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Study of influence of tremors on combined hazards. Longwall mining operations in co-occurrence of natural hazards. A case study

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ABSTRACT

Combined hazards occurring in areas of hard coal mines were characterised. A possible course of processes leading to a mining catastrophe, associated with occurrence of combined hazards, was discussed. An example of a cause and effect chain is presented, where rockburst hazard initiates – with co-occurring climatic hazard – an increase in the level of spontaneous fire hazard, methane explosion hazard and coal dust explosion hazard. Possibility of improving detection of spontaneous fire hazard in presence of co-occurring combined hazards was analysed.

1. Introduction

Underground hard coal mining is associated with recognising and fighting hazards, including those which are natural, which may result in a direct threat to health and safety. The following natural hazards may occur: rock bursts – which result in tremors of rock mass; methane hazards – which may cause ignitions and explosions; fire hazards – which lead to the emission of toxic, suffocating and explosive gases; climatic hazards – which may cause miners' fainting; coal dust explosions and outbursts of gases and rocks; water hazards – which may cause water to suddenly pass into mine workings; radiological risks – which lead to workers being exposed to radiation.

The current legal framework for underground mining contains a number of regulations concerning situations where longwall mining operations are conducted in conditions requiring special treatment. For example, longwalls in seams with category II, III or IV of methane hazard, with a co-occurring rock burst hazard or spontaneous fire hazard in the goaf, require documentation concerning the intended mining operations and that specifies measures to prevent these hazards, considering their mutual interactions. If the forecasted absolute methane-bearing capacity of a longwall area exceeds 40 m^3/min, a plan of exploitation has to be approved by a special commission appointed by the President of the State Mining Authority following Article 166 §1 point 2 Geological and Mining Law. In turn, a longwall in a seam with: III degree rockburst hazard, category IV methane hazard, III degree water hazard and susceptibility to gas and rocks outbursts, is treated as a longwall exploited in special conditions, i.e. beginning work on such a longwall requires permission from the proper mining authority.

The examples and the current regulations issued, following Geological and Mining Law, define such a term as **combined hazards**. Yet, for at least twenty years it has been known that such hazards, if they occur in a mining area and especially in hard coal mines, increase hazard levels. That is

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why it is necessary to treat co-occurring hazards with special attention.

The aim of this article is to show, by studying a longwall with the co-occurrence of hazards forming combined hazards, the influence of the most unpredictable of the hazards i.e. rockburst hazard, on other hazards. Additionally, this article aims to clearly demonstrate that a special approach to mining operations conducted in such conditions is required.

2. Characteristics of combined hazards

Combined hazards may result in rockburst hazard, methane hazard, spontaneous fire hazard, climatic hazard or coal dust explosion hazard. It is a rare situation when all these dangers co-occur in one mining area. There may be a few variants of combined hazards where the correlation of their consequences evidently forms a cause and effect chain (Trenczek, 2002) which may lead to a catastrophe.

Depending on the number of co-occurring hazards, several variants of combined hazards can be distinguished.

Simple variants of combined hazards consist of two components:

- rockburst hazard and spontaneous fire hazard;
- climatic hazard and spontaneous fire hazard.

In the first, either rock mass tremors or rockburst hazard prevention measures (shock blasting, mining blasting, etc.) cause coal seam cracking, which may initiate a process of coal self-heating and self-ignition. In the second, if there is coal in a goaf (e.g. in areas of geological disturbances, the overlying seam, from a coal "shelf" remaining between an upper – roof slice and lower – floor slice coal layer of a thick seam, etc.), climatic hazard, with characteristic high primary rock mass temperature, shortens the initial period in the process of coal self-heating, which accelerates self-ignition. The scale of danger of these variants is relatively low, as the resulting spontaneous fire is usually slow, which enables the withdrawal of personnel from the area.

Complex combined hazards, when three or even four hazards co-occur simultaneously, have much more serious consequences.

Combined hazards of three elements, consist of a spontaneous fire hazard, methane hazard (methane explosion) and coal dust explosion hazard. Spontaneous fire may cause methane ignition and explosion, which may lead to coal dust explosion.

Four-element combined hazards may occur in two variants:

- rockburst hazard, spontaneous fire hazard, methane hazard (methane explosion) and coal dust explosion hazard;
- climatic hazard, spontaneous fire hazard, methane hazard and coal dust explosion hazard.

In the first there may be two different patterns:

- tremors crack a coal seam, leading to coal self-ignition in a goaf, which leads to methane explosion (resulting in flames from a goaf to flow-through the air and a blast wave), which causes coal dust explosion,

or

- tremor – a rock burst causes a methane explosion in a goaf (causing flames from a goaf to flow-through the air and a blast wave), leading to a coal dust explosion and the ignition of coal in a goaf, initiated by burning methane.

In the latter, the climatic hazard accompanying the spontaneous fire hazard contributes to the fire, which ignites and explodes methane in the goaf, and this in turn leads to coal dust explosion.

Five-element combined hazards involve all of the aforementioned hazards simultaneously. The cause and effect chain starts with the cracking of coal located in rock mass with a high primary temperature, which accelerates the self-heating processes leading to a spontaneous fire, which, in turn, initiates methane combustion and explosion, which eventually causes coal dust explosion.

In the division of the combined hazards presented above, it can be observed that co-occurring coal dust explosion hazard is the very last link of the cause and effect chain and causes the state of highest hazard. Methane hazard is the second most significant hazard, being either initial, middle or ultimate link of the chain.

Fighting each of the hazards separately has a range of efficient preventive methods, yet it is difficult to synchronize these methods to fight all the combined hazards simultaneously. Hence, the cause and effect chain may take a developed form or a limited one. It ought to be emphasised that rockburst hazard, as the least predictable of hazards, and a hazard of more serious consequences than fire hazard, ought to be the primary object of preventative actions. Moreover such hazards are going to be, unfortunately, more and more common.

3. Methane combustion in the area of the Longwall 560

The event discussed in this paper occurred in the "Mysłowice-Wesoła" – ruch "Wesoła" coal mine. The coal seam's mining operations were carried out in the OG "Wesoła II" area located in the middle of the Upper Silesian Coal Basin (Górnośląskie Zagłębie Węglowe). Seam 510 was one of several mined seams. On 6 October 2014 in the area of Longwall 560 seam 510 Dw, where there were 37 employees, methane combustion occurred (Documentation, 2014).

Immediately after this event occurred, the dispatcher began a rescue operation. During the operation, immediately after the incident, some of the injured left the area without assistance and others were helped by their co-workers. Altogether 36 employees were evacuated, and one employee was presumed missing. He was found after 12 days of the rescue operation in a flooded section of a return-air roadway of the longwall. Altogether 36 people were evacuated from the area and transported to the surface. As a result 30 people were

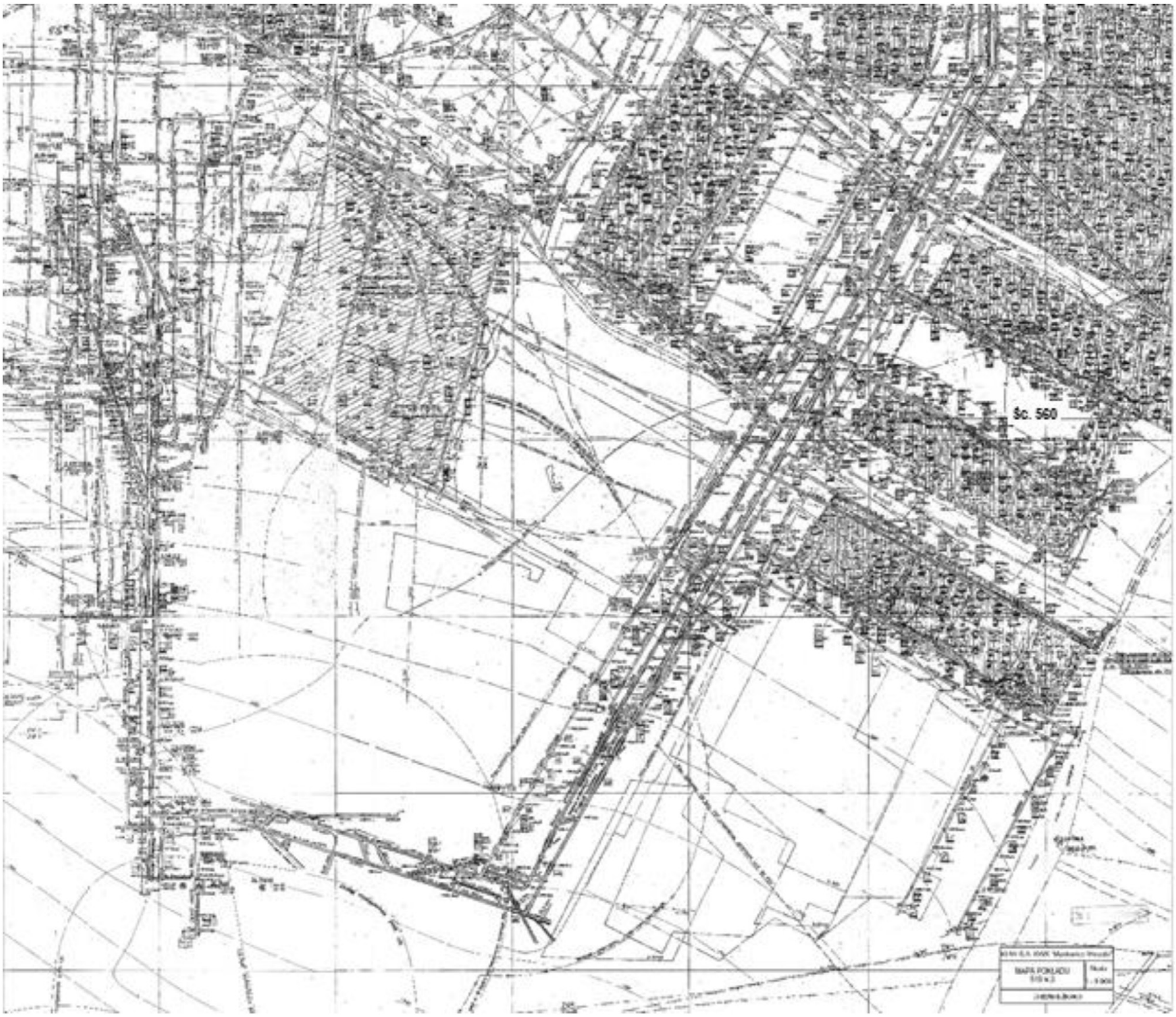


Fig. 1 – Fragment of the map of seam 510 part D East –Longwall 560 located close to the goaf.

injured: 5 of the injured died in hospital, 15 were seriously wounded, and 10 suffered minor injuries.

The area of Longwall 560, seam 510 Dw is located close to the goaf (Fig. 1) at a depth of between approximately 807 and approximately 840 m.

The hazards which were of particular significance and the co-occurrence of which increased the general hazard level, were:

- rockburst hazard in seam 510 Dw, III degree;
- methane hazard in seam 510 Dw, IV category;
- coal dust explosion hazard, B class;
- spontaneous fire hazard in seam 510 Dw, III class of susceptibility to self-ignition;
- climatic hazard in longwall area, II Critical Level.

Table 1 – Tremors in area of Longwall 560 seam 510 Dw.

Number of tremors – N						Energy	
E2 [J]	E3 [J]	E4 [J]	E5 [J]	E6 [J]	∑	∑ of tremors $A_s \cdot 10^6$ [J]	Average energy of tremor $A_s/N \cdot 10^3$ [J]
162	364	37	2	0	565	3.47	6.14

Table 2 – Natural and induced tremors in relation to the place they occurred in the area of Longwall 560 seam 510 Dw.

Location of tremors	Number of tremors: Natural (N) and induced (P)								
	E2 [J]		E3 [J]		E4 [J]		E5 [J]		Σ
	N	P	N	P	N	P	N	P	
Coal panel of Longwall 560	88	3	168	21	17	1	1	–	299
Goaf and solid coal E of Cut-through 560	71	–	171	4	19	–	1	–	266
Total	159	3	339	25	36	1	2	–	565

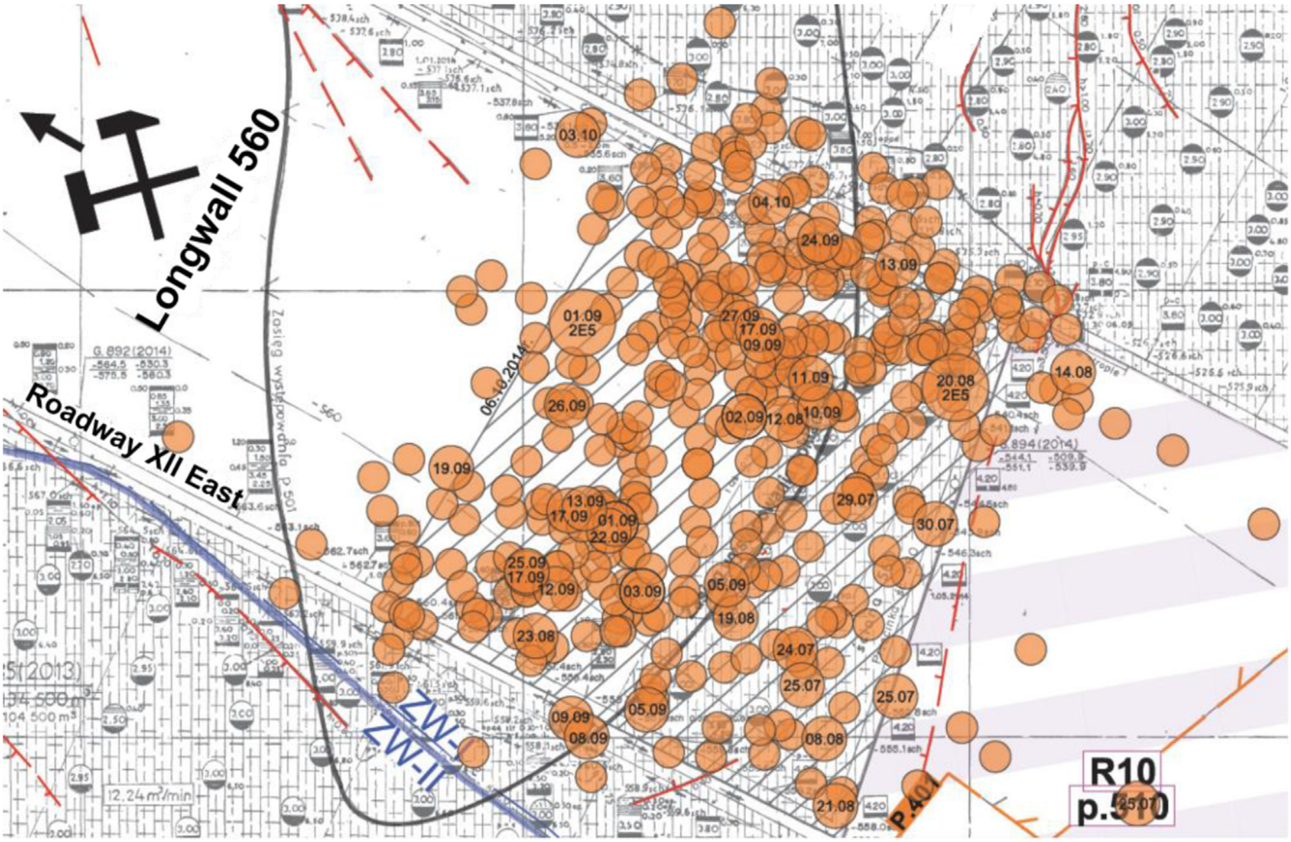


Fig. 2 – **Location of tremors of 10^3 J and higher in the area of Longwall 560 seam 510 Dw (tremors 10^4 J and higher labelled with the date of occurrence).**

4. Expected and actual level of rockburst hazard in the area of Longwall 560

During mining operations in Longwall 560 in the roof slice of seam 510 part D East (Dw) tremors of various sizes were forecast (Zorychta, 2013):

- mainly low-energy tremors with energy of 10^2 J (E2), 10^3 J (E3) and 10^4 J (E4);
- occasional high-energy tremors with energy of up to $5–10^5$ J (E5);
- occasional high-energy tremors with energy over 10^6 J (E6).

An increase in rockburst hazard was also expected while Longwall 560 was mined in strain concentration zones, especially in areas influenced by faults and in areas where the deposition of the seam and its roof layers was disturbed.

Detailed analyses of the area of Longwall 560 showed (Zorychta, 2014) that 565 tremors occurred there, between 16 July 2014 and 6 October 2014, and most of them were tremors with energy of 10^3 J (E3) (Table 1).

From start-up until 14 August 2014, there were 101 tremors, on average over 3 tremors per day; during normal mining operations in the longwall. By 6 October 2014, there had been 464 more tremors, on average almost 9 tremors per day. Out of these, 534 were of natural origin, 31 were tremors caused by inducer shooting with the use of explosives. The tremors had different locations in relation to the mining face (Table 2); Fig. 2 shows epicentres with tremors of about 10^5 J (the biggest circles) and 10^4 J – described with dates and tremors (without descriptions) of about 10^3 J.

The high seismic activity in the area of the Longwall 560 resulted from: the presence of a sandstone layer directly in the roof of seam 510 with a thickness of about 10–11 m and compression strength of up to 57.6 MPa, as well as from its location with regard to:

- goaf (Fig. 1) of the roof slice of seam 510 Dw – it was the last longwall in this part (the so called "closing longwall");
- large dislocations: on the East – Ławecki throw of 80–180 m, on the South – Luiza throw of about 70 m.

5. Results and discussion

The levels of hazards occurring in the area of longwall 560 presented above are a classic example of the most developed version of combined hazards. The seismic activity resulting from rockburst hazard is a clear initiator of a cause and effect chain.

5.1. *Influence of tremors on methane hazard*

After each recorded rock mass tremor, whether natural or induced, changes in the concentration of methane in the air

Table 3 – Tremors causing inflow of methane in area of Longwall 560 seam 510 Dw and volume of methane inflow.

No.	Date	Time [hr:min]	Tremor energy (W) [J]	Longwall sight 560 [m]	Methane hazard in the area of Longwall 560 based on sensor read-outs – Roadway XIa East 10 m westward of Longwall 560								
					Values of CH_4 concentrations in Roadway XIa East						Max. increase in CH_4 concentration [%]	Additional inflow of CH_4 associated with tremor	
					Before W		Maximum after W		When concentrations stabilise				
					Time [hr:min]	Concentration [%]	Time [hr:min]	Concentration [%]	Time [hr:min]	Concentration [%]		Time [min]	Volume [m^3]
1.	20.08.14	20:39	9E3	607.75	20:38	1.4	21:35	1.9	22:39	1.5	0.5	120	435.0
2.	31.08.14	09:24	7E3	567.75	09:23	0.8	13:02	0.9	13:13	0.8	0.1	249	180.5
3.	10.09.14	03:01	9E3	536.5	03:00	1.0	03:07	1.2	03:33	1.0	0.2	32	46.4
4.	15.09.14	14:02	1E3	521.0	14:01	0.9	14:25	1.1	15:26	0.9	0.2	84	121.8
5.	15.09.14	16:29	3E3	521.0	16:28	0.9	16:35	1.1	18:08	1.0	0.2	99	143.5
6.	19.09.14	07:09	2E3 SW	505.5	07:08	1.2	07:12	1.4	07:29	1.2	0.2	20	29.0
7.	20.09.14	07:40	2E3 SW	501	07:39	1.0	07:73	1.1	07:45	1.0	0.1	5	3.6
8.	23.09.14	03:28	7E3	492.5	03:27	1.1	04:36	1.3	04:45	1.0	0.2	77	111.6
9.	26.09.14	18:34	6E3	481	18:33	1.0	18:34	1.1	18:35	1.0	0.1	1	0.7
10.	27.09.14	05:50	9E3	478.25	05:49	1.1	05:50	1.2	06:02	1.1	0.1	12	8.7
11.	27.09.14	07:09	2E3	478.25	07:08	1.2	07:12	1.3	07:20	1.2	0.1	11	7.9
12.	27.09.14	07:48	2E4	478.25	07:47	1.1	07:55	1.3	08:29	1.2	0.1	41	29.7
13.	04.10.14	12:49	8E2	465	12:48	1.2	12:51	2.4	12:56	1.2	1.2	7	60.9
14.	04.10.14	04:03	9E2	463	04:02	0.9	06:58	1.5	10:37	1.1	0.5	394	1428.2
15.	04.10.14	22:25	8E4	463	22:24	1.2	23:47	1.4	01:44	0.8	0.2	139	201.5

Table 4 – Locations of tremors in the area of Longwall 560 seam 510 Dw causing methane inflow.

No.	Date	Time [h:min]	Energy [J]	Longwall sight 560 [m]	Location of tremor (W) – distance in straight line: – From junction of Longwall 560 and Roadway XII East (XII) [m], – from junction of Longwall 560 and Roadway XIa East (XIa) [m]								
					In front of Longwall 560						Behind of Longwall		Vertical distance “z” to seam 510: Above (+), below (–), [m]
					Mined area		Northward		Southward		Mined goaf of Longwall. 560		
					XII	XIa	XII	XIa	XII	XIa	XII	XIa	
1.	20.08.14	20:39	9E3	607.75	185	60							+16
2.	31.08.14	09:24	7E3	567.75							125	120	–30
3.	10.09.14	03:01	9E3	536.5	195	50							+24
4.	15.09.14	14:02	1E3	521.0	75	170							+25
5.	15.09.14	16:29	3E3	521.0	215	30							+42
6.	19.09.14	07:09	2E3 SW	505.5	155	90							–5
7.	20.09.14	07:40	2E3 SW	501	75	170							+26
8.	23.09.14	03:28	7E3	492.5							145	100	+82
9.	26.09.14	18:34	6E3	481	120	125							+31
10.	27.09.14	05:50	9E3	478.25			250	5					+85
11.	27.09.14	07:09	2E3	478.25	210	35							+155
12.	27.09.14	07:48	2E4	478.25							190	55	+71
13.	03.10.14	12:49	8E2	465							40	205	+108
14.	04.10.14	04:03	9E2	463							220	25	+25
15.	04.10.14	22:25	8E4	463							240	5	+29

flowing from Longwall 560 were checked. In several cases methane concentration increased (Table 3).

The table shows that tremors of between 8–10^2 J and 8–10^4 J led to an increase in methane concentrations. They were: 2 tremors of 10^2 J, 11 tremors of 10^3 J (including 2 tremors induced with shock blasting) and 2 tremors of 10^4 J.

Increases in methane concentrations were differentiated:

- by 0.1% and 0.2%–6 cases each;
- by 0.5%–2 cases;
- by 1.2%–1 case.

Values of the extra methane emitted were further differentiated:

- marginal – 6 cases of below 10 m^3 CH_4 inflow,
- low – 4 cases of up to 100 m^3 CH_4 inflow,
- medium – 2 cases each of up to approx. 100 and 200 m^3 CH_4 inflow,
- high – 1 case of approx. 1428 m^3 CH_4 inflow.

Further analyses of the data concerning the energy of the tremors and the concentrations of methane emitted after their occurrence (Table 4) as well as their location (Fig. 3a–o) showed that it is impossible to find any specific correlations between the energy and the location of a tremor in Longwall 560 and increase in methane concentration. The increase in methane concentration was caused by tremors of various amounts of energy located at various distances from the front of Longwall 560.

5.2. *Influence of rock mass tremors on changes in the level of spontaneous fire hazard*

The adverse influence of seismic activity resulted from the location of the epicentres of some of the tremors (Fig. 4):

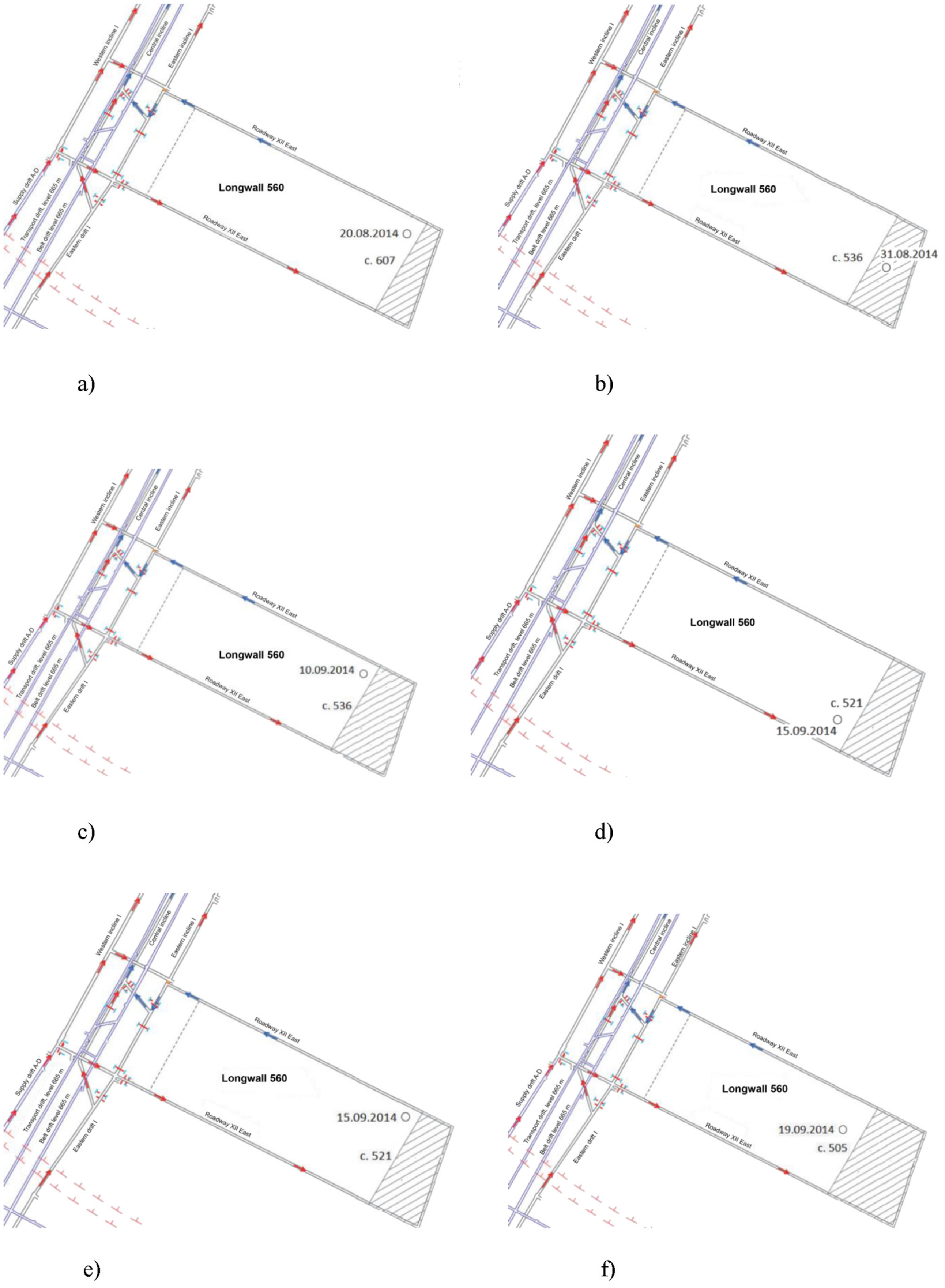
- in a belt up to 20 m north and south of Roadway XIa East there were 52 tremors – 9.2% of the total;
- in a belt up to 20 m north and south of Roadway XII East there were 22 tremors – 3.9% of the total, which altogether equals 13.1%.

As a consequence of the tremors, coal pillars were significantly cracked, resulting in the increased migration of goaf gases and initiation of complicated processes of self-heating and self-ignition of coal (Adamus, 2007; Anez, Torrent, Pejic, & Olmedo, 2015; Clemens, & Matheson, 1996; Kostjenko, & Zawjałowa, 2007; Maciejasz, & Kruk, 1974).

In a typical coal pillar a few metres thick, a fire can start in cracks filled with coal dust, which is most prone to oxidation. The lower temperature for the ignition of coal grains of diameter below 1 mm, which ranges between 190 and 220 °C, also favours such a process, which was confirmed by Świętochowski and Grochowski's research in the late 1940s (Urban, 1951) (Fig. 5).

When the oxidation process transforms into the self-heating process, its development inside a crack advances against the air flow, i.e. towards its entrance, until it leads to self-ignition and fire. Fires in solid coal usually occur at a depth of between 0.5 and 3 m, but occasionally up to 5 m from the surface of a sidewall (Maciejasz, & Kruk, 1974). The actual fire is small in size and is surrounded by the following zones (shown in Fig. 6): oxidation 2 (coal oxidation and emission of carbon dioxide), reduction 3 (part of carbon dioxide gets reduced to carbon monoxide, and hydrogen can be emitted as well), dry distillation of coal 4 (methane, ethane and other hydrocarbons are formed and emitted). Then, gas products of the combustion, emitted from the crack, flow with the air 1 through the crack towards the crack's exit.

Taking into account the conditions occurring in the area of Longwall 560 (Fig. 4) and the processes above mentioned, one



a)

b)

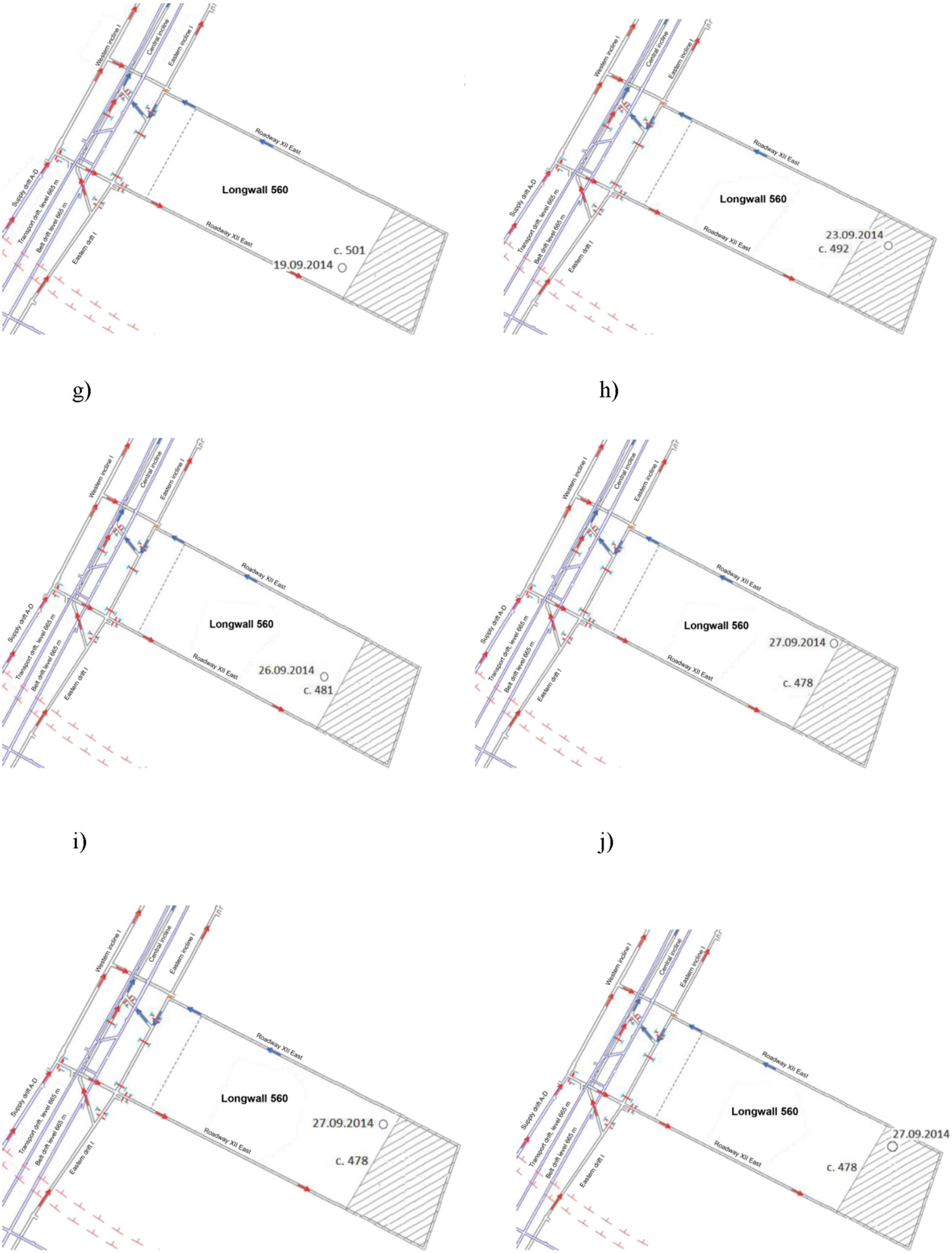
c)

d)

e)

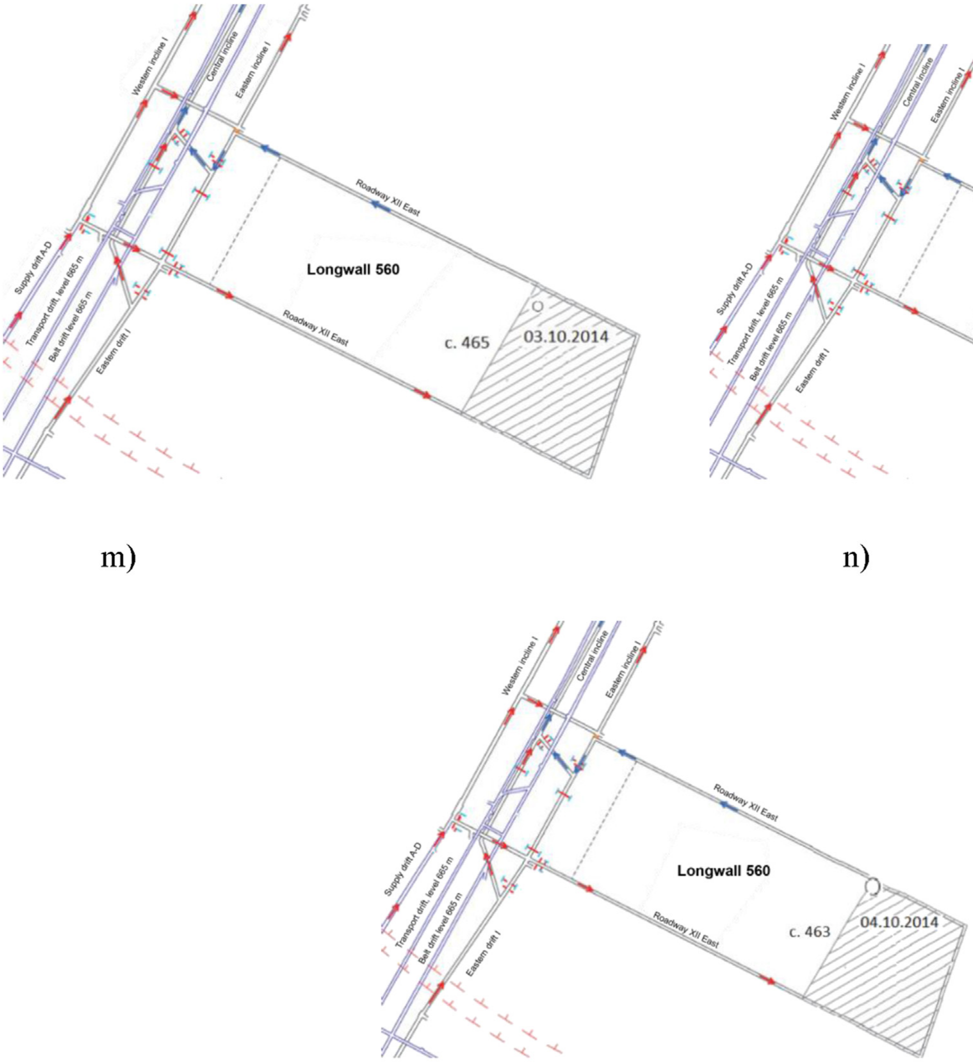
f)

Fig. 3 – Location of tremors resulting in methane inflow in relation to the longwall face according to Numbers 1–15 of Table 4.



g) h) i) j) k) l)

Fig. 3 – *continued.*



m)

n)

o)

Fig. 3 – *continued.*

may assume that such migration of the air through coal pillars and the goaf of this Longwall was possible from the goaf of Longwall 561 northward (due to the southward inclination of seam 510 Dw) towards the goafs of nearby longwalls. Moreover, by ventilating Longwall 560 with a U-type system, there was further deep eastward migration of intake air (oxygen) from Roadway XII East and Longwall 560 to its goaf. Hence, the conditions for the self-heating process were reached. This process was additionally accelerated by the relatively high temperature of goaf gases, resulting from the high primary rock mass temperature of approximately 35 °C.

It means that products of self-heating processes, and possibly of the initial stage of a fire, flowed to the goafs of the longwall located northward. Thus, in practice, they could not be detected with the chemical analyses of gas samples collected in the return air and in the goaf in the area of Roadway XIa East. Only a more developed fire produced enough combustion products – mainly carbon monoxide – which had not enough place in goaf and migrated therefore to workings with flow-through air – it could be seen in a return-air roadway. Early detection of a spontaneous fire is still achieved through the sampling of air from behind seals separating goafs, yet their frequency, of at least every 30 days, and the inertia of goafs, as far as migration of gases is concerned, means that such products reach seals after a long time. The chances of detecting these processes at an early stage are very low in practice. Thus, despite use of correct methods of early detection of spontaneous fires, the fire took place.

5.3. *Discussion conclusions*

In cases similar to the one described above, i.e. mining activities conducted in conditions of the occurrence of combined hazards, rockburst hazard with significant seismic activity, explicitly

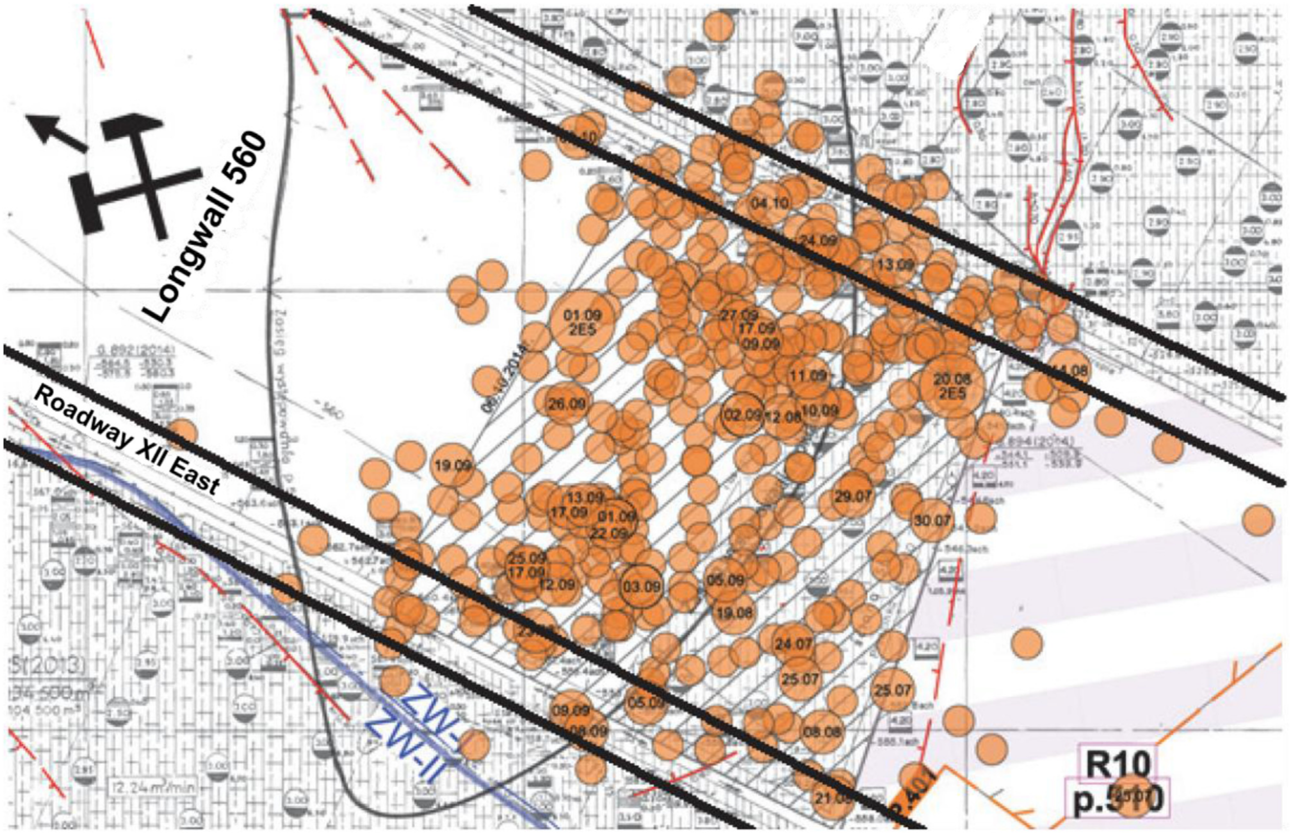


Fig. 4 – Location of tremors in goaf belts in relation to Longwall 560 w seam 510 Dw.

contributes to initiating processes, which occur in the cause and effect chain of events of spontaneous fire and methane hazards.

A standard method for the early detection of spontaneous fire, which follows all the required regulations (Act 2011; Regulation 2002), may fail. In such situations it seems sensible to apply additional measures.

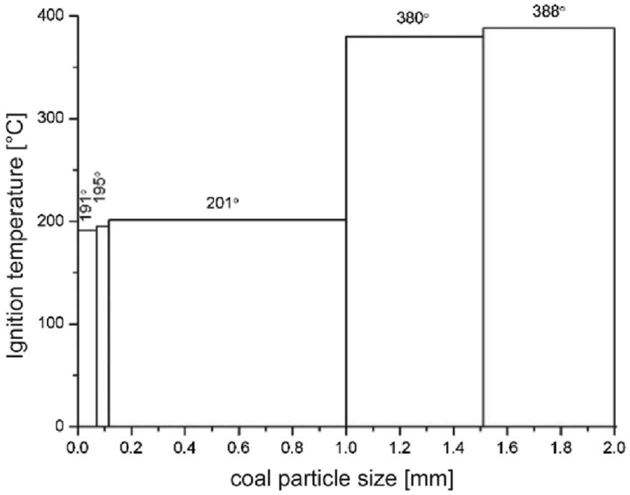


Fig. 5 – Coal dust ignition temperature depending on particle size.

Expanding the early detection of spontaneous fire may mean, for example, taking additional samples of goaf gases with a probe placed as deep as possible within the goaf. Sampling pipes periodically left in goafs to collect samples could be another alternative. It would also be necessary to increase the frequency of taking samples from behind the seals separating the goaf in the direct vicinity of a given active longwall, e.g. to take samples once a week instead of the present requirement of once a month. The chance of detecting products from self-heating processes would then be four times higher.

In conclusion, it is reasonable to introduce changes in mining regulations in order to deal with the issues of the early detection of spontaneous fire in the conditions of combined hazards.

6. Summary

Rockburst hazard, methane hazard, spontaneous fire hazard, climatic hazard and coal dust explosion hazard can form different variants of combined hazards. The co-occurrence of all of these hazards poses the greatest threat.

Rockburst hazard in the area of Longwall 560, with high seismic activity, had a clear unfavourable influence on spontaneous fire, which, with the co-occurring high level of climatic hazard, contributed to the acceleration of coal oxidation and self-heating processes, and after entering the self-ignition

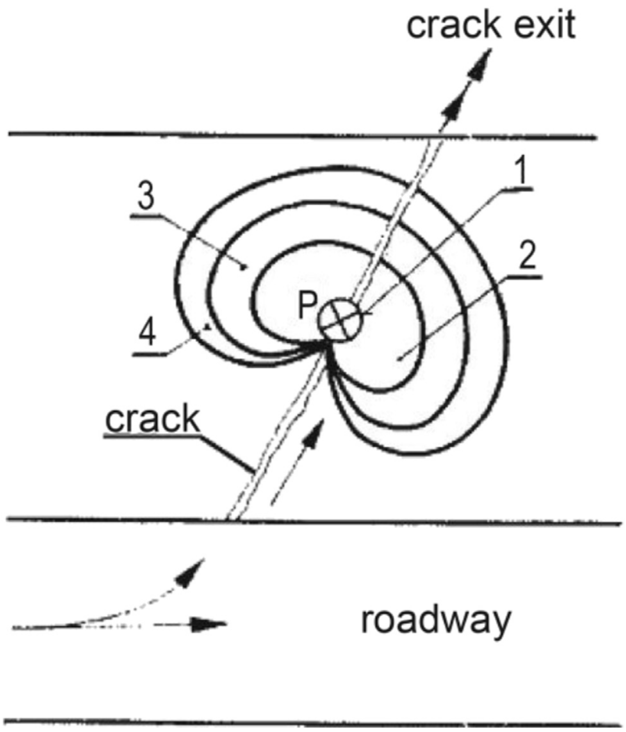


Fig. 6 – Fire in solid coal.

stage, to an increase in methane hazard, i.e. to methane ignition and combustion.

Due to the relatively small volume of methane-air mixture of explosive limits, there was no methane explosion (Documentation, 2015), thus, the cause and effect chain did not develop into a methane and coal dust explosion, which would have taken place in absence of the proper preventive measures.

Self-heating processes and pillar fires, at their initial stage, are hard to identify with the current methods of the early detection of spontaneous fires.

The accidents taking place in areas of combined hazards show that it is necessary to change regulations concerning the early detection of spontaneous fires within the scope of the control of longwall areas with mining operations in the vicinity of goaf with "coal pillars" left there.

Acknowledgements

I conducted the research while working on "Analysis of rockburst hazard considering: forecast and preventive actions in the area of Longwall 560 seam 510 layer III level 665 m in the context of other natural hazards and mining and geological conditions resulting from the goaf in the vicinity of the longwall, influence of potential mining operations in seam 510 layer III level 665 m with longwall 522 on tightness of a sealed off fire area, formed for Longwall 560 in Mysłowice-Wesoła coal mine" – supervised by Professor Andrzej Zarychta DSc, Eng and commissioned by the President of the State Mining Authority as one of expert opinion for the Commission investigating the causes and circumstances of methane combustion and the incident of 6 October 2014 in Katowicki Holding Węglowy S.A. Mysłowice-Wesoła Ruch Wesoła coal mine, Mysłowice. Only a small fraction of the research data was published in the paper mentioned above.

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