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CONTENS

RAW MATERIALS PROSPECTION AND DISCOVERIES

MINING METHODS

MATERIALS RECYCLING & WASTE MANAGEMENT

RAW MATERIALS EDUCATION

DIM-ESEE Conference

The variation of safety pillar's width with depth under the influence of thermo-mechanical stresses in Underground Coal Gasification

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Abstract

Underground coal gasification is one of the main trends of green mining. The basic principles of underground gasification have been long known. However, the practical implementation of this technology is unfortunately still not widespread. Recently, the Parallel Controlled Retraction Injection Points method has been actively developed, which is the subject of research in this article. An open problem of this technology is the determination of the pillar's width between reactor cavities taking into account the influence of thermo-mechanical destruction of coal. In this study, numerical simulation by ANSYS 17.2 software was used to solve it. The distribution of thermo-mechanical stresses in a coal pillar was studied. Mohr's theory was proposed to predict the destruction of a coal pillar at different depths. It was found that the coal seam failure near the production well and injection well leads to a reduction in the functional width of the safety pillar. Although, contrary to expectations, this effect is not particularly significant. The greater the depth of the seam, the greater the width of the zone of thermo-mechanical destruction of coal in the pillar. In this case, the main reason for the destruction of the coal pillar is the abutment pressure, increased as a result of the collapse of rocks above the gasification cavity in the post-gasification period.

Keywords: "underground coal gasification", "pillars stability", "safety pillar width", "thin coal seam gasification", "thermal stress"

1. Introduction

The most important component of sustainable development in recent years is the reduction of carbon emissions. The implementation of global commitments involves a planned reduction of greenhouse gas emissions and decarbonization **(UNFCCC: 2021)**. In the energy sector this can be achived primarily due to a decrease of fossil coal dependence, which is considered the main source of environmental pollution. The energy crisis caused by the war in Ukraine has shown the world's unwillingness to abandon coal **(Allam et al., 2022)**. However, an analysis of trends in global coal production shows that, contrary to expectations, the world is gradually increasing coal production, with its transfer to developing countries **(URL 1)**. According to various experts, if current trends in global energy will stay, coal will remain one of the key energy sources for at least the next ten years. In such conditions, along with the development of alternative "green" energy sources, technologies for reducing carbon emissions based on fossil coal usage as an energy resource are becoming increasingly relevant. In a global context, this is reflected in the increased scientific and engineering interest in underground coal gasification technologies (UCG).

Energy independence is one of the key factors for the survival of the economy during the war and development during the post-war reconstruction of Ukraine. Significant explored coal reserves of destroyed mines and promising areas which are, according to various estimates, guarantee the provision of the domestic market with this energy resource for a period of 100 to 250 years. At the same time, the integration of Ukraine into the European space includes reducing greenhouse gas emissions, which creates a contradiction between the necessity to increase generation, which can be realized by burning fossil coal, and obligations to reduce the carbon footprint. The solution to this contradiction is possible through the widespread implementation of UCG, which reveals the regional context of the relevance of this technology.

Nowadays experimental research is being conducted in underground gas generators and in laboratory conditions. Significant progress has been made in controlling the front of the UCG face; the optimal ranges of changes in the pressure rate of the blast mixture and the influence of the concentration of gases and steam on the gasification process have been determined; new methods of underground gasification have been introduced **(Dychkovskyi et al., 2025; Kostúr et al., 2018; Laouafa et al., 2016; Lozynskyi et al., 2024; Saik et al., 2016)**. Among the problematic issues limiting the use of UCG are the environmental hazards. First of all, there is a high risk of subsidence of the Earth's

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surface, flooding and water pollution due to the evolution of fractures in the overlying strata and the displacement of rocks above the UCG reactor cavities **(Sakhno et al., 2025)**.

Parallel Controlled Retraction Injection Points (CRIP) method was investigated in this research. This method is more promising as it has higher efficiency of synthesis gas production, more stable gas production levels and increased coal utilization rates (**Lozynskyi et al., 2024; Seifi al., 2015)**. The stability of overburden rock over gasification panels with the CRIP method largely depends on the stability of the safety pillars.

Many scientists have studied the parameters of safety pillars in the case of using of the CRIP method **(Li et al., 2015; Najafi et al., 2014; Jiang et al., 2024)**. However, the influence of thermo-mechanical destruction of coal near production wells and injection wells on the width of the pillar between reactor cavities has not been sufficiently studied. Coal near the UCG panel are subjected to high temperatures which may be more then 1000 °C. This causes irreversible changes in the properties of coal, increased fracturing and a decrease in bearing capacity in the heat-affected zone. As a result of heating, the coal expands, creating additional thermal stress in the pillar. Thus, the functional pillar width becomes less than the geometrically designed width. The specified problem forms the explored surface of the study.

2. Methods

In this study finite element method in Ansys software was used. The three-dimentional coupled thermal-mechanical numerical model was used. The model was 100 m wide, 130 m high, and 50 m long (Figure 1). The model included two goaf cavities and one UCG reactor. The length of the reactor was 30 m. In this study, the coal pillar's width was also 30 m. A caved zone was modeled above the gasification panel during the post-gasification period. This zone in goaf had the arch shape. The height of the caved zone was 8 times higher than the thickness of the coal seam (**Zhang et al., 2019; Sakhno, et al., 2025)**. The goaf was filled with combustion material and self-collapsed rocks. The lateral boundaries of the model were fixed against the corresponding horizontal displacements, and the bottom boundaries were fixed against the corresponding vertical displacements. The vertical pressure was equal to the weight of the rock strata at the corresponding depth. The coal seam's depth varied from 200 m to 600 m.

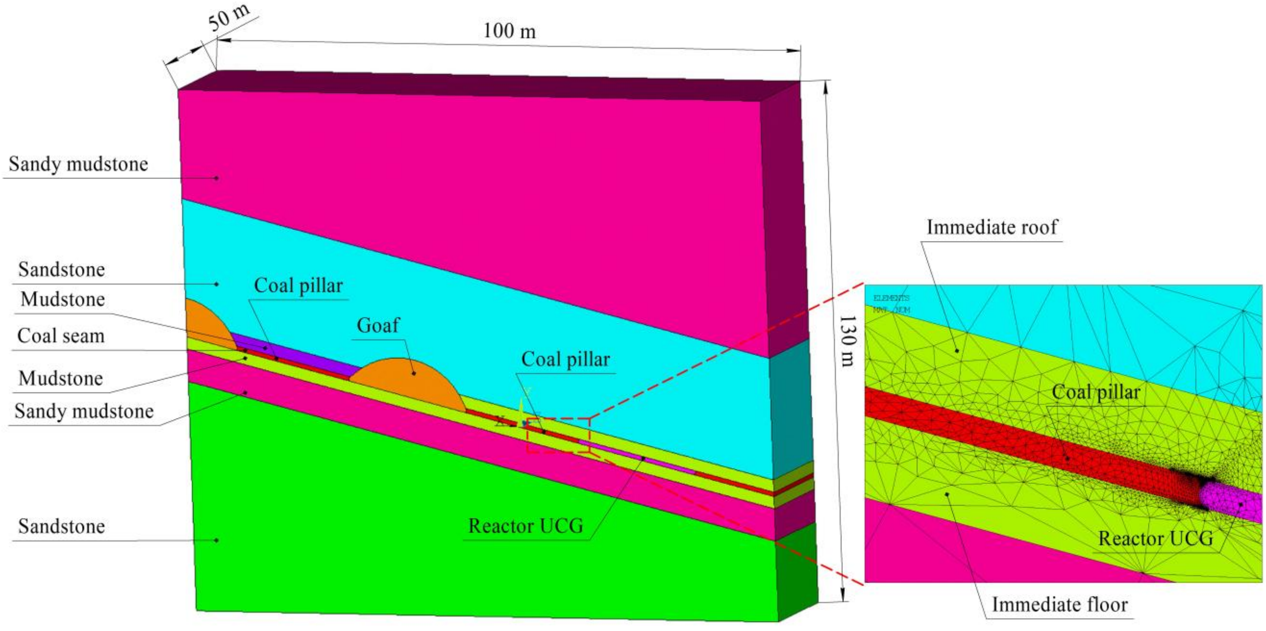


Figure 1. Numerical model

The Drucker-Prager model was used to simulate the behavior of rock mass outside the thermal influence of UCG reactor. The Hoek–Brown Failure Criterion was used to calculate the properties of rock mass **(Hoek et al., 2002).** The method for calculating rock mass parameters is described in the work (**Sakhno, et al., 2024)**.

The temperature of the rock mass was adopted as 27 °C. The temperature in the UCG face was 1000 °C. The behavior of rocks in the zone of influence of the UCG reactor was simulated temperature-independent for reasons described in more detail in the article (**Sakhno et al., 2025)**. The properties of coal in the heat-affected zone were adopted on the basis of research **(Song et al., 2024, Wang et al., 2023)**. The properties of the mudstone in the immediate roof and floor within the thermal impact of the UCG reactor were calculated taking into account studies **(Otto et al., 2015, Zhang et al., 2014)** (**Table 1**).

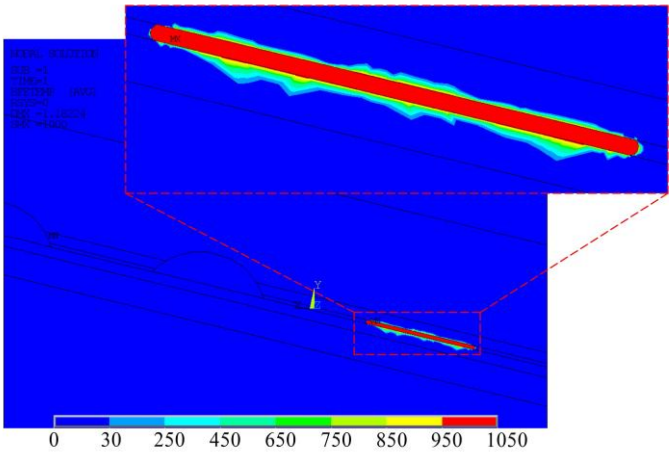
3. Results

Stress-strain analysis and analysis of temperature distribution have created the basis for understanding the mechanism of loss of pillar's bearing capacity and studying the laws of reduction of the functional width of the coal pillar depending on the depth.

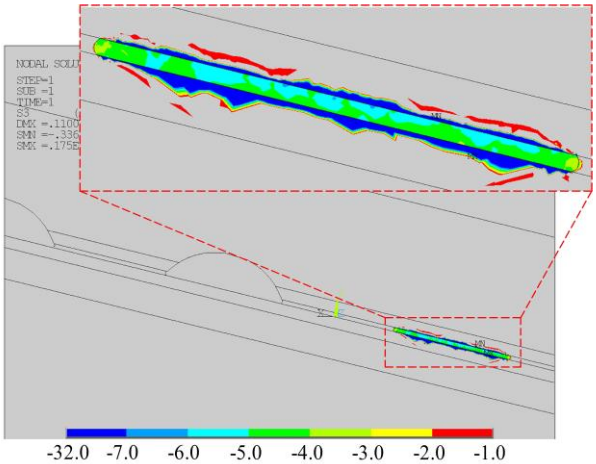
Table 1. Rock mass parameters in the zone of thermal influence of UCG.

Linear thermal expansion coefficient (α) (K^{-1})	Specific heat capacity (CP) (J/(kg K))	Thermal conductivity (λ) (W/(mK))	Tensile strength (MPa)	Deformation modulus (GPa)	Poisson's ratio	Cohesion value, (MPa)	Angle of internal friction (deg)
Immediate roof/floor (mudstone)							
$3.0\ 10^{-5}$	800	1.67	0.36	1.17	0.3	2.7	27
Coal seam							
$1\ 10^{-5}$	620	0.16	0.27	0.5	0.4	1.13	20

Figure 2a shows the temperature distribution in the model. It should be noted that the model takes into account the thermal destruction of coal in the sides of the production and injection wells, which leads to the formation of non-rectangular reactor walls. The thermal impact zone of the reactor, which is limited by a 250 Celsius degree in the reactor walls, according to the simulation results does not exceed 30 cm. In this case, the maximum width of the temperature increase zone in the sides of the reactor is concentrated in the middle part of the coal seam thickness.



a)



b)

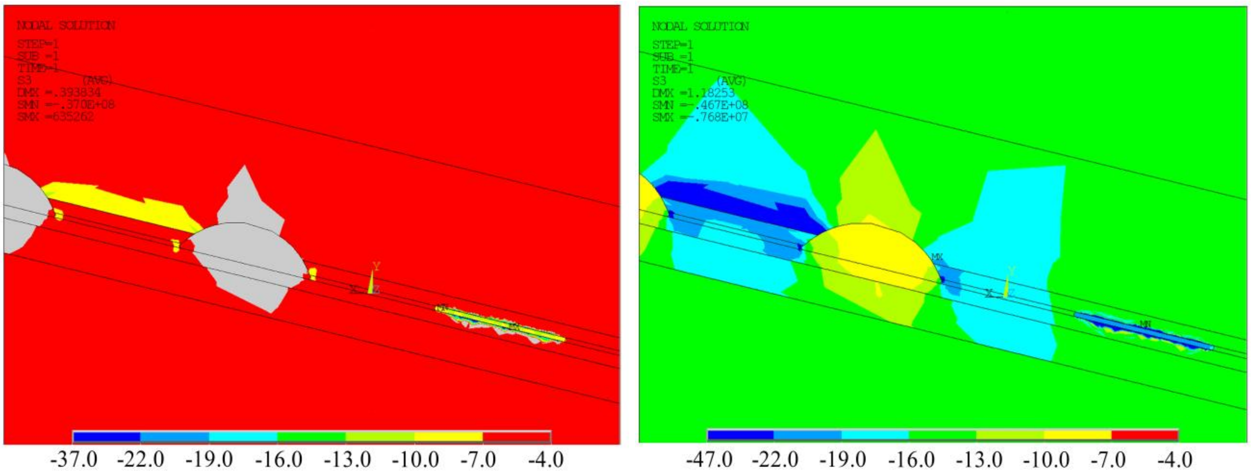
Figure 2. Distribution of temperature in Celsius degree (a) and thermal stress (b) in the model.

Figure 2b shows the distribution of thermal stresses around the reactor cavity. Thermal stresses caused by rock expansion in the temperature-influenced zone have a minus sign. This means that these stresses are compressive. Thus, thermal stresses increase the minimum principal mechanical stresses in the surrounding rocks. Since thermal stresses do not depend on depth, the share of their influence on sum of thermo-mechanical stresses decreases with depth. The value of maximum thermal stresses in the walls of the reactor cavity is 3,6 MPa. At a depth of 200 m, this is an additional 72% to geostatic stresses, and at a depth of 600 m, only 24%. Thus, coal pillars located at a shallow depth are more sensitive to thermal stresses according to the principle of superposition.

Coal pillars are fractured in the result of compression, therefore the critical stresses for them are the principle minimum stresses. The distribution of coupled mechanical and thermal stresses in the surrounding rocks of the UCG reactor at a depth of 200 and 600 m is shown in **Figure 3**. Stress field at different depths vary significantly both on the face of the UCG reactor and in its walls.

Figure 4 shows the change of the coupled compressive stress in a coal pillar with depth. The monitoring line is located in the center of the coal seam and extends from the wall of the reactor cavity to the wall of the previously gasified cavity. The increase of stresses in the pillar (relative to lithological stresses) from the side of the previously worked out cavity is caused by the abutment pressure increased as a result of the collapse of rocks above the gasification cavity in the post-gasification period. This process is well studied and does not cause interest. The increase in stresses from the side of the UCG reactor is caused by thermal stresses. There, a sharp increase in compressive stresses is observed with a peak value on the surface of the reactor wall. The depth of the thermal influence of the reactor on the distribution of minimum principal stresses does not exceed 50 cm for the geological conditions of this study.

It is evident from **Figure 4a** that the increase in stress near the reactor is not constant and is 3.07 MPa, 3.09 MPa, 3.20 MPa, 3.32 MPa, 3.44 MPa for depths of 200 m, 300 m, 400 m, 500 m, 600 m, respectively. This is explained by the combined effect of thermal and mechanical stresses in the UCG cavity wall. Moreover, since the cavity has an arched shape and the coal properties are simulated nonlinearly, an indirect relationship is observed between the increase in depth and the stresses in the UCG cavity wall at a constant value of thermal stresses. Since the arched shape allows to reduce compressive stresses on the contour, the sum of increase in thermo-mechanical stresses in the studied range is less than thermal stresses. However, in the skewbacks of the arch from the roof and floor sides, increased compressive stresses arise. However, they do not have a significant effect on the fracturing of the coal pillar.



a) b)

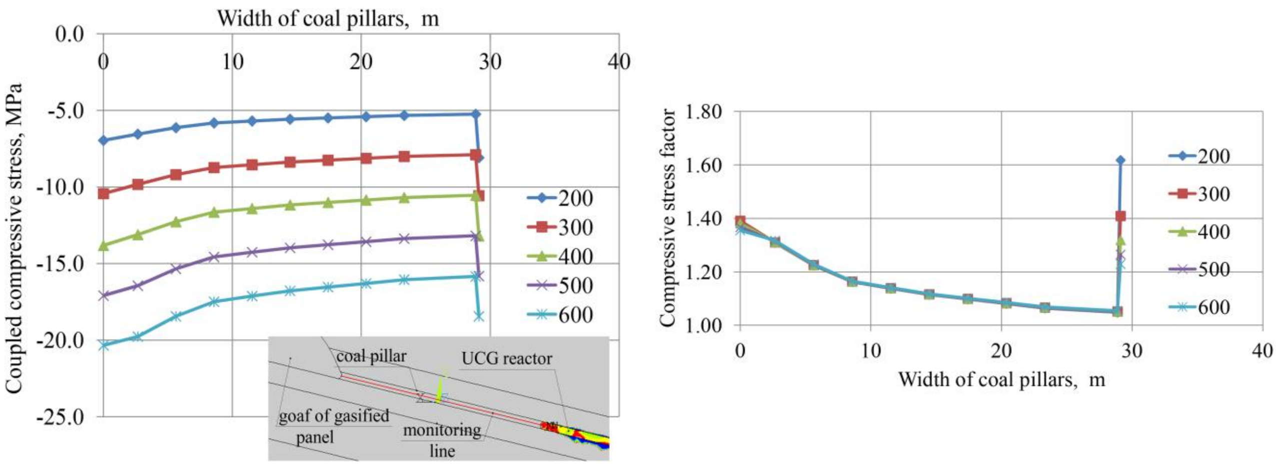
Figure 3. Distribution of minimum principal stresses (MPa) in the model at a depth of 200m (a) and 600 m (b).

Figure 4b shows the change in the stress concentration coefficient in the pillar at different depths of the coal seam. The compressive stress factor (k_{cs}) is:

$$k_{cs} = \frac{\sigma_{sum}}{\sigma_0}, \tag{1}$$

where are:
σ_{sum} – coupled thermo-mechanical stress, MPa,
σ_0 – lithological stress, MPa.

As anticipated, the share of thermal stress influence decreases with depth. Thus, the compressive stress factor on the surface of reactor wall is 1.62 for a depth of 200 m and 1.23 for a depth of 600 m.



a) b)

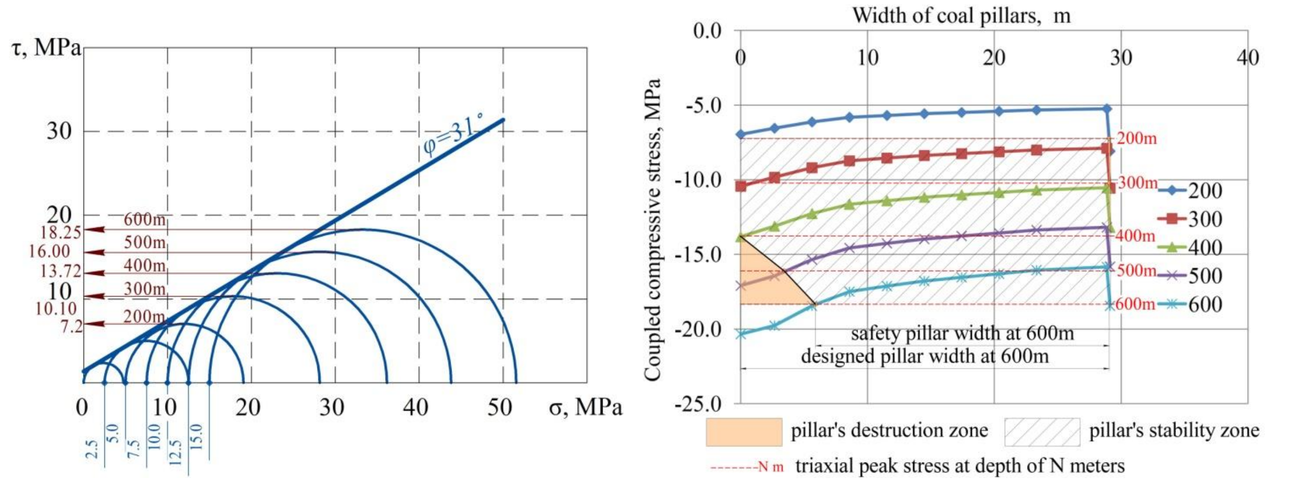
Figure 4. Variation of thermo-mechanical stresses (a) and stress concentration factor (b) in a coal pillar at depth of 200m – 600 m.

4. Discussion

In this study is proposed to use the Mohr criterion to determine the depth of the coal pillar fracturing near the reactor cavity. It is known that the strength of rock in the volumetric stress field increases. With a certain degree of simplification, the increase in depth can be interpreted as an increase in confined stresses. Thus, the results of coal testing in a volumetric stress field can provide data for assessing the pillar failure at different depths. As an example, the results of coal specimens testing in a triaxial compression machine are used in this article; the experimental technique was described in detail in the previous study (**Sakhno, et al., 2018).**

During laboratory tests, an increase in the coal seam depth was simulated by increasing the confined stress. Thus, a depth of 200 m, 300 m, 400 m, 500 m, 600 m corresponded to a lateral pressure of 5.0 MPa, 7.5 MPa, 10.0 MPa, 12.5 MPa, 15.0 MPa. At the initial stage of the specimens loading, the vertical and lateral pressures had been being increased simultaneously. After reaching the required level of confined stress, the vertical pressure had been increased until the specimens were destroyed. The Mohr circles for long-flame coal are shown in **Figure 5a**.

Triaxial peak stress at depth of 200 m, 300 m, 400 m, 500 m, 600 m is 7.20 MPa, 1.10 MPa, 13.72 MPa, 16.00 MPa, 18.25 MPa respectively. The angle of internal friction (φ) of coal is 31 degrees. **Figure 5b** combines the results of laboratory tests and numerical simulation. The part of the pillar in which the stress is higher than the triaxial peak stress (according to Mohr's theory) will be failured. Thus, the intersection points of the peak stress and coupled compressive stress lines at the corresponding depth characterize the peak states.



a) b)

Figure 5. The Mohr circles for long-flame coal (a) and variation of safety pillar's width (b) at depth of 200m – 600 m.

For the case illustrated in **Figure 5 b**, it can be concluded that thermal stresses will lead to the destruction of the pillar on the side of the UCG reactor only at a depths of 200 mand 300 m, since for these depths the peak stress line cuts off part of the coupled compressive stress curve. The fracturing zone is only a few centimeters. On the side of the worked out cavity, at depths of 500 m and 600 m, coal fracturing is observed, which leads to a decrease in the safety of the pillar's width. The width of the fracturing zone at a depth of 500 m is 3.4 m, and at a depth of 600 m – 6.1 m. The safety pillar's width is reduced on the mentioned values, which should be taken into account during designing of the pillars. However, the main reason for this is mechanical stress. Thus, it can be concluded that for the conditions considered in the article, thermal destruction of coal in the walls of the UCG reactor does not significantly reduce the safety pillar's width.

5. Conclusions

This study was focused on the issue of the calculation of safety pillar's width in Underground Coal Gasification. Thermo-mechanical stresses in the coal pillar were studied. Specific attention is paid to the area of the coal pillar near the UCG reactor. Mohr's theory is proposed to predict the failure of a coal pillar at different depths. Based on the results of this investigation, the following conclusions can be drawn:

(1) In the coal pillar from the UCG reactor side, two processes causing destruction are observed. The first one is thermal destruction as the result of temperature increase. The second one is mechanical fracturing of coal caused by its expansion in a result of heating, i.e. thermal stress. The depth of the thermal destruction zone does not exceed 30 cm. The depth of the destruction zone caused by thermal stress is about 10 cm. Thus, it can be concluded that for the conditions considered in the paper, thermal destruction of coal in the walls of the UCG reactor does not significantly reduce the safety pillar's width.

(2) In the coal pillar on the side of the worked out cavity, the fracturing of the pillar was caused by the abutment pressure increased as a result of the collapse of rocks above the gasification cavity in the post-gasification period. When calculating the safety pillar's width, it should be taken into account that mechanical stress increases with depth. The results of the study showed that with a designed width of 30 m, at depths of 500 and 600 m, the safety pillar's width decreases to 26.6 and 23.9 m, respectively. The reason for this is the fracturing of coal in the zone of increased stresses.

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Author's contribution

Svitlana Sakhno (associate professor): conceptualization, investigation, methodology, software and writing – review. **Ivan Sakhno** (professor): project administration, resources, software, supervision and writing – original draft. **Serhii Bashynskyi** (associate professor): formal analysis, visualization and editing. **Munkhtsetseg Oidov** (associate professor) methodology, validation and editing.