Analysis of costs of prevention against spontaneous fire hazard based on selected longwalls

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Abstract. The paper provides the number of spontaneous fires that have occurred in hard coal mines within the last years as well as exhibits the range of preventive works conducted by mining plants. The authors have provided the characteristics of three longwalls in case of which preventive works against fire hazard were conducted. The range of the preventive works aimed at limiting the fire hazard affecting the exploitation using longwalls has been presented as tables, along with the costs of such works. The costs of the preventive works against fire hazard were listed and analyzed for the selected longwalls based on the specified cost indices.

1. Introduction
The Polish hard coal mining industry is coping with numerous natural and technical hazards. Among the natural hazards affecting the ventilation systems and causing the necessity for continuous preventive practices to maintain safety, the most common are: methane hazard, coal dust explosion hazard and spontaneous fire hazard.

From among these three hazards, only in case of coal dust explosion hazard the prevention procedures have been regulated by the provisions of the mining law.

In case of methane hazard and spontaneous fire hazard, the mines develop prevention plans by their own means. In mining plants, a situation where these two hazards co-occur is a significant problem. This is because the prevention practices against these hazards are opposite [1, 2, 3]. The mines are then forced to select the hazard prevention method in such a manner so as not to increase the opposite hazard. Due to the magnitude of the hazard, usually methane hazard is considered as the leading threat, while spontaneous fire hazard is considered as a second priority mostly due to its slow development dynamics.

Unfortunately, such a situation leads to an increase in the frequency of spontaneous fires (table 1).

Table 1. Number of fires in coal mines [4].

| Years | 2012 | 2013 | 2014 | 2015 | 2016 |
|-------|------|------|------|------|------|
| Number of exogenous fires | 3    | 2    | 4    | 4    | 1    |
| Number of spontaneous fires | 4    | 4    | 1    | 5    | 7    |

The increasing number of spontaneous fires [4] unfortunately has an impact on the costs borne by mines for the prevention of this hazard.
In the subsequent part of this article, the costs of preventive works against spontaneous fire hazard shall be presented based on three selected longwalls in which different hazard prevention methods were used.

2. Characteristics of the regions of the longwalls
All the analyzed longwalls [5] were exploited in the years 2013-2015. Their common characteristic was the longitudinal exploitation system with caving. The length of the longwalls was similar and was within the range of 240-249 m, while the panel length was similar and amounted to 685 and 675 m for longwalls 1 and 2, while for longwall 3 it was 1345 m. The basic data characterizing the analyzed longwalls are presented in table 2.

Table 2. Characteristics of mining/technical/other conditions of the longwalls [5].

|                      | Longwall 1          | Longwall 2          | Longwall 3          |
|----------------------|---------------------|---------------------|---------------------|
| Length of the longwall| 243÷246 m           | 240÷249 m           | 240 m               |
| Face height           | 3.42÷4.20 m         | 3.5÷4.4 m           | 3 m                 |
| Longitudinal inclination of the longwall | max. 6.2°; mean: 2.7° | from 5° to 16° | max. 6°            |
| Transverse inclination of the longwall | max. 13.9°; mean: 6.3° | - 10° to +12° | max. 8°            |
| Panel length          | 685 m               | 675 m               | 1345 m              |
| Mean output           | 1635 t/day           | 3642 t/day           | 1318 t/day           |
| Exploitation system   | longitudinal with caving | longitudinal with caving | longitudinal with caving |
| Ventilation system    | “Y” from boundaries | “U” from boundaries | Short “Y” from boundaries |
| Methane hazard        | methane hazard class IV | methane hazard class I. | methane hazard class IV |
| Absolute methane content | 20.14 m³CH₄/min | 3.52 m³CH₄/min | 54.89 m³CH₄/min |
| Fire hazard           | Spontaneous combustion group I | Spontaneous combustion group II | Spontaneous combustion group III |
| Spontaneous fire incubation | 62 days           | 82 days             | 60 days             |
| Coal dust explosion hazard | Class B            | Class B             | Class B             |
| Climatic hazard       | Critical level II   | Critical level I   | Critical level II   |
| Primary temperature of rock mass | Approx. 38.0 °C. | 27.0 °C.           | 39.5 °C.            |
| Rock burst hazard.    | No rock burst propensity | No rock burst propensity | Level III |
| Water hazard          | 1 – II degree       | 1 degree            | 1 degree            |
| Longwall exploitation period | 327 days          | 166 days           | 989 days           |
| Total output from the longwall | 534 585 Mg        | 604 617 Mg         | 1 303 819 Mg        |

Active prevention against all natural hazards related to ventilation was conducted in longwall 1. In terms of methane hazard, it was actively handled by applying methane removal and auxiliary ventilation devices in the vicinity of the longwall and at the crossing with the top gate. To limit the unfavorable climatic conditions, the air was cooled by local air conditioning devices located in gates as well as by air coolers installed directly in the longwall crosscut.

In case of the analyzed spontaneous fire hazard, the exploited seam was classified into the spontaneous combustion group I and was characterized by a very low propensity for combustion. As a part of the fire prevention, inertization of goafs using nitrogen gasified at the surface was conducted on a current basis. To limit the migration of air to the goafs, chemical foams were used to insulate the goafs from the bottom gate side, and gas samples for detailed chromatographic analysis were collected to assess the hazard. Figure 1 presents a diagram of the longwall 1 region.
The active prevention against natural hazards related to ventilation in longwall 2 was mainly focused on the fire hazard. Preventative works related to the methane and climatic hazard were provisional.

The exploited seam was classified into the spontaneous combustion group II and was characterized by a low propensity for combustion. The preventative works pertaining to fire hazard were mostly aimed at the permanent inertization of goafs using nitrogen, feeding a water and ash mixture to the goafs, application of chemical foams to limit the migration of air to the goafs and collecting gas samples for measurements in the mining plant’s laboratory and for detailed chromatographic analysis. Figure 2 presents a diagram of the longwall 2 region.

Similarly to longwall 1, in longwall 3, methane, climatic and fire hazards were subject to active preventive practices. The methane hazard prevention consisted in the methane removal from the rock mass and the use of auxiliary ventilation devices at the crossing of the longwall and the top gate. The prevention against climatic hazard was related to the application of air conditioning devices in the gates. In case of fire hazard, although the seam was classified into the spontaneous combustion group
III, the active prevention was limited to isolating the locations where air could potentially migrate to the goafs using chemical foams and mineral-cement-bonds. To assess the hazard, thermovision inspections of side-walls of workings were conducted. Figure 3 presents a diagram of the longwall 3 region.

![Diagram of the longwall 3 region](image)

**Figure 3.** Diagram of the longwall 3 region [5].

3. **Fire prevention costs for the selected longwall regions**

Mining plants apply multiple methods of spontaneous fire prevention that allow to limit the development of the hazard itself and that allow for the active liquidation of the fire in case it occurs.

The costs that were borne by the mines for tackling the fire hazard included the prices of:

- structural and chemical materials used for sealing and insulation of goafs and sidewalls of gates,
- laboratory tests required to assess the hazard level,
- inertization works,
- man-days of the employees conducting preventative works,
- power and utilities.

The range of the preventive works for the analyzed longwalls along with the costs thereof has been presented in tables 3-5 [5, 6].

**Table 3.** List of costs of fire prevention practices for longwall 1 [5, 6].

| No. | Name of the cost                                      | No./Amount | Unit cost     | Total cost     |
|-----|-------------------------------------------------------|------------|---------------|----------------|
| 1.  | Use of chemical materials:                           | 10 356 dm³ | 5.58 zł/dm³   | 57 786.48 zł   |
|     | - light foams                                         |            |               |                |
| 2.  | Additional works for the application of chemical      |            |               |                |
|     | materials (boreholes, injection)                      |            |               |                |
| 3.  | Use of mineral materials:                             |            |               |                |
|     | - mineral-cement bonds                                |            |               |                |
|     | - cement                                              | 10 t       | 260.00 zł/t   | 2 600.00 zł    |
|     | - sand                                                | 10 t       | 24.00 zł/t    | 240.00 zł      |
| 4.  | Additional works for the application of mineral       |            |               |                |
|     | materials (boreholes, injection)                      |            |               |                |
| 5.  | Cuboid concrete blocks                                | 2 000 pcs. | 3.54 zł/piece | 7 080.00 zł    |
| 6.  | Performance of packwalls (1 running meter)           |            |               |                |
| 7.  | Other construction materials                         |            |               |                |
| 8.  | Laboratory tests of gas samples for early detection  |            |               |                |
|     | of spontaneous fires conducted by the mining facility | 0 pcs.     |               |                |
9. Laboratory tests of gas samples for early detection of spontaneous fires conducted at an order 1 045 pcs. 20.85 zł/piece 21 788.25 zł

10. Additional measurements (thermographic camera, pyrometer) 500 pcs. - -

11. Use of inert gases – N₂ or CO₂ 2 492 890 m³ 0.75 zł/m³ 1 869 667.50 zł

12. Inertization works 100 man-days 293.95 zł 29 395.00 zł

13. Lease or cost of use of inertization devices 3 075 zł/month lease of N₂ tank and nitrogen generator 86 678 zł/month generator 1 560 204.00 zł

14. Man-days related to preventing the fire hazard 197 man-days 293.95 zł/man-day 57 908.15 zł

15. Man-days of mine rescue workers working at preventive works 564 man-days 386.80 zł/man-day 218 155.20 zł

16. Use of water and other utilities 18 615 m³ 1.55/m³ 28 853.25 zł

17. Total cost of the preventive works 3 909 027.83 zł

Table 4. List of costs of fire prevention practices for longwall 2 [5, 6].

| No. | Name of the cost | No./Amount | Unit cost | Total cost |
|-----|------------------|------------|-----------|------------|
| 1.  | Use of chemical materials: | - light foams | 19 584 dm³ | 2.50 zł/dm³ | 48 960.00 zł |
| 2.  | Additional works for the application of chemical materials (boreholes, injection) | - | - | - |
| 3.  | Use of mineral materials: | - mineral-cement bonds, | 160 t | 314.50 zł/t | 50 320.00 zł |
|     | | - cement, | 5 t | 340.00 zł/t | 1 700.00 zł |
|     | | - sand, | 18 t | 18.91 zł/t | 340.38 zł |
| 4.  | Additional works for the application of mineral materials (boreholes, injection) | - | - | - |
| 5.  | Cuboid concrete blocks | 3.000 pcs. | 3.54 zł/piece | 10 620.00 zł |
| 6.  | Performance of packwalls (1 running meter) | None | - | - |
| 7.  | Other construction materials | None | - | - |
| 8.  | Laboratory tests of gas samples for early detection of spontaneous fires conducted by the mining facility | 723 pcs. | 34.00 zł/piece | 24 582.00 zł |
| 9.  | Laboratory tests of gas samples for early detection of spontaneous fires conducted at an order | 135 pcs. | 249.00 zł/piece | 33 615.00 zł |
| 10. | Additional measurements (thermographic camera, pyrometer), Temperature measurements | 8 measurements | 500.00 zł | 4 000.00 zł |
| 11. | Use of inert gases – N₂ or CO₂ | 1 848 600 m³ Price of N₂ in lease | 0.00 zł |
| 12. | Inertization works | 2417 man-days | 548.00 zł | 1 324 516.00 zł |
| 13. | Lease or cost of use of inertization devices | 240 days | 2 600 zł/day | 624 000.00 zł |
| 14. | Man-days related to preventing the fire hazard | 612 man-days | 593.33 zł/man-day | 363 117.96 zł |
| 15. | Man-days of mine rescue workers working at preventive works | 124 man-days | 645.16 zł/man-day | 79 999.84 zł |
| 16. | Use of water and other utilities | Water 7 180 m³ Ash 4 970.7 Mg Zwilkop 27 000 kg | 5.80 zł/kg | 156 600.00 zł |
| 17. | Total cost of the preventive works | 2 722 371.18 zł |
Table 5. List of costs of fire prevention practices for longwall 3 [5, 6].

| No. | Name of the cost                                      | No./Amount           | Unit cost [zł] | Total cost [zł] |
|-----|------------------------------------------------------|----------------------|----------------|-----------------|
| 1.  | Use of chemical materials:                          |                      |                |                 |
|     | - light foams                                       | 5 000 dm3            | 5.66 zł/dm3    | 28 300.00 zł    |
| 2.  | Additional works for the application of chemical     | 100                  | 409.00 zł      | 40 900.00 zł    |
|     | materials (boreholes, injection)                    |                      |                |                 |
| 3.  | Use of mineral materials:                           |                      |                |                 |
|     | - mineral-cement bonds,                              | 45 t                 | 1 100.11 zł/Mg  | 49 504.95 zł    |
|     | - cement,                                            | 5 t                  | 384.99 zł/Mg   | 1 924.95 zł     |
| 4.  | Additional works for the application of mineral      | 120 man-days         | 409.00 zł/day  | 49 080.00 zł    |
|     | materials (boreholes, injection)                    |                      |                |                 |
| 5.  | Cuboid concrete blocks                               | 1750 pcs.            | 3.32 zł/piece  | 5 810.00 zł     |
| 6.  | Performance of packwalls (1 running meter)          | -                    | -              | -               |
| 7.  | Other construction materials                         | -                    | -              | -               |
| 8.  | Laboratory tests of gas samples for early detection | 0 pcs.               | -              | -               |
|     | of spontaneous fires conducted by the mining facility|                      |                |                 |
| 9.  | Laboratory tests of gas samples for early detection | 0 pcs.               | -              | -               |
|     | of spontaneous fires conducted at an order          |                      |                |                 |
| 10. | Additional measurements (thermographic camera,       | 180 man-days         | 409.00 zł/day  | 73 620.00 zł    |
|     | pyrometer)                                           |                      |                |                 |
| 11. | Use of inert gases – N2 or CO2                      | 0 m3                 | 0 zł/ m³       | 0.00 zł         |
| 12. | Inertization works                                  | -                    | -              | -               |
| 13. | Lease or cost of use of inertization devices        | -                    | -              | -               |
| 14. | Man-days related to preventing the fire hazard       | 90 man-days          | 409.00 zł/day  | 36 810.00 zł    |
|     |  Man-days of mine rescue workers working at          | 3 800 man-days       | 409.00 zł/day  | 1 554 200.00 zł |
|     | preventive works                                     |                      |                |                 |
| 15. | Use of water and other utilities                    | -                    | -              | -               |
| 16. | Man-days of mine rescue workers working at          |                      |                |                 |
|     | preventive works                                     |                      |                |                 |
| 17. | **Total cost of the preventive works**              |                      |                | 1 840 149.90 zł |

4. Costs of prevention and cost indices

The following cost indices have been determined as a part of the assessment of the costs of aerological prevention practices [7, 8, 9, 10]:

- percentage of costs in proportion to the obtained revenue \( U_p \), %,
- cost of prevention per 1 Mg of excavated coal \( K_{PMg} \), zł/Mg,
- cost of prevention per 1 running meter of longwall advancement \( K_{Pmb} \), zł/m,
- cost of prevention practices per 1 day of longwall advancement \( K_{Pd} \), zł/day.

The percentage constituted by cost of prevention \( (U_p) \) was calculated based on the following formula:

\[
U_p = \frac{K_p}{P_c} \cdot 100\%, \text{ (\%)} \quad (1)
\]

where:

\( K_p \) – prevention cost, zł,
\( P_c \) – total revenue, zł.

The cost of prevention per 1 Mg of excavated coal \( (K_{PMg}) \) was calculated based on the following formula:
\[ K_{PWM} = \frac{K_P}{W_C}, \text{ (zł/Mg)} \]  

(2)

where:

\( W_C \) – total output from the longwall, Mg.

The cost of prevention per 1 running meter of longwall advancement \((K_{pmb})\) was calculated according to the following formula:

\[ K_{pmb} = \frac{K_P}{w_{lc}}, \text{ (zł/m)} \]  

(3)

where:

\( w_{lc} \) – total panel length of the longwall, m.

The cost of prevention per 1 day of longwall advancement \((K_{pd})\) was calculated according to the following formula:

\[ K_{pd} = \frac{K_P}{l_d}, \text{ (zł/day)} \]  

(4)

where:

\( l_d \) – number of working days of the longwall advancement, day.

The percentages and the total costs of the prevention practices are a sum of percentages or costs of the individual prevention practices related to ventilation.

The percentages constituted by costs of prevention practices and prevention costs have been presented in tables 6 and 7.

**Table 6. Costs of fire prevention and other prevention practices.**

|                | Total output | Total revenue | Cost of the fire prevention | Cost of other ventilation-related prevention | Total cost of ventilation-related prevention |
|----------------|--------------|---------------|-----------------------------|---------------------------------------------|---------------------------------------------|
|                | \( W_C \)    | \( P_C \)     | \( K_{PP} \)                | \( K_{PIn} \)                                | \( K_P \)                                   |
| Longwall 1     | 534 585      | 130 251 635.25| 3 909 027.83                | 10 741 670.20                              | 14 650 698.03                              |
| Longwall 2     | 604 617      | 147 314 932.05| 2 722 371.18                | 611 620.00                                 | 3 333 991.18                              |
| Longwall 3     | 1 303 819    | 317 675 499.35| 1 840 149.90                | 10 091 050.34                              | 11 931 200.24                              |

As it has been mentioned before, exploitation works in the analyzed longwalls were conducted in the years 2013-2015. Based on the annual mean price of 1 Mg of power coal calculated based on the ARA [11] mean coal price rate and the annual mean American Dollar exchange rate [12] in 2013-2015, the price of 1 Mg of power coal was 243.65 zł/Mg.

Three longwalls in seams classified into different spontaneous combustion groups were considered in the analysis of the costs of preventive works related to the fire hazard. It should seem obvious that in case of a higher hazard group, the costs borne for the prevention should be higher. This conclusion may not, however, be drawn directly based on the determined indices.
Table 7. Costs of fire prevention and other prevention practices.

|                | $U_{PP}$ (%) | $U_{Pl}$ (%) | $K_{PMgPo}$ (zł) | $K_{PMgIn}$ (zł) | $K_{PmbPo}$ (zł) | $K_{PmbIn}$ (zł) | $K_{PdPo}$ (zł) | $K_{PdIn}$ (zł) | Cost of fire prevention per 1 Mg of output | Cost of fire prevention per 1 running meter of advancement | Cost of fire prevention per 1 day of advancement |
|----------------|--------------|--------------|------------------|------------------|------------------|------------------|------------------|----------------|------------------------------------------|----------------------------------------------------------|------------------------------------------|
| Longwall 1     | 3.00         | 8.25         | 7.31             | 20.09            | 5 706.61         | 15 681.27        | 11 954.21        | 32 849.14      | 20 091.05                                | 10 091.05                                  | 11 954.21                                |
| Longwall 2     | 1.85         | 0.41         | 4.50             | 1.01             | 4 033.14         | 906.10           | 16 399.83        | 3 484.46       | 16 399.83                                | 16 399.83                                  | 16 399.83                                |
| Longwall 3     | 0.58         | 3.18         | 1.41             | 7.74             | 1 368.14         | 7 502.64         | 1 860.62         | 10 203.29      | 1 860.62                                 | 1 860.62                                  | 1 860.62                                 |

As it may be noted in figure 4, the costs of the fire prevention practices are relatively low, as compared to costs of other prevention practices related to ventilation. Similar differences in costs of prevention against natural hazards related to ventilation have also been exhibited in other publications [7, 8, 9, 10]. Only in the case of longwall 2, the costs of other preventative activities are highly limited as it was not necessary to apply any practices against methane and climatic hazards, which are usually the main cause of additional costs.

![Figure 4](image)

**Figure 4.** Fire prevention costs and costs of other prevention practices related to ventilation.
Figure 5. Percentage constituted by prevention costs and costs of other prevention practices related to ventilation in the total revenue.

The percentage constituted by the prevention costs results directly from the total output. The share of the fire prevention costs in case of longwall 3 is several times lower than the share in case of longwalls 1 and 2. This is caused by the fact that the goafs are not subject to inertization, which usually leads to a significant increase of the total cost of prevention, thus causing the increase of the share of the prevention itself.

Figure 6. Fire prevention costs and costs of other prevention practices related to ventilation per 1 Mg of output.
One of the main indices characterizing the prevention costs is the cost of a given prevention practice in the price of 1 ton of coal. As it has been shown in table 7, the highest prevention cost per ton of output was exhibited by longwall 1 and it amounted to 7.31 zł/Mg of output, although – as it was exhibited before – longwall 1 was characterized by the lowest fire hazard. The cost, however, results from the lowest total output and the highest cost of fire prevention among the analyzed longwalls. Nevertheless, it is still relatively low as compared to the total costs of prevention practices related to ventilation per 1 Mg of output, namely 27.40 zł/Mg. This constitutes less than 27% of the total costs per 1 ton of output. This cost constitutes only approx. 3% (figure 6) of the mean coal price.

Quite interesting conclusions may be drawn based on the last two analyzed indices, namely the cost of fire prevention per 1 running meter of longwall advancement (figure 7) and the cost of prevention practices per 1 day of longwall advancement (figure 8).

The index of prevention cost per 1 running meter of longwall advancement is similar to the index of that cost per 1 ton of output. The correlation of these two indices is extremely high. This may be observed while comparing figures 7 and 8. The prevention costs for longwall 1 per 1 running meter of advancement amounted to 5 706.61 zł, while in case of longwall 3 it was 1 368.14/meter. Such a high difference in prevention costs results from the difference by nearly one panel length between longwalls 1 and 3.

The last of the determined indices is the cost of prevention per 1 day of longwall advancement (figure 8). The highest cost in that respect was exhibited by longwall 2 – due to the shortest time of longwall advancement, that is, only 166 days. The prevention cost per 1 day progress to 16 399.83 zł (table 7). Longwall 3, on the other hand, was exploited for a very long period of 989 days, which resulted in the cost of 1 860.62 zł per 1 day of longwall advancement.
5. Summary
The costs of the conducted natural hazard prevention practices related to ventilation are a necessary part of the total costs borne by mining plants in the exploitation process.

Unfortunately, due to the continuous intensification of the natural hazards, these costs are also rising.

Among all preventive works related to ventilation, prevention against fire hazard is the least predictable. The application of standard procedures developed based on mining experience in terms of this prevention practice does not always allow for the complete liquidation of the hazard.

To date, no algorithm was developed for any procedure pertaining to the fire hazard that would be required by regulations and that would allow the ventilation divisions to take up appropriate activities towards the limitation of the hazard – as in the case of e.g. coal dust explosion hazard. Although climatic or methane hazards also lack adequately prepared procedures, in case of methane hazard the regulations require the application of a methane removal system and when the allowable climate equivalent temperature is exceeded, the application of adequate methods of limiting the temperature or the working hours.

Although the prevention practices for the limitation of the fire hazard allow for the widest range of methods that may be applied against the hazard, the costs of the prevention practice – as compared to other prevention practices related to ventilation – are relatively low (figure 3). The largest part of the fire prevention costs is constituted by the cost of inertization of goafs. In case of the longwalls in concern, this cost constituted 94.7% of total prevention costs for longwall 1 and 71.6% for longwall 2. In case of longwalls where inertization of goafs was not applied, the largest parts of prevention costs were constituted by man-days related to the prevention of fire hazard, especially the man-days of the rescue-workers operating within preventative works (84.5%).

It should also be noted that a higher group of fire hazard does not always correspond to higher total prevention costs, which was exhibited by providing the example of longwalls 1 and 3.

Figure 8. Fire prevention costs and costs of other prevention practices related to ventilation per 1 day of longwall advancement.
Many analyses have exhibited that prevention works require a proper selection of methods to be applied against the hazard. The development of an adequate algorithm providing a procedure of conduct in case of this hazard is thus well substantiated.

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