Study of the ‘lifeline’ as the measure allowing for safe self-rescue of miners in conditions of lack of visibility caused by underground fire

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Abstract. The article presents statistical data regarding the evacuation of miners affected by underground fire hazards. The data indicates that the hazard remains considerable. Due to the increasing lengths of escape routes, measures should be introduced in the longwall regions, which shall improve the safe evacuation of miners, especially in conditions of highly limited visibility or the lack thereof. Within the research project No. 12, entitled: ‘The development of orientation systems and systems for signalling the direction of crew withdrawal for escape routes in longwall gates’, which is a part of the Strategic Research Project entitled ‘The improvement of work safety in mines’ financed by the National Centre for Research and Development, a ‘lifeline’ was designed – that is, a measure that is very effective in the evacuation of staff. Subsequently, tests of time of passage were conducted in the ‘Krupiński’ coal mine in conditions of lack of visibility. The tests have confirmed the suitability of the ‘lifeline’ as the measure used for orientation towards the correct direction of evacuation, which increases the pace and the confidence while travelling through the escape route. The mean speed of passage through the heading with an upwards inclination of 11° was 22 m/min, while in case of a nearly horizontal longwall gate, it was 39 m/min.

1. Introduction
Fire hazard is one of the main hazards occurring in hard coal mines. Currently, a large number of outbreaks of spontaneous fires constitutes a problem. Exogenous fires, usually more dangerous than the spontaneous fires, are currently rather rare. This is not only related to the considerable limitation of flammable substances held in underground workings, the prohibition against using open fire, but also due to the appropriate design of the preparatory headings system in the region of the exploitation field [1]. The outbreak of a fire it is most often manifested by the increase of concentration of fire-related gases in the mine’s atmosphere [2, 3], especially carbon monoxide.

In the years between 1990 and 2014, 8 exogenous and 33 spontaneous fires occurred in hard coal mines [4].

In case of occurrence of a fire hazard in the longwall region, the staff should be withdrawn from the endangered region using escape routes to a location with streamlined air that is not affected by fire-related gases.

Escape routes are specified in the Mine Rescue Plan, in line with the Ordinance of the Minister of Economy dated June 28th, 2002 [5] and the Ordinance of the Minister of Economy dated June 12th, 2002, regarding the mine rescue operations (Journal of Laws No. 94, pos. 838) [6].
In line with the ordinance [5], ‘the highest allowable length of routes with independent air current shall be determined given consideration to the time of operation of the applied respiratory protection measures’. This general wording, which does not directly state the conditions that must be fulfilled by the escape route, only indicates the fact that while designing the exploitation in a given location of the deposit, one should note the necessity of ensuring the safe withdrawal of the crew in the event of the occurrence of a fire.

The efficiency of the escape route is dependent on many technical and human factors [7, 8, 9]. The technical factors include:

- the geometrical parameters of the escape route heading,
- obstacles present in the headings (devices, belt conveyors, pipelines and equipment),
- the direction of withdrawal – the upwards or downwards inclination angle,
- the distribution of communication devices,
- the marking of the escape route,
- the escape respirators.

The human factors include [7, 8, 10]:

- the ability to use the escape respirator,
- the ability to proceed through the escape route,
- the resistance to stress related to conditions occurring in the heading due to the fire,
- the ability to make decisions during the staff self-rescue operation.

Within the first stage of the research project No. 12, accident reports and hazard occurrence reports were compiled and analyzed while giving special consideration to the division into exogenous and spontaneous fires. The analysis encompassed the period from 1990 to 2013. In the period in concern, per 61 cases of evacuation related to fires, as many as 42 were related to spontaneous fires, while only 19 were caused by exogenous fires (figure 1). The highest number of spontaneous fires (17) occurred in 2009 and 2010, while the highest number of exogenous fires (4) occurred in 2008. In 1990 and in 2006 no fire hazard causing the evacuation of miners was noted.

![Number of Crew Evacuations Due to Fire Hazard](image_url)

**Figure 1.** Number of crew evacuations due to fire hazard [11].
The conducted analysis of crew evacuations caused by fire hazards (figure 2) in the years 1990-2013, exhibited that a total of 2574 people were evacuated from the affected headings: 1312 people were evacuated due to spontaneous fires and 1262 people were evacuated due to exogenous fires. The highest number of people evacuated during a single operation was reached in 2005 in the ‘Bielszowice’ hard coal mine. The exogenous fire resulted from a short-circuit in a 6 kV cable duct at the surface and connected with the downcast shaft. Due to that, 488 people were evacuated from the underground headings.

Figure 2. Number of people evacuated due to a fire hazard [11].

Figure 3. Number of people evacuated from longwall regions due to fire hazard [11].
Among all 61 occurrences related to fire hazards in hard coal mines, as many as 34 [11] concerned the longwall areas, while only 6 of them were exogenous fires. The fires which occurred in the longwall regions constitute 56% of all fires in hard coal mines. The total number of people evacuated from the region of longwalls was 1147 (figure 3). Out of this number, 272 people were evacuated due to exogenous fires and 875 people were evacuated due to spontaneous fires.

According to accident protocols [12], during the development of a fire, both exogenous and spontaneous, considerable smoke often occurred in the headings which constituted the escape route from the affected region. The smoke led to a significant decrease in visibility. Due to the above, there is a necessity to equip the escape routes in measures allowing the withdrawal of the crew in the correct direction. The binding mining law contains a provision stating that the escape routes should be ‘appropriately marked’ [5], while it does not state which measures should be used. Currently, mines apply various methods for marking the escape routes and the direction of crew evacuation. Metal signs with the name of the heading and the direction of the evacuation through the escape route are most often applied. Such marking only serves its purpose in case of good visibility, while during the occurrence of dense smoke, it would not be visible.

Due to the above, a universal system for the orientation and direction of crew in case of evacuation by means of escape routes should be introduced. Such system should allow for the choice of the correct direction of evacuation, even in conditions of complete lack of visibility. The conducted analysis of Polish mining literature has exhibited that no non-electronic system serving the orientation and signalling the withdrawal direction in high smoke density conditions that completely or highly limits the visibility, is used in the Polish coal mines.

The complete lack of visibility or a high limitation thereof, causes the evacuated crew to only decide on their direction of evacuation based on sound signals or their sense of touch.

Figure 4 exhibits the number of accidents which occurred during the withdrawal of crews from the longwall regions. A total of 36 fatal accidents occurred. It is worth noting that all the fatal accidents were caused by the combustion or explosion of methane.

Two accidents occurred in 2003:
- ‘Brzeszcze’ hard coal mine – methane was ignited due to an exogenous fire, which resulted in 1 fatal accident,
− ‘Sośnica’ hard coal mine – methane was ignited due to a spontaneous fire, resulting in the death of 3 employees.

In 2008, also 2 accidents occurred – the ignition and explosion of methane in ‘Borynia’ coal mine resulted in 6 fatalities, while the spontaneous fire in ‘Mysłowice-Wesola’ coal mine caused the ignition of methane and the explosion of coal dust, which resulted in two fatal accidents (1 employee died during the explosion, the second one died in hospital due to injuries).

In 2009, the ignition and explosion of methane in the ‘Wujek’ hard coal mine, Śląsk section, caused the death of 20 miners.

In 2011, the combustion of methane in the ‘Krupiński’ coal mine resulted in 3 fatalities.

2. ‘Lifeline’ as an element supporting the evacuation of staff from the affected region

In the research project No. 12 of the Strategic Research Project named ‘Improvement of work safety in mines’ financed by the National Centre for Research and Development, the so-called ‘lifeline’ was proposed as a measure used for the orientation in terms of the correct direction of staff evacuation. The notion is from literature as a measure supporting staff evacuation in mines and is related with Anglo-Saxon mining tradition. In the available literature, however, the structure of the ‘lifeline’ has not been described in detail.

The structure of the ‘lifeline’ should be simple and allow for easy memorization of markings. It was proposed that only three types of markers should be used: a cone, a cylinder and a sphere (figure 5). All the markers exhibit a similar diameter of 80 mm. The length of the cylinder and the cone is 120 mm.

Figure 5. Markers used in the ‘lifeline’ [11].

The cone indicates the direction of evacuation along the heading. This relates to the graphical representation of direction – an arrow. The cone plays the role of the arrow-head showing the evacuation direction – one should proceed from the base towards the direction shown by the tip.

The cylinder denotes the passage through a crossing in line with the direction of the longitudinal axis of the cylinder. The sphere denotes attention required in relation to further marking or obstacles on the escape route (such as a platform over water).

The sphere also precedes the cylinder which denotes the crossing.

The requirement to move to the other side of the heading is denoted by two cones connected by their tips. The cones are preceded by a sphere, which requires attention to further marking.

A larger amount of spheres denotes a hindrance in the passage such as a low suspended railway, temporary flooding etc. For a person using the escape route it denotes that they should pay attention to all possible hindrances assembled at a small length of the heading.
The ‘lifeline’ should be suspended at a height of approximately 1.1 m from the floor level, that is, at a height similar to rails in buildings. The evacuating people should move their hands along the ‘lifeline’ while reading the markers on the way.

It was proposed that the distance between the markers indicating the direction of evacuation at straight sections of the headings should be approximately 5 m. While approaching the markers indicating a change in direction, the density is increased to 2 m and subsequently to 1 m.

The combinations of the markers exhibited below allow for conveying the information concerning navigating through the escape route.

A passage to the other side of the heading is denoted by two truncated cones directed towards each other with the narrower end and preceded by a sphere indicating the necessity to increase attention. The arrow in the figure (figure 6.) denotes the direction of the crew evacuation.

\[\text{Figure 6. Passage to the other side of the heading [11].}\]

Such a combination of markers should be read as the following order:

Stop. Turn back to the ‘lifeline’. Move to the other side of the heading.

Shall the miner not notice the above combination of markers, a meter further a pair of markers is placed which informs them of the wrong direction of evacuation. That group of markers is presented in figure 7.

\[\text{Figure 7. Change in the direction of evacuation [11].}\]

A complete combination of markers denoting the passage to the other side of the heading including the information regarding the wrong direction of evacuation has been presented in figure 8.

\[\text{Figure 8. Marking denoting the passage to the other side of the heading [11].}\]

During the evacuation along the escape route, it might be necessary to go straight at a crossing. For that purpose, a combination of the sphere and cylinder markers should be suspended on the ‘lifeline’. Such a combination was presented in figure 9. The arrow denotes the direction of passage.
An example of markers at a ‘lifeline’ has been presented in figure 10. The drawing shows a case of evacuation using the escape route on the right side of the heading. The miners proceed along the direction of the flow of smoke. During the evacuation they find markers denoting the necessity to pass through a crossing on the ‘lifeline’. After passing the crossing, they find another ‘lifeline’, providing the further direction of evacuation. After passing a certain section of the heading, the miners find another combination of markers on the ‘lifeline’, which informs them on the necessity to pass to the other side of the heading.

An example of a ‘lifeline’ installed in a heading has been shown in figure 11. It illustrates a combination of markers requiring an increased attention (sphere), and subsequently the requirement to move to the other side of the heading (two cones with tips directed towards each other). Subsequent markers inform the miner on the wrong direction of evacuation and the order to move back to the two cones directed towards each other.
3. Verification tests using the ‘lifeline’

Three stages of verification tests were conducted in underground headings of the ‘Krupiński’ coal mine. The tests were conducted in conditions of simulated loss of visibility. The complete loss of visibility was simulated using special glasses.

The first stage of the tests was conducted in a technological drift and in a collective ventilation roadway. The total length of the evacuation route was 100 m. Figure 12 presents the diagram of the evacuation using the escape route with the ‘lifeline’ suspended in the headings of the auxiliary ventilation road.

![Diagram of evacuation route](image)

**Figure 12.** The placement of the ‘lifeline’ in the ventilation road in the first stage of measuring the speed of passage [11].

The first stage of the tests encompassed 22 miners employed by the mine. The length of the route was 100 m, including a 90 m section of drift with an inclination angle of 10° and a section of 10 m of a horizontal gallery. Table 1 presents the passage times and the speeds of passages of the
rescue route using the ‘lifeline’. The mean speed was 22.0 m/min. The minimal speed was 13.4 m/min, while the maximal speed was 34.7 m/min.

### Table 1. Passage times and speeds of the escape route using the ‘lifeline’ in stage I of the tests [11].

| Worker No. | Time of passage (min:sec) | Speed (m/min) |
|------------|---------------------------|---------------|
| Worker No.1 | 4:01                      | 24.9          |
| Worker No.2 | 4:06                      | 24.4          |
| Worker No.3 | 3:38                      | 27.5          |
| Worker No.4 | 3:40                      | 27.3          |
| Worker No.5 | 3:25                      | 29.3          |
| Worker No.6 | 3:31                      | 28.4          |
| Worker No.7 | 6:31                      | 15.3          |
| Worker No.8 | 4:23                      | 22.8          |
| Worker No.9 | 7:27                      | 13.4          |
| Worker No.10 | 5:26                     | 18.4          |
| Worker No.11 | 6:33                     | 15.3          |
| Worker No.12 | 7:08                     | 14.0          |
| Worker No.13 | 5:53                     | 17.0          |
| Worker No.14 | 4:30                     | 22.2          |
| Worker No.15 | 4:41                     | 21.4          |
| Worker No.16 | 5:16                     | 19.0          |
| Worker No.17 | 4:59                     | 20.1          |
| Worker No.18 | 5:41                     | 17.6          |
| Worker No.19 | 6:32                     | 15.3          |
| Worker No.20 | 4:20                     | 23.1          |
| Worker No.21 | 2:58                     | 33.7          |
| Worker No.22 | 2:53                     | 34.7          |

Mean time of passage | 4:53
Minimal time of passage | 2:53
Maximal time of passage | 7:27
Mean speed | 22.0
Minimal speed | 13.4
Maximal speed | 34.7
Standard deviation | 6.2

In the second stage of the experiment, the ‘lifeline’ was suspended partially in a technological drift and partially in the collective ventilation road No. 2. The placement of the lifeline is presented in figure 13. The length of the line was 135 m and the route was 110 m. The tested group was comprised of 10 people including 5 mine rescue workers and 5 employees of the Institute of Mining of the Silesian University of Technology in Gliwice. The trial of passing the escape route was conducted twice. The results of the measurements have been presented in table 2.
Figure 13. The placement of the ‘lifeline’ in the ventilation road in the second stage of measuring the speed of passage [11].

Table 2. Passage times and speeds of the escape route using the ‘lifeline’ in stage II of the tests [11].

| No. | Worker No. | 1st time of passage (min:sec) | 1st speed of passage (m/min) | 2nd time of passage (min:sec) | 2nd speed of passage (m/min) |
|-----|------------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|
| 1.  | Worker No.1| 5:29                          | 18.2                        | 3:45                          | 26.7                          |
| 2.  | Worker No.2| 2:48                          | 35.7                        | 2:13                          | 43.8                          |
| 3.  | Worker No.3| 4:45                          | 21.1                        | 2:53                          | 34.7                          |
| 4.  | Worker No.4| 4:16                          | 23.4                        | 2:55                          | 34.3                          |
| 5.  | Worker No.5| 7:53                          | 12.7                        | 3:45                          | 26.7                          |
| 6.  | Mine rescue worker No.1 | 2:58 | 33.7 | 2:56 | 34.1 |
| 7.  | Mine rescue worker No.2 | 3:04 | 32.6 | 2:02 | 49.2 |
| 8.  | Mine rescue worker No.3 | 2:53 | 34.7 | 2:42 | 37.0 |
| 9.  | Mine rescue worker No.4 | 2:38 | 38.0 | 2:12 | 45.5 |
| 10. | Mine rescue worker No.5 | 2:17 | 43.8 | 2:11 | 45.8 |

| Mean time of passage | 3:54 | 2:45 |
| Minimal time of passage | 2:17 | 2:02 |
| Maximal time of passage | 7:53 | 3:45 |
| Mean speed | 29.4 | 37.8 |
| Minimal speed | 12.7 | 26.7 |
| Maximal speed | 43.8 | 49.2 |
| Standard deviation | 9.9 | 8.0 |

All people participated in the test for the first time and did not know the route indicated by the ‘lifeline’.

During the first passage, the employees of the Silesian University of Technology reached speeds that were significantly lower than that of the ‘Krupiński’ mine rescue team members. Their passage...
The speeds were in the range from 12.7 m/min up to 35.7 m/min, while the rescuers were moving at speeds from 32.6 m/min up to 43.8 m/min. The mean speed of passage calculated for all the participants of the experiment was 29.4 m/min.

The speeds achieved by each of the participants in the second passage were higher than in the case of the first passage. A larger change was noted in the group of the Silesian University of Technology’s employees. In case of this group the speeds were in the range from 26.7 m/min up to 34.7 m/min. The passage speeds of the rescuers was in the range from 34.1 m/min up to 49.2 m/min. The mean value of speed calculated based on individual speeds of each of the participants of the experiment was 37.8 m/min.

The considerable increase in the speed of passage in the second stage indicated a significant impact of the knowledge of the escape route on the speed. This means that bringing the crew out through escape routes significantly increases the fire safety in a mine.

The third stage of the passage speed measurement in conditions of lack of visibility was conducted in the N-6 top gate of the N-8 longwall in the 330/2 seam. The length of the ‘lifeline’ was 210 m. The line was comprised of three equal sections. The first and the last one was on the right side of the heading while the middle one led through the left side of the heading. Figure 14 presents the cross-section of the N-6 gate of the N-8 longwall.

![Cross-section of the N-6 gate of the N-8 longwall in the 330/2 seam](image)

**Figure 14.** Cross-section of the N-6 gate of the N-8 longwall in the 330/2 seam at the ‘Krupiński’ coal mine [11].

19 miners, including 6 rescue team members, 12 members of the crew working at the longwall and one employee of the Silesian University of Technology were subjected to the test. All participants of the experiment used KA-60 type escape respirators.

The mean speed of passage was 39.0 m/min. The minimal speed of passage was 21.8 m/min while the maximal speed was 53.8 m/min. The coefficient of variation (a ratio of the standard deviation and the mean speed expressed as a percentage) was 18.4%, which means that the group of participants was relatively uniform.

The experiment received large interest and approval of the participating miners.
Table 3. Passage times and speeds of the escape route using the ‘lifeline’ in stage III of the tests [11].

| Worker  | Time of passage (min:sec) | Speed of passage (m/min) |
|---------|---------------------------|--------------------------|
| Worker 1 | 9:11                      | 21.8                     |
| Worker 2 | 5:31                      | 36.3                     |
| Worker 3 | 5:38                      | 35.5                     |
| Worker 4 | 5:06                      | 39.2                     |
| Worker 5 | 4:34                      | 43.8                     |
| Worker 6 | 5:16                      | 38.0                     |
| Worker 7 | 3:43                      | 53.8                     |
| Worker 8 | 4:55                      | 40.7                     |
| Worker 9 | 5:47                      | 34.6                     |
| Worker 10 | 5:05                     | 39.3                     |
| Worker 11 | 5:05                     | 39.3                     |
| Worker 12 | 6:00                     | 33.3                     |
| Worker 13 | 4:39                     | 43.0                     |
| Worker 14 | 4:33                     | 44.0                     |
| Worker 15 | 3:58                     | 50.4                     |
| Worker 16 | 5:22                     | 37.3                     |
| Worker 17 | 4:44                     | 42.3                     |
| Worker 18 | 4:54                     | 40.8                     |
| Worker 19 | 7:11                     | 27.8                     |

Mean time of passage 5:19
Minimal time of passage 3:43
Maximal time of passage 9:11

Mean speed 39.0
Minimal speed 21.8
Maximal speed 53.8
Standard deviation 7.2

4. Summary
Underground fires in coal mines occur despite the considerable progress in fire hazard prevention. Such fires constitute a high risk for the crew and may cause extensive material losses.

Currently, fires caused by methane ignition are considered to be the most dangerous. Shall such a fire occur in the goafs in the vicinity of a longwall, the fire develops rapidly, a considerable increase in temperature of the flowing air is observed and other substances are combusted (such as coal, wood, bonding agents, conveyor belts etc.), which, in turn, results in production of large amounts of fumes. A methane fire in goafs may not be extinguished and the only method to save lifes is to evacuate the affected headings as fast as possible. In dense smoke, the visibility is largely limited and the conditions in the heading force the miners to withdraw from the affected zone as soon as possible.

At a highly limited visibility, or the lack thereof, the evacuating miners may lose orientation regarding the correct direction of evacuation. Especially the horizontal or just slightly inclined headings as well as crossings of headings are dangerous in that respect. In conditions of dense smoke the miners may only use their senses of touch and hearing.

The conducted research exhibited that the ‘lifeline’ may be a very helpful measure used in the evacuation from the hazard zone in conditions of a complete loss of visibility.
Based on the values of passage speed through the headings obtained in experiments, it may be stated that the ‘lifeline’ has considerably increased the speed of passage in conditions of complete lack of visibility.

The ‘lifeline’ should be suspended in such a manner that it would lead the evacuating miners to communication devices and escape respirator replacement chambers.

The arrangement of the ‘lifeline’ in crossing areas should require the verification whether air without smoke reaches the crossing. The ‘lifeline’ has received a very positive reception by the miners participating in the experiments conducted in the ‘Krupiński’ coal mine.

The markers used in the ‘lifeline’ should be equipped with reflective strips facilitating the orientation in terms of the evacuation direction and allowing to find where the lifeline is suspended.

Evacuation of the staff in a direction opposite to the airflow direction is usually conducted in an air stream not containing smoke. The evacuation of the crew in a direction opposite to the flow of smoke may only be applied when it reduces the length of the escape route and it excludes the possibility of reaching the centre of the fire.

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