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Research Article

Mine Fires, Experiences in Extinguishing Large Underground Mine Fires

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Abstract

Mine fires are common the underground exploitation of mineral raw materials. With the development of mining science and practice, the methods of extinguishing mine fires using new methods and materials were also developed. Today, in mining practice, direct fire extinguishing with water or fire extinguishers, isolation of oxidation zones with insulating walls, installation of torket concrete on the walls of the pit room or use of special foams are most often used. Methods based on ventilation methods or the use of inert gases can also be encountered. All these methods are used to extinguish local oxidation processes, fires are localized in a part of the pit, ventilation department or goafs. This paper presents methods of extinguishing a mine fire where the fire zone covered a larger area and it was not possible to localize it in one part of the underground mine, the pit is completely closed and isolated until the oxidation process subsides due to lack of oxygen. At the time of the complete closure and isolation of the pit, several gas detectors remained in operation in the pit, through which the change in the composition of the pit air could be monitored during the still active pit fire. At the same time, samples of the pit atmosphere behind the isolation walls were regularly taken, their analysis was performed and they were compared with the data obtained using active gas detectors. The key question was when to reopen the pit, conduct an inspection and try to reactivate the pit operations. Although it is an underground brown coal mine, some experiences and knowledge can be applied and used in underground mines of other mineral resources threatened by pit fires. Experiences can also be applied in case of fire, where it is possible to control the fire zone only through insulating walls. It was established that changes in the activity of the pit fire were manifested both on the insulation walls and on the active gas detectors.

Keywords

Mine Fire, Monitoring, Extinguishing Methods, Reopen Pit

1. Introduction

In RMU "Banovići", underground exploitation, high-quality brown coal is mined using a mechanized longwall with the mechanized preparation of new mining fields. The mine is methane with explosive coal dust. Ventilation is central, depressed [2]. The pit is elaborated and divided into two independent ventilation areas that can be separated and isolated at any time. The pit has three independent openings through which it is connected to the surface of the field, two are used for incoming fresh air flow (JUG 1 and JUG 2) and one is used as an outlet for spent return air flow (JUG 3). The average depth of

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the pit is 300 m. The thickness of the coal seam is 15 m, and excavation is carried out in belts from higher to lower. The pit rooms are supported and secured by an iron foundation, steel mesh and wooden planks.

Transport of coal from the mine is organized continuously, using rake conveyors and rubber belt conveyors. As a rule, means of transport are installed in rooms with fresh air flow.

Control of gases and ventilation parameters in the pit is carried out with manual gas indicators, remotely continuously using appropriate detectors and laboratory analysis of pit air samples.

On March 29, 2021, in a fresh air current at the place of overflow from the rubber belt conveyor of the internal number T-5 to the rubber belt conveyor of the internal number T-4, the accumulated coal dust spontaneously ignited. The accumulated coal dust at the overflow site ignited as a result of the heating caused by the friction of the rubber canvas against the structure of the belt conveyor T-5 (Figure 1).

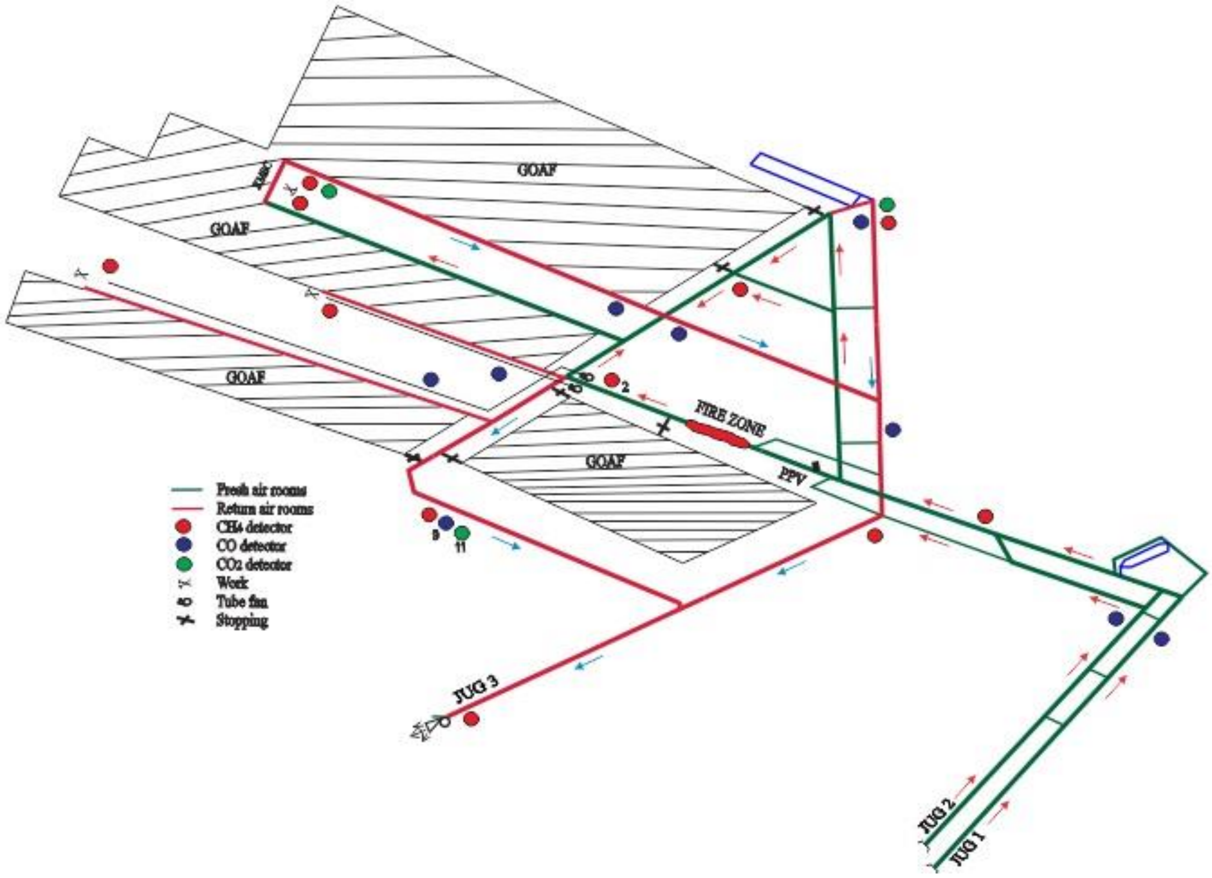

Figure 1. *Location of the fire.*

2. Research Method

Due to the sudden appearance of the pit fire, it was not possible to prepare for monitoring its origin and development by installing special equipment and special monitoring of the place of origin.

In the stage of development of the fire and its rehabilitation, the data obtained from the measurement points already installed in the pit (those that remained in operation) were analyzed, as well as the effects of the measures implemented during the fire extinguishing phase. Based on the data obtained in this way, the following measures were taken and the effects of their application were further monitored.

3. Initial Fire Extinguishing

The fire started at a time when there were no workers in that part of the mine.

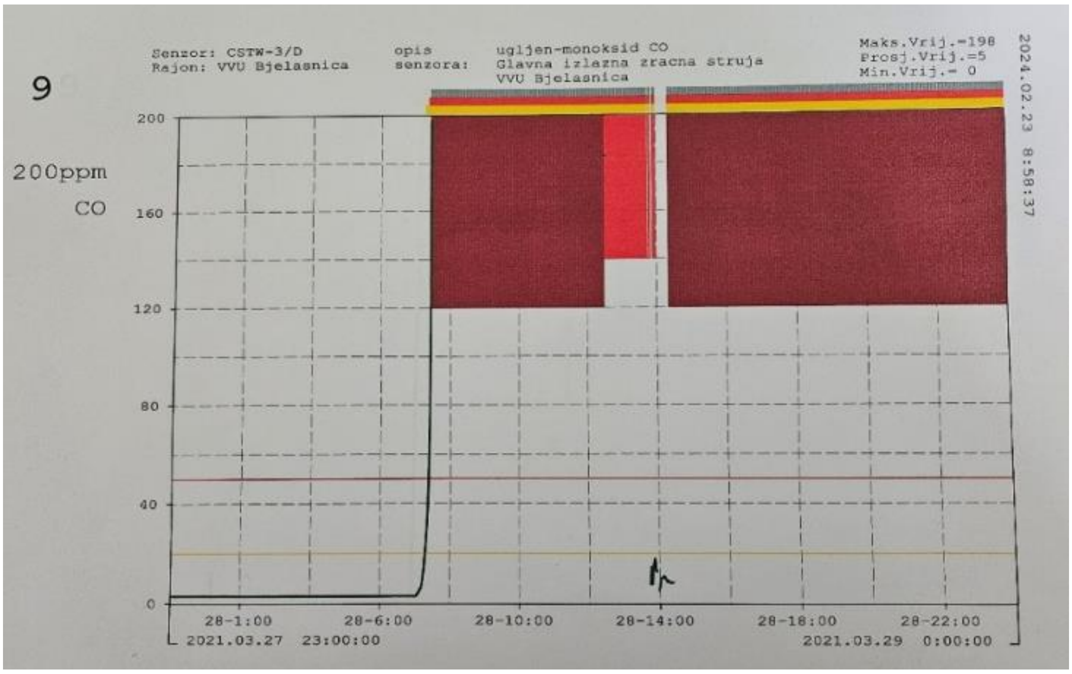

Figure 2. Detector CO internal number 9.

The first data on the occurrence of the oxidation process in the pit were detected through the detector of carbon monoxide (CO) internal number 9 at 6:56 a.m., methane (CH_4) internal number 2 and carbon dioxide (CO_2) internal number 11 at 7:42 a.m. (Figure 2, Figure 3 and Figure 4).

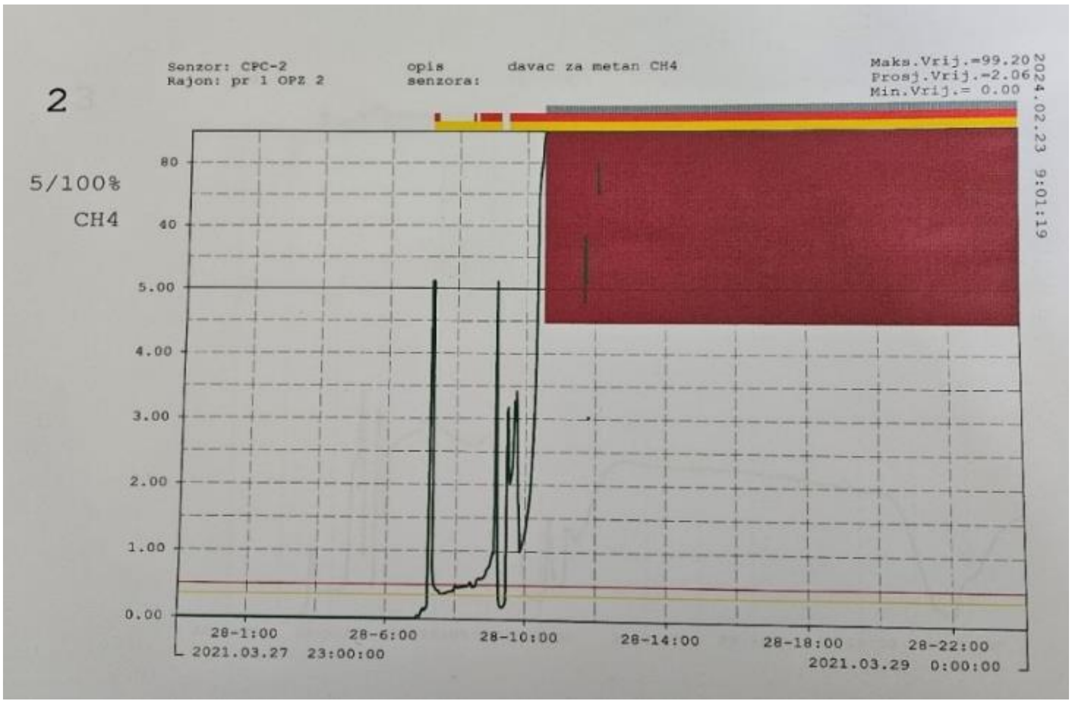

Figure 3. Detector CH_4 internal number 2.

How strong the fire depression was in the beginning is shown by the concentration of methane on detector 2. Under normal pit ventilation conditions, this detector does not register methane [16]. Due to the fire depression, methane is released from the goaf into the room through the pillar and the insulating wall.

Figure 4. *Detector CO_2 internal number 11.*

The first teams of workers who were able to visually determine the origin of the fire arrived at the site at 7:00 a.m. Since it is a fresh air stream with an air speed of 2.87 m/s and a volume flow of 1290 m^3/min, the fire had all the conditions for rapid development. The fire covered the entire profile of the room. The wooden planks, electrical installations and plastic pipeline were completely burnt in a length of more than 200 m observed from the place of origin of the fire. The fire spread in both directions from the place of origin [7]. The rubber canvas on the installed conveyor burned out, even though it was type K, it had a non-combustible coating. Due to the high speed of the air current and the large volumetric air flow, the fire spread intensively in the direction of air movement, the air quickly carried the combustion products, creating the conditions for the fire to spread [5]. The coal that made up the sides and floor of the room was not burning.

Immediately before the place where the fire started, there was a fire door (PPV) in the fresh air stream, which enabled quick isolation and separation of this ventilation department [17]. Also, the amount of fresh air reaching the fire zone could be reduced very quickly by distributing the air in the pit. The mode of operation of the main ventilation plant could be changed by regulating the number of revolutions of the engine, which would reduce the total amount of fresh air used to ventilate the mine.

Organized firefighting begins at 8:30 a.m. using water and the installed hydrant network. The fire was extinguished by specially trained persons using all the necessary equipment and isolation devices. Very soon after the fire broke out, three water hydrants were turned on to extinguish the fire. The initial results in extinguishing the fire were very good and the fire was extinguished in a section of about 150 m. This initial success in extinguishing the fire caused that the fire area was not isolated from the rest of the pit by closing the fire doors and the amount of fresh air that was not reduced the pit was ventilated. At one point, the problem was the lack of substructure and protection during the movement of the workers when extinguishing the fire due to the fact that in the ceiling part of the room there was no longer a wooden planks that secured the ceiling of the mining room [4]. Threatened safety during the movement of workers during firefighting caused the wrong decision to be made at 1:00 p.m. to temporarily stop active firefighting with pressurized water and to withdraw all workers who were fighting the fire from the pit, without taking any other measures. The use of special foams [6], although the mine has them, was not possible due to the size of the fire zone and the intensity of the burning [11]. At 10:00 p.m., the main ventilation system was turned off and the pit was ventilated exclusively under the influence of natural depression.

31.03.2021. the main ventilation plant was put into operation again with significantly reduced amounts of air used to ventilate the pit. A special team, while visiting the fire zone, came to the fire zone from the other side and determined how far the fire actually spread. Also, upon returning, it was determined that the fire had spread to other parts of the pit, it had engulfed the rooms of the outgoing air flow (Figure 5). It was no longer possible to isolate it in a separate ventilation department by making isolation walls [2]. Due to the decrease in the amount of fresh air used to ventilate the pit, and based on the data from the methane generators that were still in operation, there was a noticeable accumulation of methane [15] in the zone of the mechanized longwall (KMSC). There was a possibility of its movement towards the fire zone and ignition and explosion.

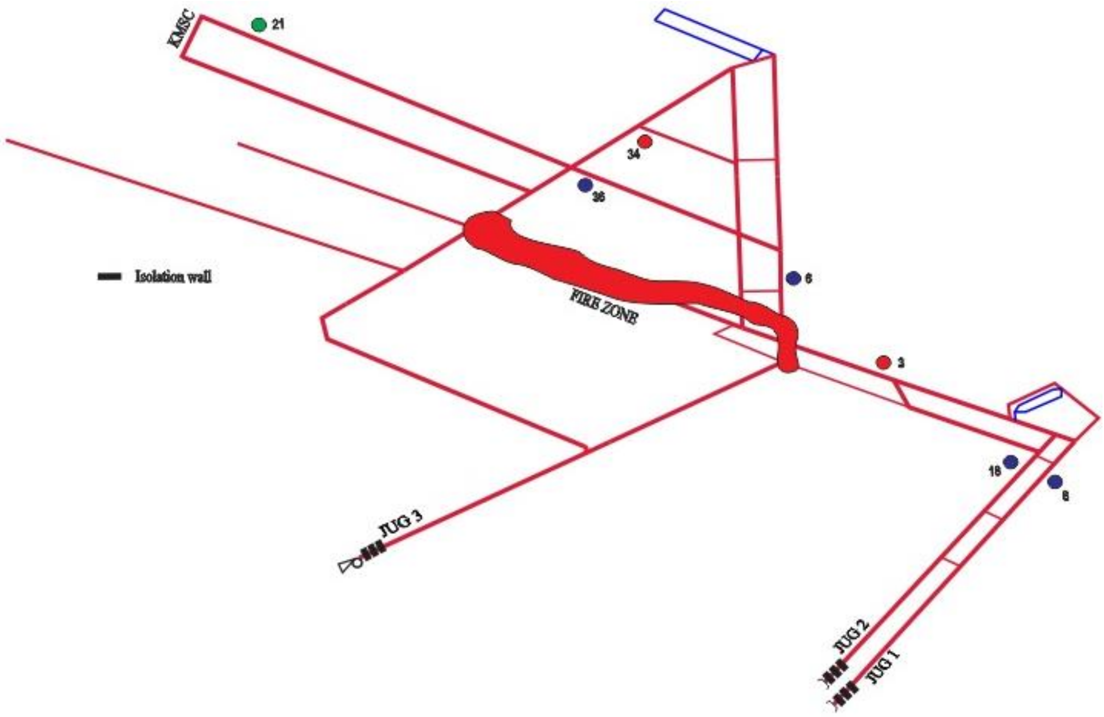

Figure 5. Fire zone at the time of pit close.

01.04.2021. a decision was made to withdraw all workers from the pit, to stop ventilation of the pit and to hermetically close and isolate the pit at the entrances. At all three entrances (JUG 1, JUG 2 and JUG 3) three isolation walls were made. Openings were left on the insulation walls for monitoring and taking samples of pit air.

4. Fire Monitoring and Extinguishing

At the time of the fire, several detectors of CH_4, CO, CO_2, temperature and air current speed were in operation in the pit [3]. Most of these detectors have lost their function (damage to cables due to fire or immersion in water), and some of them remained in operation even after the pit was closed and isolated, and the data from them was monitored via a central station located outside the pit. The most interesting are the data from the CO detector internal numbers 6, 8, 18, and 36, the CH_4 detector internal numbers 3 and 34, and the CO_2 detector internal number 21, which remained in operation.

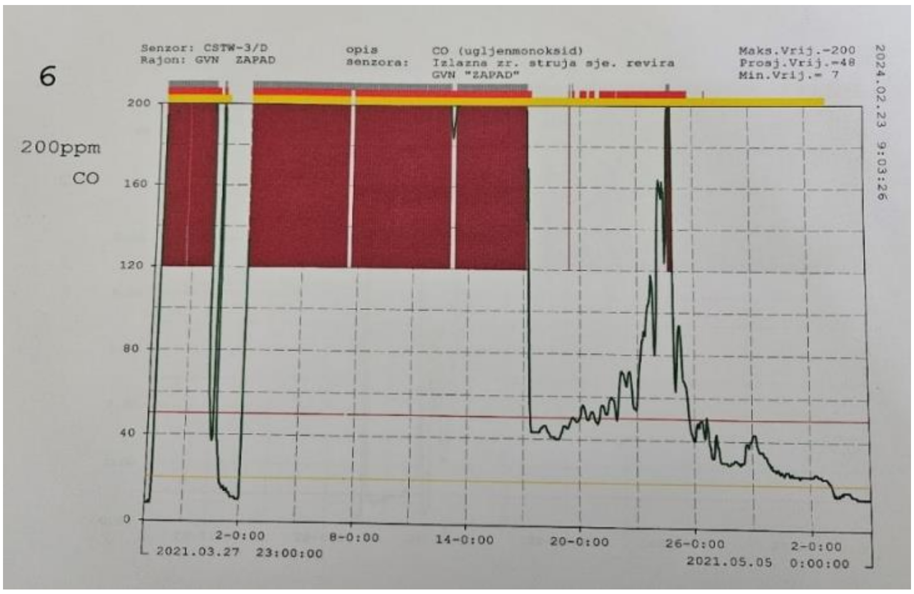

Figure 6. Detector CO internal number 6 in the time period 27.03.-05.05.

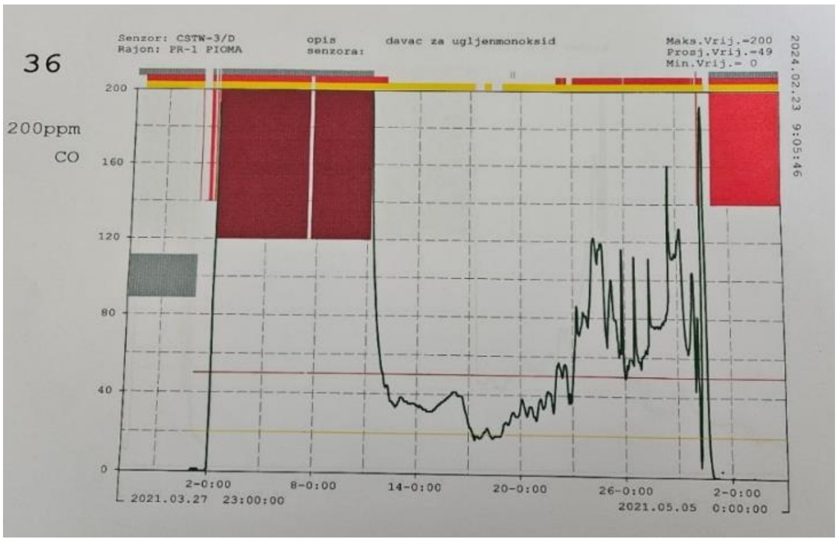

Figure 7. Detector CO internal number 36 in the time period 27.03.-05.05.

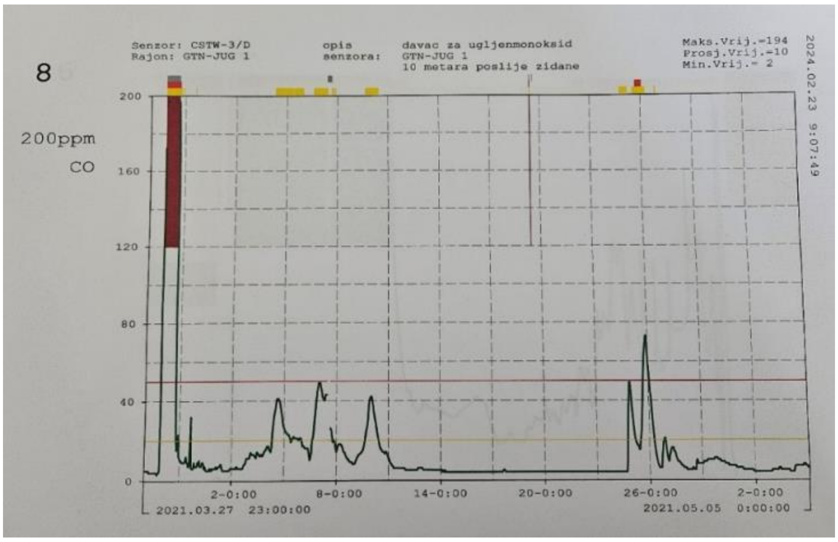

Figure 8. Detector CO internal number 8 in the time period 27.03.-05.05.

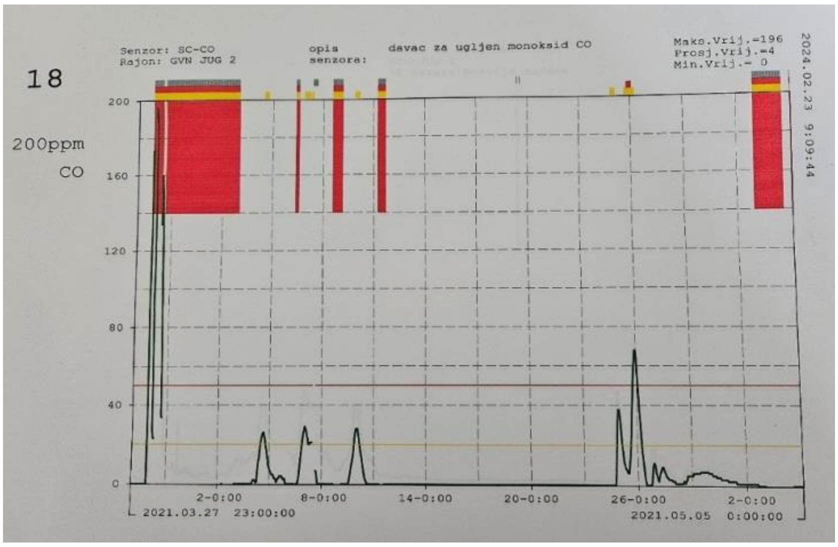

Figure 9. Detector CO internal number 18 in the time period 27.03.-05.05.

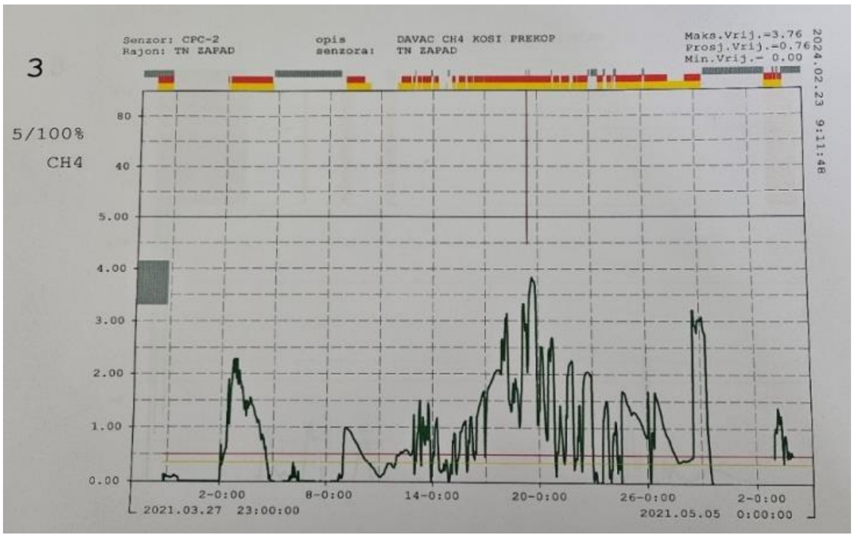

Figure 10. *Detector CH_4 internal number 3 in the time period 27.03.-05.05.*

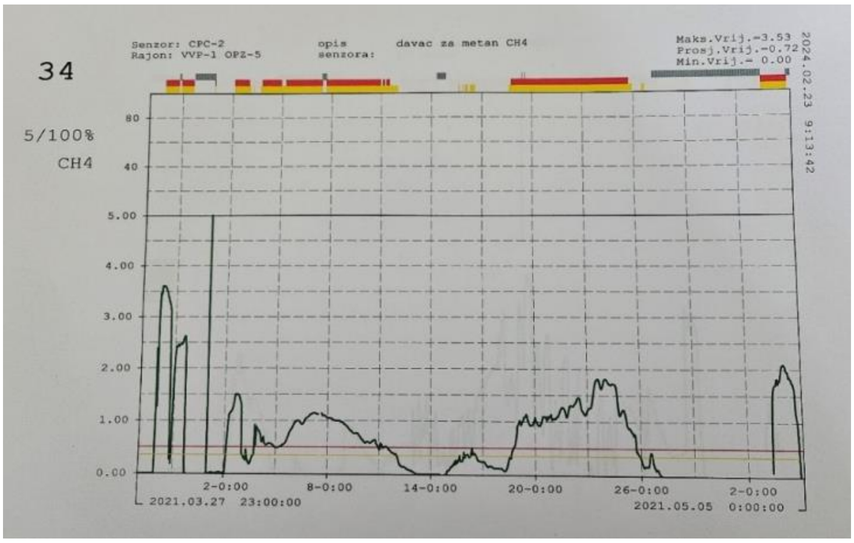

Figure 11. *Detector CH_4 internal number 34 in the time period 27.03.-05.05.*

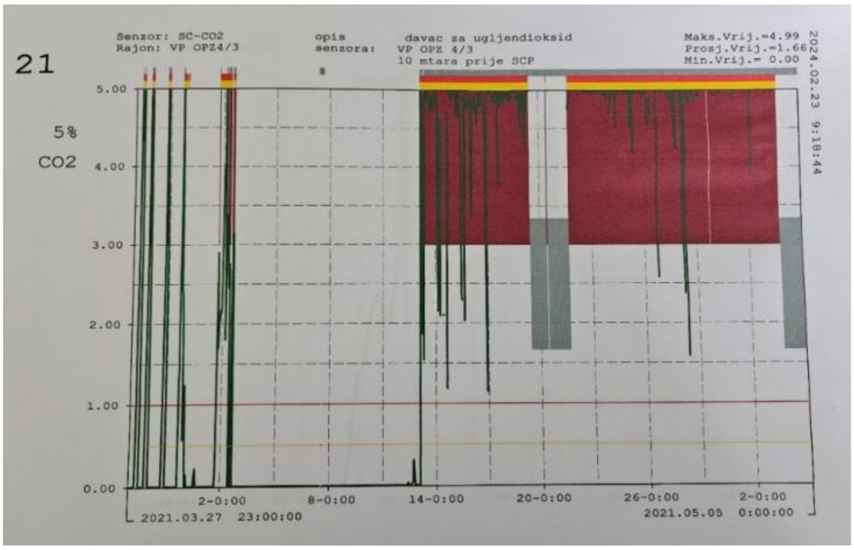

Figure 12. *Detector CO_2 internal number 21 in the time period 27.03.-05.05.*

Table 1. Gas condition behind the insulating walls.

Date	JUG 1				JUG 2				JUG 3			
	CO ppm	CO_2 %	CH_4 %	O_2 %	CO ppm	CO_2 %	CH_4 %	O_2 %	CO ppm	CO_2 %	CH_4 %	O_2 %
02.04.	3,41	0,0	0,0	20,45	3,42	0,13	0,01	20,37	2145	13,49	0,42	5,89
03.04.	1,24	0,19	0,07	20,10	0,57	0,14	0,06	20,30	1921	83,03	0,13	4,58
06.04.	1,32	0,00	0,00	20,56	1,17	0,00	0,00	20,60	1537	11,69	0,91	4,00
09.04.	1,74	0,00	0,00	20,17	2,70	0,00	0,00	20,20	1647	11,50	0,55	3,27
10.04.	1,68	0,10	0,00	20,45	3,05	0,06	0,00	20,51	854	9,12	0,59	4,31
11.04.	2,39	0,09	0,01	20,34	2,73	0,00	0,00	20,52	266	8,34	0,60	3,96
14.04.	1,15	0,00	0,00	20,09	0,83	0,00	0,00	20,14	191	8,19	0,83	4,21
17.04.	1,75	0,28	0,00	20,20	1,48	0,20	0,00	20,02	93	7,03	0,75	4,25
20.04.	0,87	0,12	0,00	20,21	0,65	0,00	0,00	20,30	78	7,90	1,02	6,30
23.04.	0,98	0,14	0,00	20,30	0,51	0,00	0,00	20,42	120	6,94	0,71	6,93
25.04.	1,88	0,24	0,00	20,07	1,52	0,56	0,00	19,57	241	7,20	0,75	5,64
26.04.	0,67	0,00	0,00	20,33	0,89	0,00	0,00	20,34	85	8,54	0,00	4,10
27.04.	1,19	4,11	0,43	12,23	2,62	4,83	0,54	11,08	13	7,44	0,87	6,81
28.04.	0,21	4,89	0,67	10,08	1,35	5,16	0,74	9,62	4	7,62	0,94	6,19
29.04.	0,72	2,72	0,37	14,45	1,62	1,11	0,08	18,67	2	7,50	0,56	10,00
30.04.	1,55	1,64	0,25	17,35	1,83	1,75	0,17	18,36	2	7,99	0,97	5,58
01.05.	1,72	5,64	1,62	4,74	2,46	2,91	0,88	11,52	3	7,93	1,16	2,26
02.05.	2,55	1,52	0,46	16,10	1,84	0,16	0,01	20,06	3	7,53	1,85	3,20
03.05.	0,81	0,22	0,00	20,28	0,42	0,00	0,00	20,65	1	4,01	0,97	12,30

After the pit was closed, a larger amount of water was let into the pit through the already existing pipelines. The exact location of the water in the pit was unknown, as were the actual effects of its release, but it was assumed that it cooled the pit to some extent and that the water would create plugs in the pit floor that would prevent the transmission of fire and fire gases. Of course, there was also a danger of submersion of equipment in the pit, especially that of KMSC.

Water was let into the pit in a controlled manner until April 27. that on 28 and 29.04. through the existing pipeline, through JUG 1 and JUG 3, a total of 13 tons of liquid nitrogen (LN_2) were injected into the pit [13].

All the time, a laboratory analysis of the composition of the pit air taken at the isolation walls (Table 1) was performed, at least three times during the day, and the pressure difference on the isolation walls [8] made at the entrances to the pit and the temperature were measured (Table 2).

Laboratory analyzes of pit air samples showed the presence of CO, CO_2 and CH_4, with the highest content on the isolation walls made at the exit from the pit (JUG 3). The content of these gases in all samples initially changed dynamically, rising and falling, but as time passed, the fluctuations became less and less and their total content fell slightly. And the gas detectors, which were still in operation, showed changes in the measured values. It is noticeable that around 25.04. increased concentration of CO in the pit (laboratory analysis and detectors) as the cause of burning in the space with the presence of sufficient amounts of oxygen. Also, the drastic increase in CO_2 concentration from 27.04. on the isolation walls in JUG 1 and JUG 2 corresponds to a significant drop in CO concentration on the isolation walls in JUG 3.

Table 2. Potential difference on insulating walls.

Date	JUG 1		JUG 2		JUG 3	
	h (Pa)	t (^{0}C)	h (Pa)	t (^{0}C)	h (Pa)	t (^{0}C)
03.04.	-73	18	-59	9	90	33
06.04.	-110	7	-124	5	44	21
09.04.	22	14	7	17	105	14
10.04.	0	12	0	12	97	15
11.04.	0	11	0	12	100	15
14.04.	15	8	5	8	83	9
17.04.	0	10	0	9	72	12
20.04.	0	10	0	10	48	14
23.04.	-36	12	-44	12	0	9
25.04.	0	12	0	10	12	13
26.04.	-38	13	-36	13	0	15
27.04.	-8	12	-3	12	0	15
28.04.	0	12	0	12	0	13
29.04.	0	11	5	11	0	13
30.04.	0	14	0	15	0	16
01.05.	0	14	0	15	0	16
02.05.	0	17	0	20	0	20
03.05.	70	14	72	16	0	14

Immediately after the construction of the isolation walls, until the potential balance is established in the pit, through the isolation walls in JUG 1 and JUG 2, air tries to continue moving into the pit, so the space behind these walls is under pressure. In JUG 3, warm air is trying to escape from the pit and the space behind these insulating walls is under pressure [9]. Potential fluctuation was detected around 25.04. and coincides with the recorded increase in CO concentration in the pit. Isolation walls on JUG 2 were opened on 03.05. which corresponds to a change in gas state and potential in JUG 1 and JUG 2.

5. Fire Extinguishing Results and Experiences

On May 3, 2021, several teams of specialized workers entered the pit via JUG 2. The pit was gradually degassed using separate fans, part by part. During the inspection (Figure 13) and tour of the pit, the following was determined:

1) in the parts of the pit where the pit fire was active, easily combustible material (wood, plastic, electrical installations, etc.) burned completely [5],
2) the fire covered pit rooms with a total length of about 500 m,
3) the fire was extinguished due to lack of oxygen, water and nitrogen additionally cooled the isolated space and nitrogen further reduced the oxygen concentration [10],
4) pillars and insulation walls that were used at the time of the fire, it will be determined later, did not suffer any damage. Due to the fire depression at the time when the fire was active, methane from the nearby goaf moved into the pit rooms through cracks and pores in the protective columns [15],
5) a significant increase in CO concentration (around April 25) was registered by laboratory analysis of air samples behind the isolation walls in JUG 3, but also by active detectors in the pit and was monitored by a change in potential,
6) significant increase in CO_2 concentration in air samples (JUG 1 and JUG 2) was accompanied by a significant drop in CO concentration in JUG 3,
7) only in one pit room, in which there was a large amount of deposited coal dust and crushed coal, did the fire

reactivate after the pit was opened [14]. This room is additionally insulated and filled with inert material (the sand),

8) in rooms made of coal with stable sides (walls), the coal layer did not ignite or burn,
9) the signal that the fire subsided was the equalization of the potential on the insulation walls,
10) in several rooms where the wooden pledge that was used as a support for the ceiling of the room burned, larger ruins were found that completely destroyed parts of these rooms. Such rooms were subsequently renovated or replaced by making new ones,
11) it was noticed that the humid parts of the rooms where LN_2 leaked out also suffered some damage. The degree of damage is directly related to the intensity of humidity, the more humid the room, the greater the damage [12].
12) visibility in the cave rooms was very good, without smoke with increased humidity,
13) the temperature in almost all rooms was within the permitted limits. With high-quality ventilation, the temperature in the heated parts of the pit very quickly reached the permitted limits [1],
14) 12.05. the main ventilation plant was put into operation with small amounts of air used to ventilate the pit, and with certain corrections (construction of temporary walls) the ventilation system of the pit was established,
15) pumping out water from submerged parts of the pit and rehabilitating existing damaged rooms and building a new room took the next four months.

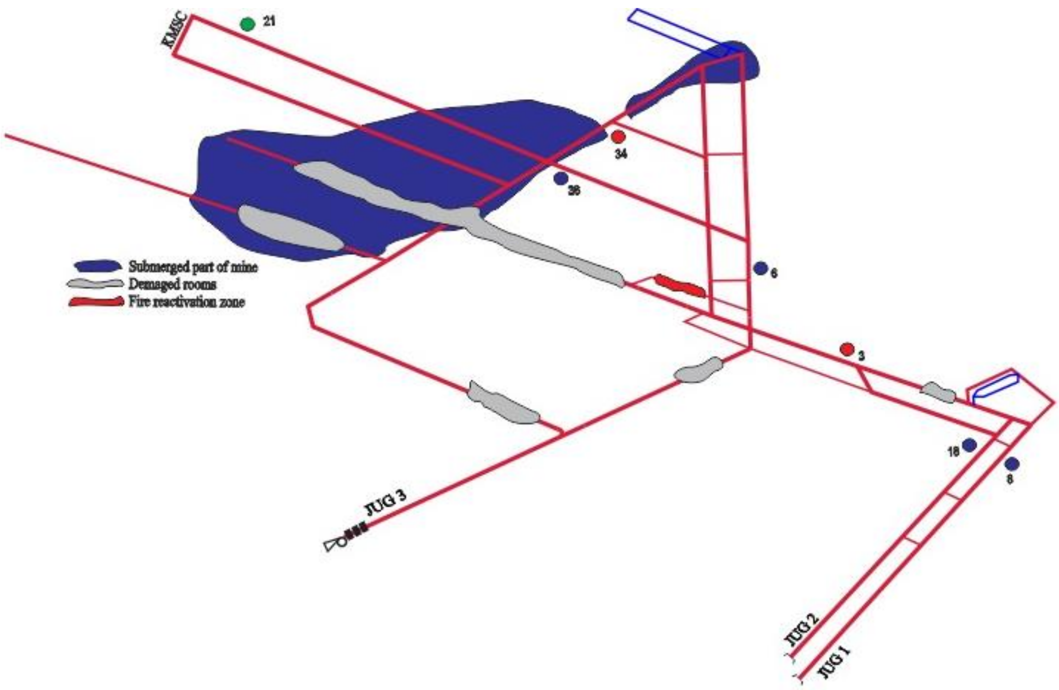

Figure 13. Pit rooms at the moment of pit opening and degassing.

6. Conclusion

In the underground mine RMU "Banovici" several pit fires have been registered throughout history. Most often, due to friction, deposited coal dust was ignited or self-ignition of crushed coal occurred in fault zones and goafs. All these fires were local and mine employees had extensive experience in extinguishing and rehabilitating them.

In 2021, for the first time, the entire pit had to be temporarily closed due to a fire. It was known from experience that isolating and closing the pit will prevent the flow of oxygen into the pit rooms as well as to zones with active fire. Due to the lack of oxygen, the fire will go out, but the area around it will remain heated.

What was not known was whether the coal layer was burning, what condition the pit rooms are in, to what extent they are heated, what the visibility is, and most importantly when to reopen the pit without reactivation of the fire.

By analyzing data from monitoring the composition of pit air, especially data obtained from detectors that were in operation in the pit, a good estimate of the moment of re-opening of the pit was made. Preparations and the pit degassing procedure itself were properly selected, the part of the pit where the fire reactivated was isolated in time and filled with inert material. The controlled injection of water and LN_2 into the pit certainly did not extinguish the fire [10], but it lowered the temperature in the pit. Also, good visibility in the pit rooms during the degassing phase of the pit is something we did not hope for.

It was again shown that an increase in the concentration of CO_2 and a decrease in the concentration of CO in the isolated space is a sure indicator of the calming down of the oxidation process [5].

Abbreviations

JUG 1: Main Transport Shaft Jug 1
JUG 2: Main Ventilation Shaft Jug 2
JUG 3: Main Ventilation Shaft Jug 3
KMSC: Mechanized Longwall

Conflicts of Interest

The authors declare no conflicts of interest.

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