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Estimation of Gas Bearing Capacity and Gas Dynamic Behaviour of Rocks of Salt and Shaly-Carbonate Rock Units in the Mine Field of the Mine of the Second Mining Department of Belaruskali JSC

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Оценка газоносности и газодинамических характеристик пород соляных и глинисто-карбонатных пачек на шахтном поле рудника Второго рудоуправления ОАО «Беларуськалий»

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Potash mine, gas dynamic phenomena, shaly-carbonate rock units, salt rock units, potash horizons, opening slopes, nonassociated gas bearing capacity, initial gas emission rate, nonassociated gas pressure, sealer, gas accumulations.

The paper presents results of quantitative estimations of gas bearing capacity and gas dynamic behaviour of shaly-carbonate and salt rock units along the geologic profile of the Starobinsky potash field between the III and IV potash horizons. Underground experimental studies of the gas bearing capacity and gas dynamic behaviour of the shaly-carbonate and salt unit rocks were conducted in the slopes opening the IV potash horizons in the mine field of the mine of the Second Mining Department of Belaruskali, JSC. The underground experimental research procedure provided for quantitative estimation of the following indicators: nonassociated gas bearing capacity, initial gas emission rate and gas pressure of rocks in the 12th, 10th and 8th shaly-carbonate units, as well as the 11th and 9th salt units.
Based on the underground experimental research data, a quantitative estimation of the gas bearing capacity and gas dynamic behaviour of rocks in the 12th, 10th and 8th shaly-carbonate units as well as the 11th and 9th salt units was performed.
Identified were the most gas-bearing beds of rocks in the shaly-carbonate and salt rock units, as well as the pattern of changes in the gas bearing capacity and gas dynamic behaviour of rocks in the geologic profile between the III and IV potash horizons.

Ключевые слова:
калийный рудник, газодинамические явления, глинисто-карбонатные пачки, соляные пачки, калийные горизонты, вскрывающие уклоны, газоносность по свободным газам, начальная скорость газовыделения, давление свободных газов, герметизатор, скопления газов.

Приведены результаты исследований количественной оценки показателей газоносности и газодинамических характеристик пород глинисто-карбонатных и соляных пачек, расположенных по геологическому разрезу Старобинского месторождения калийных солей между III и IV калийными горизонтами. Шахтные экспериментальные исследования газоносности и газодинамических характеристик пород глинисто-карбонатных и соляных пачек проводились во вскрывающих IV калийный горизонт уклонах на шахтном поле рудника Второго рудоуправления ОАО «Беларуськалий». Методикой шахтных экспериментальных исследований предусматривалась количественная оценка следующих показателей: газоносности по свободным газам, начальной скорости газовыделения и давления свободных газов в породах 12, 10, 8-й глинисто-карбонатных пачек, а также 11-й и 9-й соляных пачек.
На основании результатов шахтных экспериментальных исследований дана количественная оценка показателей газоносности и газодинамических характеристик пород 12, 10, 8-й глинисто-карбонатных и 11, 9-й соляных пачек.
Установлены наиболее газоносные слои пород глинисто-карбонатных и соляных пачек, а также закономерности изменения газоносности и газодинамических характеристик пород по геологическому разрезу между III и IV калийными горизонтами.

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Introduction

Currently, beside the rocks in the I and III potash horizons, the rocks in the 12th shaly-carbonate unit are considered hazardous by gas dynamic phenomena at Belaruskali potash mines [1-15]. During the driving of slopes that open the IV potash horizon, in addition to the 12th shaly-carbonate rock unit, intersected will be the 10th and 8th units, their geologic profile very similar to that of the 12th shaly-carbonate unit. The geologic profile of the shaly-carbonate rock units in the Starobinsky potash field conditions features a thin alternation of shale interbeds and dolomite-calcareous shales, non-layered and slightly layered rocks, sandstone and siltstone beds, rock salt beds that serve as some sort of *gas-tight screens* in the unit upper part, and organic matter in the rocks (up to 1 %) in the unit rocks. All these geologic profile features of the shaly-carbonate units enable us to provide for the nonassociated gas formation in the rock strata and, thus, the formation of near-contact and focal accumulations of the nonassociated gases. The latter may serve as seats of the gas dynamic phenomena during mining operations, i.e. the driving of opening slopes. The rocks of the 11th, 9th and 7th salt units contain beds and interbeds of non-salt rocks, halopelite, its thickness varying from a fraction of a millimetre to tens of centimetres. As evidenced in the practice of potash mining, these halopelite beds and interbeds may be associated with the near-contact accumulations of the nonassociated gas that may also serve as seats of the gas dynamic phenomena, such as a sudden rock burst (failure) of the roof (soil) of the mine workings accompanied by gas emissions. Years-long mining practice in formations with gas dynamic hazards has proved that only an in-depth study of the gas bearing capacity and gas dynamic behaviour of the shaly-carbonate and salt rocks will underpin safe working driving procedures in the gas-bearing rock [16-47].

To ensure safety of the mining operations, temporary recommendations were elaborated for safe mining during driving of opening slopes in the 12th, 10th and 8th shaly-carbonate rock units and the 11th, 9th and 7th salt rock units at the opening of the IV potash horizon in the mine field of the mine of the Second Mining Department (2nd MD) of Belaruskali. The recommendations included the parameters of the preventive gas-drainage drilling and drilling/blasting operations for torpedoing and gas-draining of the marginal area of slopes at the appearance of the gas dynamic phenomena precursors, as well as guidelines on the monitoring of warning signs and precursors of the gas dynamic phenomena. In addition, certain scientific support at driving of opening slopes is provided for, which consists in researching the gas bearing capacity and gas dynamic behaviour of the rocks in the 12th, 10th and 8th shaly-marl horizons and the 11th, 9th and 7th salt horizons for the timely adjustment and refinement of procedures to ensure a safe driving of slopes that open the IV potash horizon in the mine field of the 2nd MD mine.

Geologic Profile of the 12th, 10th and 8th Shaly-Carbonate Rock Units and the 11th, 9th And 7th Salt Rock Units

The geologic profile of the rock strata separating the III and IV potash horizons at the opening slope driving area is shown in Figure (*a*) [48-50]. The data in the Figure shows the thickness of the 12th, 10th and 8th shaly-carbonate rock units is 22.7, 19.4 and 32.1 m, respectively, while the thickness of the 11th, 9th and 7th salt rock units is 28.2, 44.6 and 28.5 m, respectively. Within the Starobinsky potash field, the 12th shaly-carbonate unit was opened by wells located mainly in the field's west and edge marginal parts.

A distinctive feature of the rock unit consists in its great thickness with a regular gradual change. The maximum thickness (45.73-46.02 m) is observed in the unit's north and north-east of the Starobinsky field. In the south and south-west, there is a gradual decrease in thickness: first to 35.60-38.90 m, then to 28.0-33.41 m, finally, in the field's western periphery, and in the southern half of the central area its thickness goes as low as 23.95-25.0 m. The unit's minimum thickness (20.95 m) is in the south of the western periphery and in the south of the main area. Therefore, from the north-east to the south-west, the unit's thickness is reduced by half, going down from 45.78-46.02 m to 20.95 m.

Normally, the geologic profile of the 12th shaly-carbonate rock unit features four beds. The unit is distinct in thick sandstone interbeds at the base of some beds, as well as an overall increase in sandy and silty fractions in the terrigenous rock composition. The first (lower) bed has an average thickness of 4.0-5.0 m. A slightly increased thickness (7.5-6.0 m) is observed in the north and north-east of the field. The first bed features a reduced thickness (2.0-3.5 m) in the south and south-east of the field. The lower part of the first bed is composed of alternating thin beds (from several mm to 2-3 cm) of dolomite marl and shale of varying carbonate contents. There are one millimetre-thick interbeds of yellowish-grey siltstone, and carbonate-anhydrite and pelitic-anhydrite rocks. The upper part of the first bed is composed of dark grey marl that is dense and indistinctly layered with sandstone interbeds.

The second bed differs from the first one by the presence (in its lower part) of a sandstone bed with a thickness between 1.5 and 6.0 m. The thickness of the sandstone bed, as well as the total thickness of the bed, increases from the south to the north. The sandstone has a yellowish or brownish-grey colour, is fine- and small-grained, with inclusions of coarse grains of quartz-feldspathic composition. The sandstone's texture is layered, cemented by halite. The upper half of the bed features multiple pockets of anhydrite. Mottled clay passing in interbeds into dolomite marl is above the sandstone bed. Anhydrite interbeds of up to several centimetres thick are found occasionally. The unit ends up with shaly-marl rocks with interbeds of rock salt and occasional interbeds of anhydrite. The second bed thickness varies between 5.6-7.0 m in the field's south-east and west and 11.0-15.2 m in the field's north.

The third bed at its base also has a sandstone bed that passes into siltstone in the field's western periphery and the north. The bed's thickness is 0.4 m in the field's west, 1.7-2.2 m in the south and south-east, and 6.2 m in the north. The sandstone has a pinkish-grey and grey colour, and is cemented by halite. Above the sandstone there is a shale/dolomite marl alternation area. The shale beds are 1 mm to 10 cm thick, the thickness of marl is 1 mm to 20 cm. The shale is occasionally sandy. In the upper part of the bed, the shale passes into shaly-marl, which is indistinctly layered and occasionally silty. There are sporadic beds of siltstone (up to 2 cm thick), and less frequent beds of anhydrite (up to 0.5 cm thick). The third bed ends up with a bed of rock salt with a thickness of 2.0-3.6 m. There is no rock salt bed in the field's western periphery. The third bed's thickness also changes sharply: in the southern and western periphery of the field, the thickness is 7.2-9.6 m, while in the north and north-east, it amounts to 14.6-17.0 m. The decrease in thickness in the third bed is mainly due to its non-salt section and partly owing to the absence of a rock salt bed in the bed's roof in the field's western periphery only.

Upper and lower parts composed of different rock types can be identified in the unit's fourth (upper) bed in the field's northern and western periphery only, which is not feasible for the field's south. The description of the latter, therefore, only includes silty shale with rock salt interbeds. In the northern and western periphery of the field, these shales compose the fourth bed's upper part, while in the lower part there are interbeds of dolomite-anhydrite rock and sandstone interbeds. The thickness of the top bed varies between 2.7-3.0 m in the field's south-east and 3.2-7.6 m in the south and west. In the north and north-east, the thickness of the unit's fourth layer increases to 7.9-12.0 m.

In general, the change in each bed's thickness in the rock unit is subject to a general pattern of its increase from the south-west to the north-east. The thickness changes in the 12th shaly-carbonate unit owing to the change in the thickness of each bed, while the number of beds in the unit remains the same over its entire spread.

The 10th and 8th shaly-carbonate units down the geologic profile were opened by a limited number of wells located in the western half of the field and its marginal northern and southern parts. Over the whole area (except for the south-east), the thickness of the 10th shaly-carbonate unit remains more or less constant, amounting to 19.4-23.7 m, and only in the south-east it increases to 27.5-30.3 m, while in the south-west (well No. 142) it decreases to 17.0 m. There are three beds in the structure of the 10th and 8th shaly-carbonate units, so these units, just as the 12th unit, are classified as *complex* ones, according to their geologic profile. Normally, the lower part of the first bed of these rock units is composed of shales alternating with dolomite-calcareous mudrocks, and forms approximately 40-50 % of the total bed thickness. Above are non-layered and slightly layered shaly-marl rocks, their thickness amounting to 30-40 % of the total bed thickness. Typically, sandstone and siltstone beds adjoin the top of these rocks. The bed's uppermost part (10-15 % of the total thickness) is composed of the rocks with a high content of calcium sulphate, dolomite and calcite. In general, the rock in the lower part has a layered structure. The upper parts of the beds are composed of shaly-marl rocks, almost non-layered or slightly layered, with only a few interbeds of argillaceous calcareous dolomite, dolomite calcareous marls

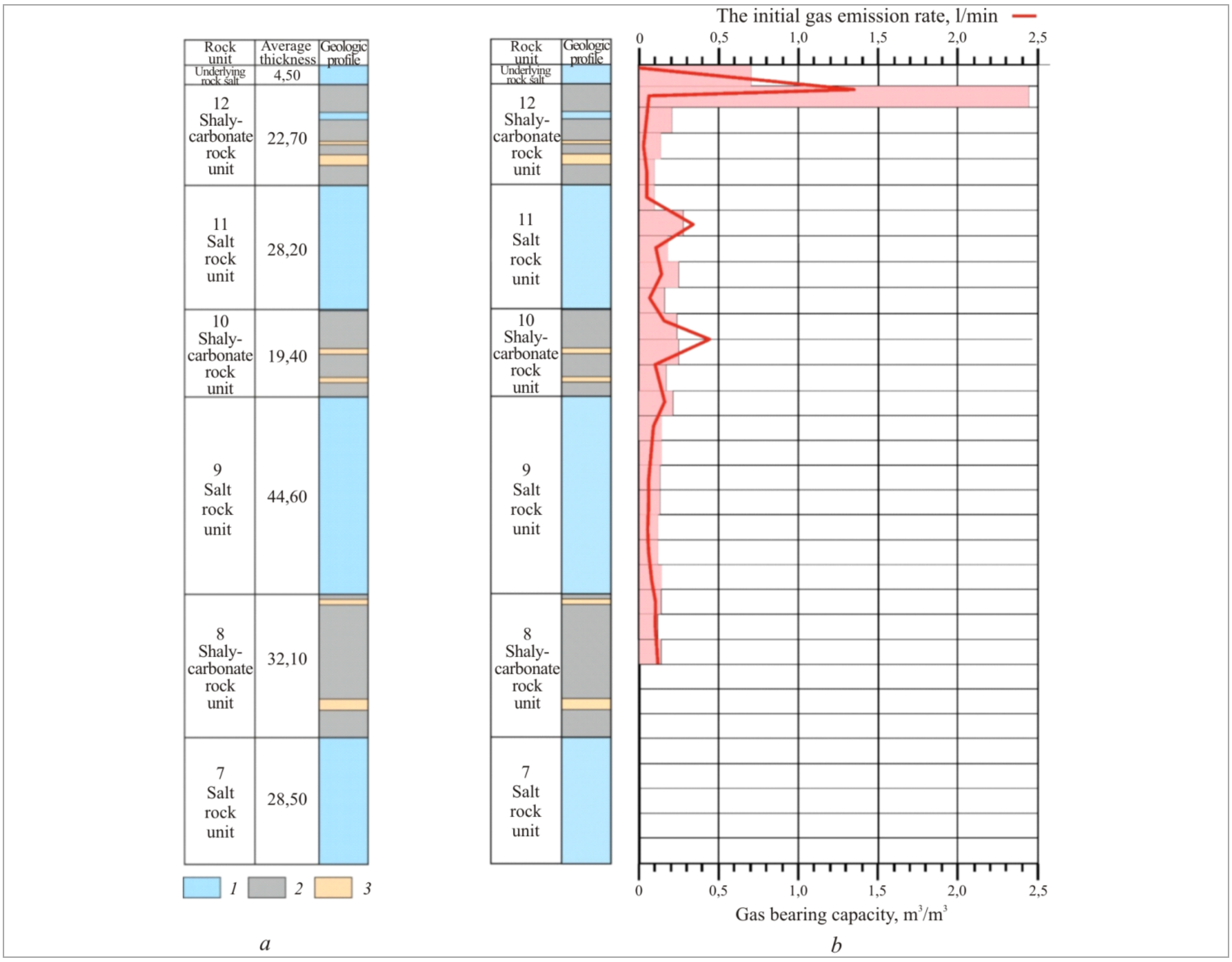

Fig. Potash horizons III and IV: *a* is the geologic profile of the rock thickness separating the III and IV potash horizons in the section of driving opening slopes in the mine field of the 2nd MD mine: *1* is rock salt; *2* is shale/marl alternation; *3* shows sandstones; *b* is the gas bearing capacity of rocks and initial gas emission rate in wells through the rock strata section between the III and IV potash horizons

and shales. The upper parts of the shaly-carbonate units feature a more homogeneous composition.

The first (lower) bed of the unit in the western periphery part is 8.7-10.0 m thick. In the field's north, north-east and centre, the thickness of the first bed is 6.7-8.4 m, while in the east it decreases to 3.2 m. The lower part of the first bed with a thickness of 3-5 m is composed of shales of dark grey colour tending to green, and interbeds of carbonate-anhydrite rocks.

According to data of well No. 396, the thickness of the 10th shaly-carbonate unit is 19.4 m. The unit is represented by alternating massive shale of dark grey, greenish-grey and greyish-brown colours. Interbeds of small-grained sandstone are identified at intervals of 60.6-60.8 m and 66.9-67.2 m. The thickness of the 8th shaly-carbonate unit is 32.10 m; the unit is composed of alternating interbeds of massive shale of dark grey and greyish-brown colours with interbeds of greenish-grey marl. Fine-grained sandstone interbeds are identified at intervals of 120.55-120.59 m, 143.20-143.40 m, and 144.55-144.90 m.

The 11th, 9th and 7th salt units are mainly represented by the rock salt containing beds and interbeds of non-salt rocks – halopelites, their thickness varying between a fraction of a millimetre to 0.15 m. As such, the 11th salt unit with a thickness of 28.20 m is represented by the rock salt of light grey to dark grey colours. The dark grey colour of the rock salt is due to the admixed shale material. The rock salt has a medium- and coarse-crystalline texture. Dark grey shale interbeds of a thickness ranging between a few millimetres and 0.10 m can be found across the entire thickness of the unit. The underlying 9th salt unit with a thickness of 44.60 m is represented by alternating interbeds of medium- and coarse-crystalline rock salts of grey and dark grey colours. In the second half of the thickness interval, there are interbeds of finely-crystalline rock salts of the yellowish-greyish colour. The dark grey shale interbeds with a thickness ranging between several millimetres and 0.15 m are found across the entire thickness of the 9th unit. The upper part of the 7th salt unit with a thickness of 5.83 m is represented by the grey rock salt with dark grey shale interbeds. The presence of shale beds and interbeds with a thickness up to 0.15 m in the rocks of the salt units indicates possible near-contact accumulations of nonassociated gases.

Study Procedure of Gas Bearing Capacity and Gas Dynamic Behaviour of Rocks of the 12th, 10th and 8th Shaly-Carbonate Units and the 11th, 9th and 7th Salt Units

The gas bearing capacity of the underlying rock salt of the 12th, 10th and 8th shaly-carbonate units and the 11th, 9th and 7th salt units was studied by sampling and performance measurements of the gas emitted from research wells [51, 52]. During the driving of the slopes that open the IV potash horizons, the wells were drilled by intervals into the floor, perpendicular to the bedding. The drilling interval was 1.0 m. The drilling assembly was then removed followed by the well sealing at 0.5 m off the bottom. The gas released from the walls and bottom of the sealed part of the borehole goes into a gas outlet connected to DPI-740 digital portable precision pressure indicator designed for laboratory and field applications. The barometer's high accuracy and repeatability ensure its application as a reference pressure gauge or absolute pressure indicator, if necessary.

DPI-740 determines the initial gas emission rate in the well by the pressure created by the gas passing through the calibrated capillary aperture, as well as the gas pressure increment in the well within 30 seconds after it is sealed, i.e. the initial gas pressure. Gas bearing performance is determined based on this reading, using pre-plotted dependency graphs of $X = f(P_r)$, where X is the rock gas bearing capacity, m^3/ m^3; P_g is the initial gas pressure [21].

Results of Experimental Studies of Gas Bearing Capacity and Gas Dynamic Behaviour of Rocks During Interval Driving of Opening Slopes at the Mine Field of the 2nd MD Mine

During the driving of the transport conveyor and ventilation slopes that open the IV potash horizon in the mine field of the 2MD mine, 14 wells were drilled to determine the gas bearing capacity and gas dynamic behaviour of the rocks of the underlying rock salt bed and the 12th shaly-carbonate unit, as well as five sets of three wells in each to study the rock gas bearing capacity of the 10th and 8th shaly-carbonate units and the 11th and 9th salt units. A total of 29 research wells were drilled in scientific support of the opening slope driving. The value distribution of the nonassociated gas and initial gas emission rates in the research wells through the geologic profile of the rock thickness between the III and IV potash horizons in the mine field of the 2nd MD mine is shown in Figure, *b*. The Figure shows that in the depth interval of 0.5-1.0 m, the gas bearing capacity was 0.54 m^3/m^3. At this drilling depth there is a contact between a bed of the underlying rock salt and the 12th shaly-carbonate unit. The initial nonassociated gas emission rate in this depth range was 0.62 l/min, while the nonassociated gas pressure at this depth amounted to 0.196 MPa.

At a depth of 1.5 m, which corresponds to a sealing depth of 1.0-1.5 m, the bedrock gas bearing capacity was 2.44 m^3/m^3, while the initial gas emission rate was 1.33 l/min, and the nonassociated gas pressure in the bedrock mass was 0.23 MPa. At this drilling depth there is a fourth (upper) bed of the 12th shaly-carbonate unit with a thickness of 6.1 m, represented by an alternation of dark grey marl and indistinctly layered, dense dark grey shale. The open porosity of rocks in this bed of the 12th shaly-carbonate unit varies between 5.6 and 11.0 % with an average value of 8 %. In this rock bed, the experimental works in the research wells proved the high probability of identifying the nonassociated gas accumulations. Further drilling and studies of the gas bearing capacity and gas dynamic behaviour of the rocks showed that down through the geologic profile, the gas bearing capacity of the rocks in the 12th shaly-carbonate unit did not exceed 0.21 m^3/m^3, the initial gas emission rate was no larger than

0.16 l/min, and the maximum nonassociated gas pressure was 0.19 MPa.

In the rocks of the 11th salt unit, the nonassociated gas bearing capacity ranged between 0.1 and 0.29 m^3/m^3, and the initial gas emission rate varied between 0.05 and 0.33 l/min. The maximum values of the gas bearing capacity (0.29 m^3/m^3) and initial gas emission rate (0.33 l/min) were observed in the middle beds of the 11th salt unit and related to halopelite interbeds. The nonassociated gas pressure in the rock mass of the 11th salt unit does not exceed 0.192 MPa.

In the geologic profile of the 10th shaly-carbonate unit, the gas bearing capacity and gas dynamic behaviour of the rocks vary non-uniformly: the nonassociated gas bearing capacity varies between 0.10 and 0.25 m^3/m^3, the initial rate of the nonassociated gas emission ranges between 0.03 and 0.41 l/min, while the nonassociated gas pressure in the rock mass does not exceed 0.192 MPa. The most gas bearing rocks are those occurring in the interval of 4.0-5.0 m from the roof of the 10th shaly-carbonate unit. Within this interval of the unit's geologic profile, the nonassociated gas bearing capacity varies between 0.21 and 0.25 m^3/m^3. The maximum values of the initial gas emission rate and nonassociated gas pressure in the rock mass of the 10th shaly-carbonate unit are limited to the same interval.

The experimental studies of the gas bearing capacity and gas dynamic behaviour of the rocks in the 9th salt unit showed that the rocks are slightly gassy, their nonassociated gas bearing capacity varies between 0.1 and 0.18 m^3/m^3, while the initial rate of the nonassociated gas emission ranges between 0.03 and 0.15 l/min. The nonassociated gas pressure in the rock mass of the 9th salt unit does not exceed 0.19 MPa.

The nonassociated gas bearing capacity of the rocks in the 8th shale-carbonate unit varies between 0.10 and 0.14 m^3/m^3. The initial rate of the nonassociated gas emissions falls within the range between 0.03 and 0.13 l/min. The nonassociated gas pressure in the rock mass does not exceed 0.19 MPa. No near-contact nonassociated gas accumulations were detected at the contact between the 9th salt unit and the 8th shaly-carbonate unit. The rock's gas bearing capacity in the 8th shaly-carbonate unit at the contact with the 9th salt unit is much lower than that by the nonassociated gas in the rocks of the 12th shaly-carbonate unit, that is 10 times more hazardous due to the gas dynamic phenomena in the mine field of the 2nd MD mine.

The study results of the gas bearing capacity and gas dynamic behaviour of the rocks during driving of slopes that open the IV potash horizon in the mine field of the 2nd MD mine show that the most gas-bearing rocks are those of the fourth (upper) bed with a thickness of 6.1 m, pertaining to the 12th shaly-carbonate unit, which is classified as hazardous by the gas dynamic phenomena. In this bed of the 12th shaly-carbonate unit rocks, there is a high likelihood of the nonassociated gas accumulations that under certain mining conditions may be the seats of the gas dynamic phenomena.

Based on the study results of the gas bearing capacity and gas dynamic behaviour of the rocks of the salt and shaly-carbonate units, to ensure the safety of mining operations, an operating procedure has been developed for driving the opening slopes of the 12th, 10th and 8th shaly-carbonate units and the 11th, 9th and 7th salt units at the opening of the IV potash horizon in the mine field of the 2nd MD mine of Belaruskali. The procedure included the application of special modes of the slope driving involving prevention methods of the gas dynamic phenomena depending on geological conditions of driving: normal driving mode in the underlying rock salt; mode of the inclined face opening of the 12th, 10th and 8th shaly-marl horizons; mode of the inclined intersection of the 12th, 10th and 8th shaly-marl horizons; mode of driving along the 11th, 9th and 7th salt horizons; mode of the intersecting zones hazardous due to the gas dynamic phenomena, when precursors thereof appear [53, 54]. Special slope driving modes subject to geological conditions provide for the inclined face drilling of exploration and gas drainage boreholes, preventive gas drainage drilling, drilling and blasting operations for torpedoing and gas-draining of the marginal area of slopes at the appearance of the gas dynamic phenomena precursors, as well as the guidelines on the monitoring of warning signs and precursors of the gas dynamic phenomena.

Conclusions

The following conclusions can be drawn based on the data of the experimental studies of the nonassociated gas bearing capacity and gas dynamic behaviour of shaly-carbonate and salt rocks of the strata separating the III and IV potash horizons in the slopes opening the IV potash horizon at the mine field of the 2nd MD mine:

1. The most gas bearing rocks are those pertaining to the fourth (upper) bed of the 12th shaly-carbonate unit. Within this bed of shaly-carbonate rocks, the nonassociated gas bearing capacity varies between 1.33 and 2.44 m^3/m^3, which is 12-20 times higher than that in other beds of the 12th shaly-carbonate unit located down through the geologic profile. The maximum initial gas emission rates that are 5-8 times higher than the initial gas emission rate of other rocks in the 12th shaly-carbonate unit located down through the geologic profile, is also limited to this bed.

2. The nonassociated gas bearing capacity and gas dynamic behaviour of the rocks in the 10th and 8th shaly-marl units are significantly lower than the corresponding values of the 12th shaly-carbonate unit. The nonassociated gas bearing capacity of the rocks in the 10th and 8th shaly-carbonate units ranges between 0.10 and 0.25 m^3/m^3. The initial nonassociated gas emission rate falls within 0.03 and 0.41 l/min. The nonassociated gas pressure in the mass does not exceed 0.192 MPa.

3. In the rocks of the 11th and 9th salt units, the nonassociated gas bearing capacity varies between 0.1 and 0.29 m^3/m^3, while the initial gas emission rate ranges between 0.03 and 0.33 l/min. The maximum values of the gas bearing capacity (0.29 m^3/m^3) and the initial gas emission rate (0.33 l/min) are limited to halopelite interbeds. The nonassociated gas pressure in the rocks of the 11th and 9th salt units does not exceed 0.192 MPa.

4. Based on the data of the gas bearing capacity and gas dynamic behaviour studies of the rocks in the salt and shaly-carbonate units, to ensure the safety of mining operations, an operating procedure has been developed for driving the opening slopes of the 12th, 10th and 8th shaly-carbonate units and 11th, 9th and 7th salt units at the opening of the IV potash horizon in the mine field of the 2nd MD mine of Belaruskali.

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