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Prospects for the use of modern technological solutions in the flat-lying coal seams development, taking into account the danger of the formation of the places of its spontaneous combustion

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Abstract. Spontaneous combustion of coal remains an important problem for coal mines, which can lead to an explosion of methane and coal dust. Accidents associated with spontaneous combustion of coal can cause significant economic losses to coal mining companies, as well as entail social damage – injuries and loss of life. Accidents are known at the Kuzbass mines, which occurred as a result of negligent attitude to the danger of spontaneous combustion of coal, the victims of which were dozens of people. The analysis of emergency situations associated with spontaneous combustion of coal shows that the existing wide range of means of preventing endogenous fires does not provide complete safety when working out coal seams prone to spontaneous combustion, therefore, spontaneous combustion places continue to occur in mines. The consequences that may arise as a result of a methane explosion initiated by a self-ignition place indicate the need to improve the used technologies.

The purpose of the work is to determine the impact of modern technological solutions used in functioning mines during underground mining of flat-lying coal seams prone to spontaneous combustion, and to develop new solutions that reduce endogenous fire hazard.

Conclusions on the influence of leaving coal pillars in the developed space, isolated air removal from the stoping face through the developed space, the length of the stoping face and the excavation pillar, and other factors on the danger of the formation of spontaneous combustion places are presented. Conclusions about the possibility of using modern technological solutions in future are also drawn.

***Key words*:** coal; spontaneous combustion of coal; underground mining; coal pillars; long-pillar mining systems; developed space; safety; economic efficiency

Introduction. In 2020, more than 55 % of the total volume of coal produced in Russia was extracted on the territory of the Kuznetsk coal basin [19]. Kuzbass companies annually increase their productivity by 4-6 %. Half of them extract coal by underground method, which is due to the high quality of coal, the modes of coal occurrence and their thickness. These factors make it possible to use modern technological solutions and the most efficient equipment [4, 30].

However, when working out coal seams in the Kuznetsk basin, it is necessary to take into account that about 70 % of the total number of seams are prone to spontaneous combustion, and more than 60 % are dangerous due to the gas factor. The main danger is associated with the fact that the resulting spontaneous combustion can cause a methane explosion, which has catastrophic consequences [9]. Several such cases are known at the companies of the Kuznetsk basin, for example, methane explosions at the Ulianovskaya mine on March 19, 2007 (110 people died) and at the Yubileynaya mine on May 24, 2007 (38 people died), two methane explosions at the Raspadskaya mine on May 8 and 9, 2010 (91 people died).

Formulation of the problem. There are a large number of special means to reduce the risk of spontaneous combustion of coal [36]: in recent years, nitrogen is often used for these purposes at the mines of the Kuznetsk coal basin [16], which, like other means, is designed to reduce the chemical activity of coal. In this case, the coal is not able to absorb the necessary amount of oxygen for heating to a critical temperature, due to which spontaneous combustion does not occur [24].

However, accidents associated with spontaneous combustion of coal continue to occur every year [11]. This indicates that the existing tools are not effective enough. The significant consequences of accidents indicate the need to develop new ways to reduce the risk of endogenous fires in conditions of constant growth in the productivity of coal mining companies [4].

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Methodology. To assess the impact of modern technological solutions on the danger of the formation of spontaneous combustion of coal, the experience of mines that have been developing coal seams prone to spontaneous combustion in the territory of the Kuznetsk basin of Russia for the last 30 years has been studied.

The modern scientific, normative and technical literature related to the issues of underground mining of coal seams is analyzed. Official information about accidents related to spontaneous combustion of coal in mines in the territory of the Kuznetsk basin and their causes were taken into account.

Discussion. For underground mining of flat-lying coal seams at the Kuznetsk coal basin, a single mining system is used – long pillars, the preparation of which is carried out by double drifts (Fig.1). When implementing this development system, coal pillars are left in the developed space.

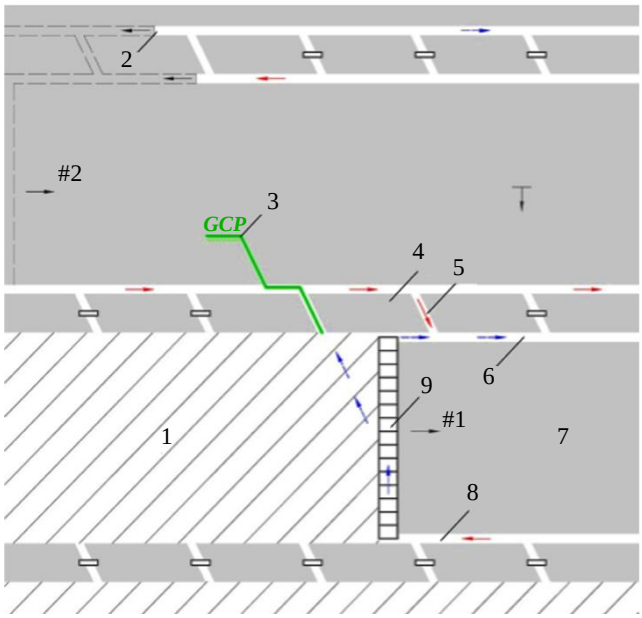


Fig.1. Technology of working out of flat-lying coal seams at high-efficiency mines of Kuzbass

1 – the developed space; 2 – a drifting face; 3 – a gas cleaning plant (GCP); 4 – a coal pillar; 5 – a connection; 6 – a ventilation drift; 7 – coal rock mass; 8 – a conveyor drift; 9 – a stoping face

The requirements of normative documents, including safety rules for coal mines, regulate the pillar leaving when working out coal seams prone to spontaneous combustion. This is due to the need for reliable isolation of previously used sites and prevention of air leaks to them [28, 31, 32].

Coal pillars are important for the possibility of implementing modern technological solutions [4, 23, 29]: they maintain the working condition during the entire period of mining of the excavation site. This allows the use of roof bolting in all the precinct mine workings. As a result, the speed of workings increases and the cost of tunneling work decreases. At the mines of the Kuznetsk coal basin, they reduce the influence of the gas factor, since they isolate the excavation site from the developed space of the neighboring site [17]. Also, the pillars allow the use of an isolated air outlet from the stoping face to the precinct mine working with a fresh stream of air through the developed space. This significantly reduces the influence of the gas factor on the operation of the stoping face [11, 20, 37], which allows the use of high-efficiency equipment in modern mines. With the help of such equipment, it is possible to extract more than 1.5 million tons of coal per month from one stoping face. For example, in September 2018 at the mine named after Yalevskiy a world record for coal production – 1.627 million tons was set. The mine is located on the territory of the Kuznetsk coal basin and develops coal seams that are dangerous due to the gas factor and spontaneous combustion, so this example well reflects the effectiveness of modern technological solutions that require leaving coal pillars [1].

The use of modern equipment makes it possible to significantly increase the length of both stoping faces and excavation sites. In some cases, at the high – efficiency mines of the Kuznetsk coal basin, the length of the stoping face reaches 400 m, and the length of the excavation site is 4700 m [1]. This is due to the reliability of modern equipment and its potential to work out large excavation sites without shutting down for repair and restoration work.

Due to the increase in productivity during the development of large-sized excavation pillars in the mines of the Kuznetsk basin, there is a tendency to increase the concentration of mining operations. Many mines have only one high-efficiency stoping face. Their experience shows that high concentration of mining operations has a positive effect on the economic efficiency of companies [4, 22].

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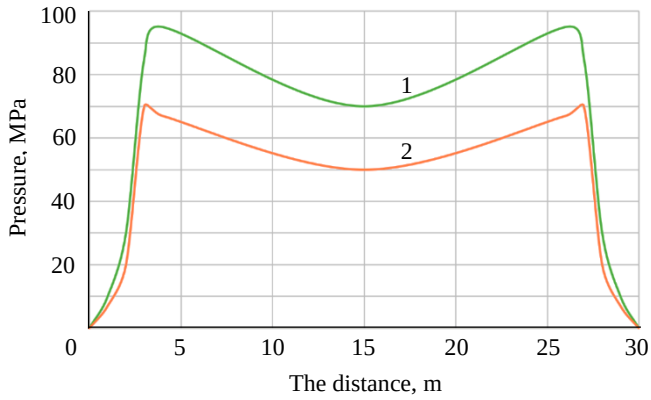


Fig.2. Pressure distribution over the coal pillar at a longwall length of 300 (1) and 200 m (2)

Due to the possibility of ensuring the high level of concentration of mining operations and high productivity, modern technological solutions with the pillar leaving are widely used. However, the coal pillar leaving in the developed space has a number of disadvantages, in particular, according to research, pillars are the main cause of the formation of spontaneous combustion places [9, 12, 17]. This may be indicated by the fact that until 2015, safety regulations required the use of non-pillar technologies with field preparation of excavation sites when working out coal seams that are prone to spontaneous combustion.

In mines, spontaneous combustion places most often form in the developed space or in zones of geological disturbances [34]. This is due to the fact that accumulations of crushed coal can form in such areas, for example, due to an increase in the size of excavation pillars. If the accumulations of crushed coal in the zones of geological disturbances are of natural origin, then this is a technological disadvantage in the developed space. The rock bearing pressure in the developed space destroys the edge parts of the coal pillars [6, 27]. With an increase in the length of the stoping face (the distance between the coal pillars), the rock bearing pressure increases (Fig.2).

Due to the fact that modern high-efficiency mines use the removal of air from the stoping face through the developed space, a part of it seeps through the formed accumulations of crushed coal (destroyed edge parts of coal pillars), which stimulates the process of oxidation and gradual coal heating [36]. When the temperature reaches a critical value, spontaneous combustion occurs [21].

Of great importance for assessing the possibility of using modern technological solutions is the fact that at high-efficiency mines, the depth of mining operations increases almost every year [25], due to which the size of coal pillars increases. This is due to an increase in rock pressure at great depth and the need to preserve the undisturbed middle part of the pillar to ensure the isolation of the developed space [3], where the influence of the rock bearing pressure on the edge parts of the pillar increases annually and, as a result, the volume of crushed coal increases.

With an increase in the length of the excavation pillars, the number of ventilation connections that pass between the site drifts during the preparation of the excavation sites by parallel workings naturally increases. At the same time, zones of disintegration of rocks can be formed both along the contour of precinct drifts and along the contour of ventilation connections [7, 18, 26]. When such zones are superimposed at the interface points of drifts and ventilation connections along a weakened air-permeable rock mass, an aerological relationship can be established between the precinct production with a fresh or outgoing air stream and the developed space. Thus, air leaks can flow to the accumulations of crushed coal of the edge part of the pillar end in the developed space, contributing to its oxidation. The resulting center can develop in the direction of the incoming air and, reaching the outer edge of the pillar, cause a methane explosion [14, 17].

It should be noted that in most modern mines, ventilation failures between parallel precinct drifts run diagonally. In this case, the edge parts of the coal pillars in the developed space have an acute-angled shape, their narrow part is more affected by the rock bearing pressure and, collapsing, forms significant volumes of crushed coal at the ventilation connections [33, 35].

Analyzing the above factors, we can conclude that when using modern technological solutions, favorable conditions for the development of spontaneous combustion places form in ventilation connections from the side of the developed space. The inevitable increase in the number of ventilation connections and the length of the excavation pillars when preparing the excavation sites with double

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drifts leads to an increase in the number of potentially dangerous zones of the formation of spontaneous combustion places. At the same time, the greatest danger are the excavation sites, where the ventilation connections between the drifts are carried out diagonally.

Results. The revealed influence of modern technological solutions used in working mines during underground mining of flat-lying coal seams on the danger of the formation of spontaneous combustion places is reflected in the block diagram (Fig.3).

When working out coal seams that are prone to spontaneous combustion, according to the requirements of current regulatory documents, it is necessary to leave the pillars intended for isolating the excavation pillars. In other words, in working mines, a large volume of self-igniting material is intentionally left in the developed space, which increases the potential danger of the formation of spontaneous combustion places.

To increase the productivity of the stoping faces, it is necessary to exclude the influence of the gas factor on the operation of the equipment [5, 8, 22]. For this purpose, modern mines use an isolated air outlet from the longwall through the developed space, where air leaks inevitably enter.

The high productivity of modern stoping faces allowed the mines to increase the economic efficiency of production by increasing the concentration of mining operations, up to the level at which all mine coal mining is concentrated in one stoping face. In addition to increasing the average speed of moving the stoping faces, this strategy has led to a significant increase in the length of longwalls and excavation pillars at existing mines. Such changes were reflected in an increase in the influence of the rock bearing pressure on the pillars and a natural increase in the volume of crushed coal

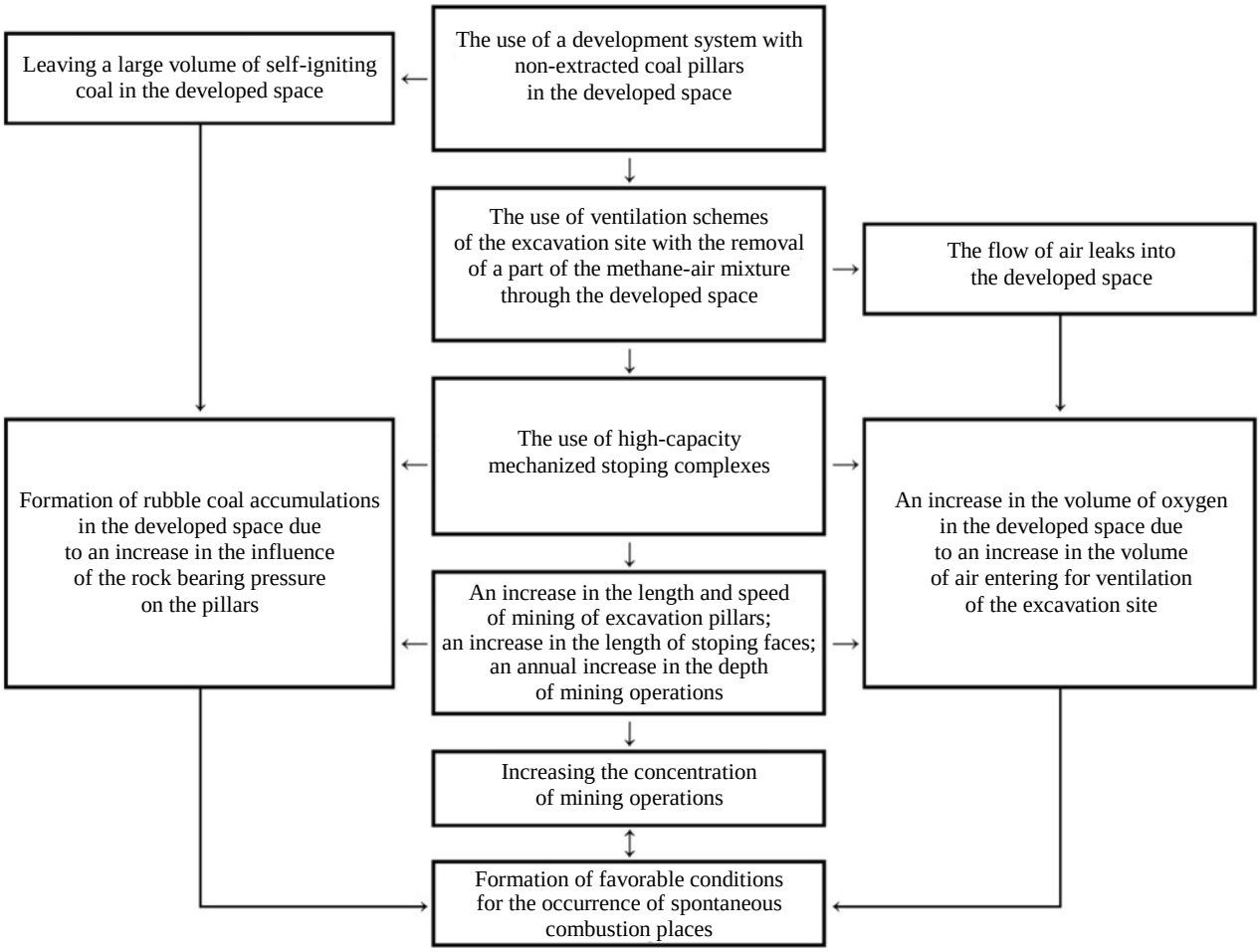


Fig.3. Assessment of the impact of modern technological solutions on the danger of the formation of spontaneous combustion of coal in mines

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accumulations in the developed space. In addition, with the increase in loads on the stoping face and the increase in the size of the excavation pillars, there is a need to increase the amount of air supplied for ventilation of the excavation site, which leads to an increase in air leaks into the developed space [13-15].

The revealed influence of modern technological solutions on the danger of the formation of spontaneous combustion places in the developed space allows to conclude that if the existing trends continue, the endogenous fire hazard in coal mines will constantly increase. Taking into account these circumstances, an important task is to develop new technological solutions that will increase the safety of mining flat-lying coal seams prone to spontaneous combustion. It is important to take into account that in a market economy, new solutions should not be inferior to existing and proven technological solutions in terms of technical and economic indicators.

It is possible to significantly increase the safety when working out coal seams that are prone to spontaneous combustion by erecting a strip of hardening materials during the preparation of the excavation site and working out a coal pillar parallel to the strip on the same line with the stoping face after it performs its main functions (Fig.4).

When implementing this technology, it is possible to use a combined ventilation scheme with an isolated discharge of a part of the air jet through the developed space, as well as the use of anchor support as the main support of precinct workings. At the same time, due to the formation of a strip of hardening materials at the boundary of the excavation pillar, it is possible to ventilate the dead-end part of the longwall without removing the air jet through blockages and collapses, and also the negative impact (in the form of methane and coal dust emissions) of the developed space of the adjacent previously extracted excavation column on the work of the stoping face is excluded.

The expenses for forming the strip are made up of the costs of the materials from which the strip is formed, the delivery of materials, increasing the cross-sectional area of the drift in which the strip is formed; the costs of equipment for forming the strip, payment of personnel engaged in the formation of the strip, and allocations for social needs. The economic efficiency of the recommended technology application is ensured by compensating costs with profit from the sale of stocks contained in the pillars.

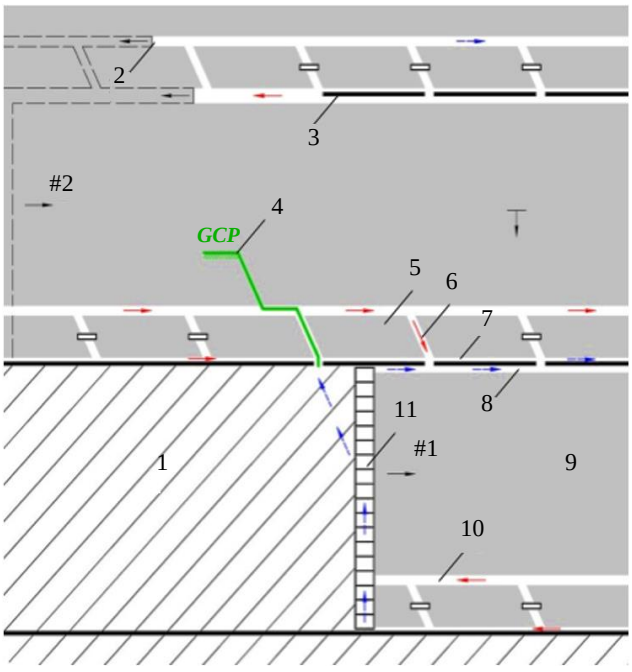


Fig.4. Technology with the development of a pillar coal on the same line with the stoping face and the construction of a strip of hardening materials

1 – the developed space; 2 – a drifting face; 3 – a strip of hardening materials; 4 – a gas cleaning plant; 5 – a coal pillar; 6 – a connection; 7 – a ventilation stopping; 8 –a conveyor drift; 9 – a coal rock mass; 10 – an air handling drift; 11 – a stoping face

To assess the economic efficiency of using the recommended technology, the parameters of the pillars were calculated using the guidelines of VNIMI, as well as the parameters of strips made of hardening materials using the instructions developed by the IGD named by Skochinskiy [2, 10]. The width of the pillars is determined from the equality

$$(B + H\text{tg}\alpha)(d + \iota)\gamma H = R_c B\iota\,(0.75 + 0.25\frac{B-q}{m}),$$

where B is the width of the coal pillar, m; H is the depth of mining operations, m; d is the total width of the ventilation connections, m; ι is the length of the pillar, m; γ is the volume weight of rocks, t/m^3; R_c is the cubic compressive strength of coal, ts/sm^2; q is a correction that takes into account the impact of drilling and blasting operations on the pillar; m is the extracted seam capacity, m.

The load on 1 m of a strip of hardening materials is determined by the formula

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$$P = \frac{\gamma h_i(b + 2.5)(b + 0.4h_i + 2.5) + \gamma l(10m - h_i)(l + 0.4h_i + 4m)}{2b - m + 5},$$

where h_i is the capacity of the immediate roof, m; b is the width of the protected workings, m; l is the caving step of the main roof, m.

The width of the strip of hardening materials, which is affected by the load, is calculated by the formula

$$b_s = \sqrt[3]{\frac{k_m^2 m P^2}{\sigma_c^2}},$$

where k_m is the margin coefficient (with a strip width of ≤1.5 m – 1.5; >1.5 m – 1.2); σ_c is the strength of the strip material for uniaxial compression, ts/m^2.

To determine the area of rational use of the recommended technology, calculations were made for different capacities of the worked out seam and the depth of mining operations.

When performing the analysis of the economic efficiency using the recommended technology, the gross profit obtained from the sale of the excavation column reserves, worked out with the leaving of coal pillars in the developed space – P_{g1}, and the gross profit from the sale of the reserves of an identical excavation column, worked out with the use of the recommended technology – P_{g2}, were compared.

$$P_{g1} = P_g Q,$$

where P_g is the gross profit from the sale of 1 t of coal, rub.; Q is the volume of coal reserves within the boundaries of the excavation column, t,

$$P_{g2} = (P_g - \Delta C)(Q + \Delta Q),$$

ΔC is an increase in the cost of 1 t of coal when implementing the developed technology, rub.; ΔQ is an increase in the volume of coal production due to the development of the pillar on the same line with the stoping face, t.

The prices accepted on the modern market were taken as the cost of materials and various types of work. The results of the performed calculations are presented on the graph (Fig.5).

The analysis allows concluding that with an increase in the depth of mining operations, the economic efficiency of using the technology with strips of hardening materials increases. The most optimal conditions for the use of this technology are flat-lying coal seams with a capacity of 2-2.5 m at a depth of more than 300 m.

Conclusion. The long columns developing system with pillars leaving in the developed space has many advantages, the main of which is high productivity. However, when working out coal seams, this technology creates a significant danger of the formation of spontaneous combustion places.

In modern conditions, when, to increase the mine productivity, the size of the excavation columns grows and an isolated air outlet from the longwall is used in the developed space, the danger of the formation of spontaneous combustion places, when using the technology with the coal pillar leaving, significantly rises.

At the current level of concentration of mining operations in mines, the resulting

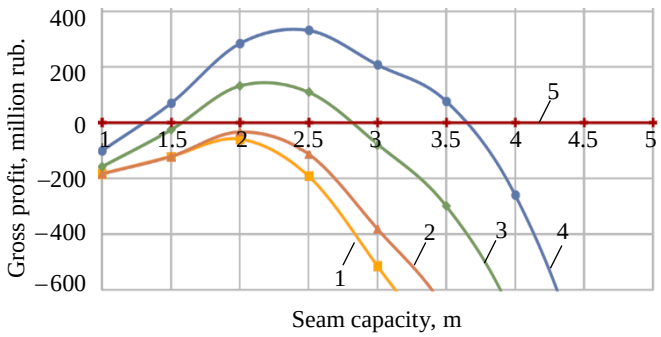


Fig.5. Dependences of the economic efficiency of the recommended technology on the seam capacity and the depth of mining operations

1 – 100; 2 – 200; 3 – 300; 4 – 400; 5 – the development system with the pillars leaving

spontaneous combustion can cause a complete shutdown of the enterprise for a long period, which threatens significant economic losses.

To increase safety, when working out coal seams prone to spontaneous combustion, it is possible to use a technology with the construction of a strip of hardening materials during the preparation of the excavation site and the development of a coal pillar parallel to the strip on the same line with the stoping face after it performs its main functions. The recommended technology combines the advantages of the technology with the pillars leaving and allows to significantly reducing the risk of the formation of spontaneous combustion places.

The economic efficiency of the application the recommended technology is ensured by compensating the costs of forming strips of hardening materials with profit from the sale of reserves contained in the pillars. The use of this technology is economically feasible when working out flat-lying coal seams with a capacity of 2-2.5 m at a depth of more than 300 m.

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