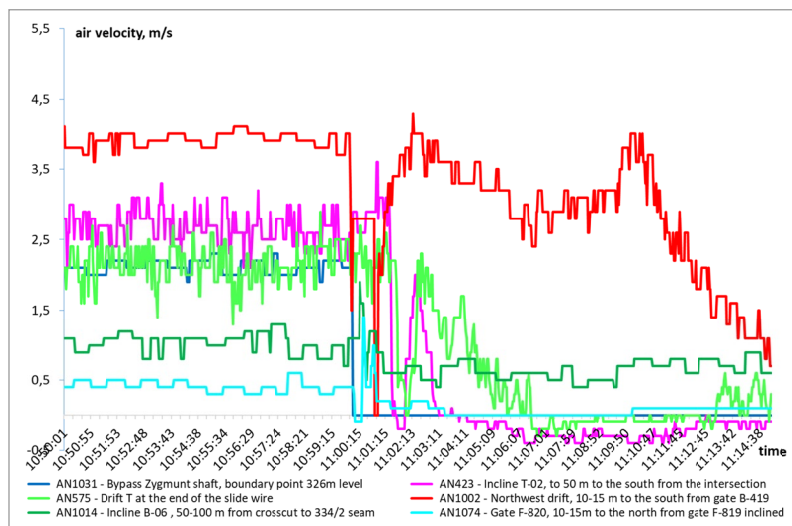


Fig. 11. Air flow disturbances recorded in the workings in area B of the mine in the area of Zygmont shaft

5. Potential sources and causes of methane outflow into ventilated workings

On 27 July 2016, the only source of methane emission into the workings of the sub-network of Zygmont shaft was the gob of sealed off longwall 65 mined in the seam 364/1-2. According to a forecast from July 2016, approximately $6.1 \text{ m}^3 \text{ CH}_4/\text{min}$ was emitted into the gob and workings of this longwall. The gob was filled with highly concentrated methane.

Due to a change in the distribution of aerodynamic potentials around the workings of the sealed off longwall 65 in seam 364/1-2, methane was flowing out to gate F-1103. Reduction of the volume of air flowing through incline-32 and gate F-1103 contributed to the increase in methane concentration in the area of stoppings sealing off the workings of the longwall 65 (gates F-1104 and F-1106.)

However, such methane emission could not cause an increase in methane concentration close to the point of an explosion at the level of 411 m near the Zygmont shaft. For this to happen, an outflow of methane had to occur, caused by a partial supply of air to the isolated space of longwall 65. Provided that through the stoppings isolating the longwall, the air was supplied from active workings, most probably from gate F-1103 to gate F-1106, it must have pushed out a 'plug' of highly concentrated methane to the active workings through which return air passes

to Zygmunt shaft. Following the distribution of airflow presented in Fig. 1, the ‘plug’ of highly concentrated methane was gradually diluted as the air was supplied. In Fig. 5, we see the increase in methane concentration as measured by the methane sensor MM1001 installed below the inlet to the ventilation duct. Thus, methane outflowing from the environment of the sealed off longwall 65 in the seam 364/1-2 caused an increase in methane concentration up to the lower limit of explosiveness at the bottom of the Zygmunt shaft at the 411 m level. Such methane outflow could only become possible due to the removal of methane from the workings of the sealed off longwall 65 in seam 364/1-2 and its supply into active workings of the ventilation network, caused by tampering with the ventilation stoppings.

Given the normal functioning of the ventilation of the workings in the sub-network of the Zygmunt shaft, it would have been impossible for methane to concentrate to a value approaching the limit of explosiveness. The rise of methane concentration could occur only in gate F-1103, which had a direct connection to the sealed off workings of longwall 65 in seam 364/1-2. In this gate, the rise of methane concentration resulted from the amount of air supplied via incline F-32. In the lower section of the incline F-32, at the intersection with the cross-cut F-32, water accumulated and was systematically pumped out. The rise of water level automatically reduced the volumetric flow of air reaching gate F-1103 and caused methane concentration to rise at the stoppings, isolating the longwall in gates F-1104 and F-1106.

The changes in methane concentration in workings, shown in Fig. 7 and Fig. 8, are the result of the methane explosion and the failure of the main fan at the Zygmunt shaft. This situation caused a change in the airflow distribution in the ventilation network, also in the mine area B and in some workings, which led to an increase in methane concentration.

6. The likely sources of the open fire that could have caused methane to explode on 27 July 2016

The explosion of methane was recorded as a pulse of air pressure after the explosion by the barometer denoted as BA2002, installed in a room adjacent to the Zygmunt shaft. The pressure pulse after the explosion is presented in Figs. 4a and 4b.

If we assume that there was a systematic increase of methane concentration in the air flowing at the 411 m level to Zygmunt shaft, as confirmed by the values recorded by the M1001 sensor in the shaft below the fan duct, then a possible initiator of methane explosion could be:

- functioning of the fans ventilating the sump of the Zygmunt shaft
- functioning of the pumps dewatering Zygmunt shaft
- an open fire (lighting a cigarette).

Taking into consideration the fact that the fan ventilating the sump of the shaft and the pump draining the shaft had been activated 5 minutes before the explosion, and considering their overall good condition confirmed by an on-the-spot examination, the possibility that those devices triggered the explosion must be excluded. Therefore, the most probable initiation of a methane explosion at the 411 m level at the bottom of the Zygmunt shaft was the appearance of an open fire. The fire could have been caused by an employee working at the bottom of the Zygmunt shaft at the 411 m level with the task of operating the drainage pump and removing water from the sump of the shaft. The employee was killed by the explosion and had probably been unaware of the level of methane concentration in the air at the bottom of the Zygmunt shaft.

7. Conclusion

The analysis has made it possible to formulate the following findings and recommendations:

1. The accumulation of methane in the workings at the 411 m level in the area of the bottom of Zygmunt shaft was a result of an outflow of a significant amount of methane from the workings of the sealed off longwall 65 in mined seam 364/1-2, the liquidation of which took place on 31 January 2016.
2. The methane explosion was initiated at the 411 m level at the bottom of the Zygmunt shaft.
3. It is very unlikely that the methane explosion at the 411 m level at the bottom of the Zygmunt shaft was initiated by the devices in operation (a booster fan or a pump). On the other hand, the methane explosion was probably caused by the appearance of an open fire.
4. A detailed analysis of the conditions and causes of the incident showed that the probable cause of the methane explosion was the lighting of a cigarette by the operator. It should be emphasised that smoking is strictly prohibited in underground mines, which would be a significant violation of mining regulations.
5. The explosion of methane damaged the isolation of the fan duct of the Zygmunt shaft and caused disruptions of air flow through the workings in the sub-network of the Zygmunt shaft. These disruptions, which continued for almost two hours, caused methane concentration to rise in distant workings not covered by return airways of the area of the sealed off longwall 65 in seam 364/1-2. Reversing the direction of air flow in incline T-02, in mine area B, caused an increase in methane concentration in this part of the mine, even to the lower limit of explosiveness (4.5% CH₄), which could have a significant influence on the safety of the employees and the operation of equipment in this section of the mine.
6. The analysis proves that it is necessary to install a methane sensor integrated into the methane hazard prevention system on the routes along which the air characterised by high absolute methane-bearing capacity is removed from the area of sealed off longwalls to monitor the concentration of methane in the current of return air directed to the shaft.

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