

On the relationship between gas emission from undermined coal-bearing stratum and the intensity of coal seam mining

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Abstract. A theoretical scheme of gas release from the coalbed under production by treatment workings has been developed. The sizes of zones of different intensity of gas release from the working thickness are set according to the characteristic points of mud shift of the earth's surface. Total amount of releasing gas is determined by the area of the developed space, over which there is an intensive movement of the mined coal. The formation of this area is associated with the development of cleaning operations within the boundaries of the excavation site and the speed of movement of the treatment face. During the development of the theoretical scheme, several assumptions were made, the validity of which was verified on the basis of experimental data obtained in the conditions of four mines at fifteen excavation sites. Coal seams with coals of grades G and A were worked out by them at a depth of 300-1195 m, the capacity of coal seams was 0.90-2.20 m, cleaning works were carried out at a depth of 300-1195 m, the length of the lavas was in the range of 74÷270 m. The monthly movement of the treatment faces and the amount of gas released during this period were taken into account for each excavation site. It is established that the relative gas release per unit area of the developed space remains a fairly constant value for some mining and geological conditions, if the total amount of gas is attributed to the area that determines the active movement of rocks over a moving treatment face. This allows you to use the previously obtained results of determining the categorical danger of mines by relative gas release per ton of coal production in terms of improving the forecast of gas release from the coalbed under production more efficiently.

1 Problem statement

In modern coal mines, the main source of gas emission is the undermined coal-bearing strata.

The relationship between the intensity of gas emission and the degree of was established several decades ago [1, 2]. The highest levels of gas emission are associated with sediments of the main roof [3] and the development of the underworked strata movement towards the earth's surface when removing waste rock. Methane emission into mine workings is possible only from the zone of underworked strata movement with a break in its continuity. In degassing wells, methane emission can also occur from lamination cavities at the contacts of rock layers with different strength properties [4].

In parallel with the influence of the underworked strata movement, the phenomenon of a decrease in the specific flow rate of methane into the stope was established with an increase in the intensity of mining of shallow coal seams [5].

The intensity of seam mining means the level of coal production and the corresponding movement of the mine face. For the safe mining of gas-bearing coal seams, it is necessary to know the mechanism of formation of methane release from the underworked coal-bearing strata. Until now, there are practically no scientific research works in which the intensity of coal seam mining (the level of coal production or the rate of mine face movement), the development of undermining and gas release from undermined sources are considered together. Research in this direction is highly relevant.

2 Purpose, idea and research methodology

The objective of the study is to develop a scheme for the influence of mine faces on the formation of zones of active movement of the undermined coal-bearing strata and the possible intensive emission of methane from them. Establish the factors that determine the gas emission in relation to its emission per unit area of the underworked area.

Idea. It is assumed that the amount of emitted gas depends on both the rate of movement of the mine face (v_{oy}), and the intensity of the movement of rocks above it and the degree of development of mining operations in the extraction area.

Methodology. It provides for the consideration of experimental data on methane emission in relation to the developed scheme of the influence of mine face on the formation of zones of active undermined coal-bearing

strata movement and gas release from the undermined strata.

Results. The layout of the methane emission zones in the undermined coal-bearing strata was developed in accordance with the formation of a displacement trough on the earth's surface [3] and the degree of development of mining operations in the mining area (Fig. 1).

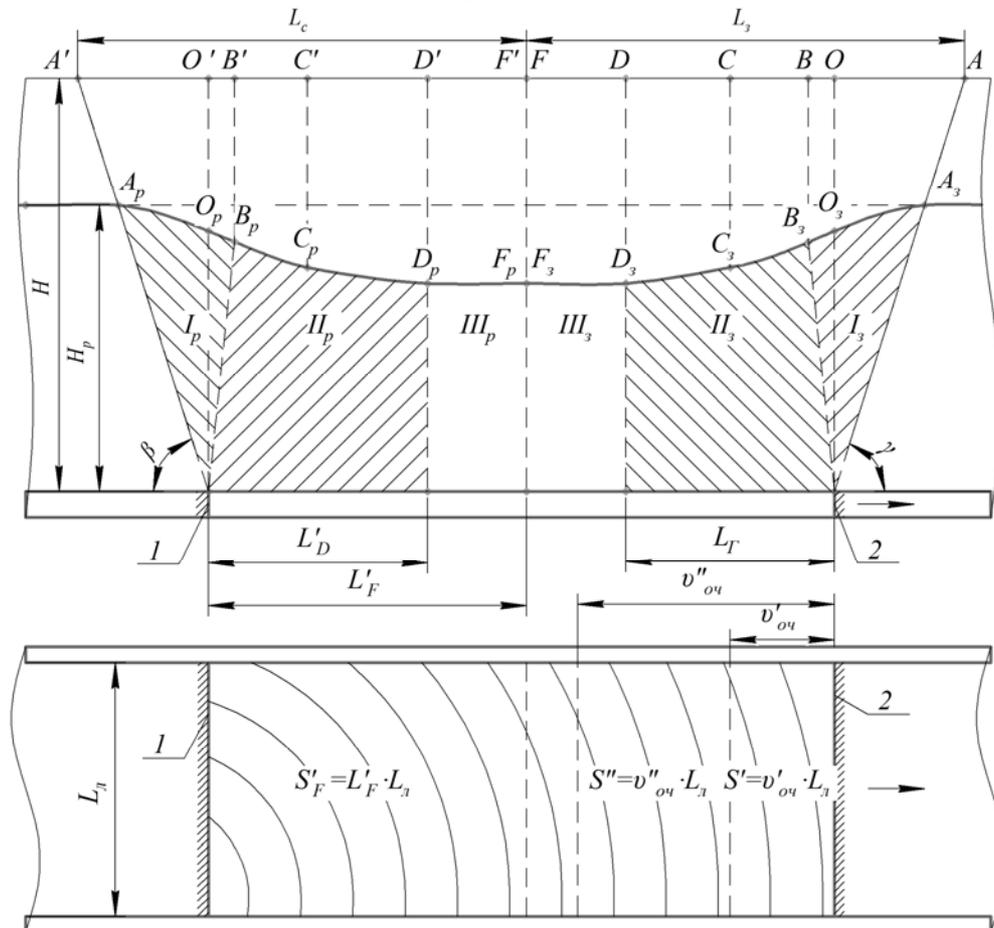


Fig. 1. Scheme of the location of gas emission zones in the undermined coal-bearing strata according to the formation of a displacement trough on the earth's surface (a) and the degree of development of cleaning work (b) in the excavation area: 1, 2 – respectively, the exposed surfaces of the seam of the cut mine and the clean face; 3 – earth surface; L_c, L_d – respectively, stationary and dynamic semi-troughs; A, O, B, C, D, F and A', O', B', C', D', F' – characteristic points of subsidence of the earth's surface of dynamic and stationary semi-troughs; A_p, B_p, C_p, D_p, F_p and A_3, B_3, C_3, D_3, F_3 – characteristic points of subsidence of a layer of undermined rocks at the edge (H_p) of a zone with a discontinuity, respectively above the open cut and the clean face; H – depth of cleaning works; I_3, II_3, III_3 and I_p, II_p, III_p – areas of possible gas emission, respectively, above the clean face and open pit; β, γ – boundary angles of influence of a working mine on the earth's surface; L'_D – the distance between the open pit and the clean face at which active gas emission occurs; L'_F – distance at which gas emission from the side of the cut furnace stops due to rock compaction; L'_G – distance from the working face, at which active gas emission occurs from the undermined coal-bearing strata above the working face; L_n – longwall length; S', S'' – the goaf, respectively, when moving the working face at a distance of v_{oy} and v''_{oy} ; \rightarrow – direction of the working face movement.

3 Results

According to this scheme, a displacement trough is formed on the surface under the influence of cleaning works, which is divided into two semi-troughs. One of them, the stationary length L_c , is formed above the split mine (1). The second is a dynamic length L_d , it is formed as the clean face moves forward (2). These semi-troughs, according to the methods [3, 6, 7], can be divided into separate periods of their formation using characteristic

points. Section $A'B'$ of the semi-trough of the earth's surface (the diagram shows a segment of straight line $A'B'$) corresponds to the initial period of the earth's surface displacement under the influence of a moving clean face. The most active earth's surface displacement occurs on the curve section $B_p D_p$, and at the point C_p the maximum subsidence rate is reached. At the point D_p , the end of the active stage occurs and the transition to damping of the processes of the earth's surface displacement occurs. At point F , the maximum subsidence is achieved and further

advancement of the clean face has practically no effect on the processes of active movement of unmined rocks and the earth's surface.

Similarly, with different intensity, the undermined rocks move above the clean face in the coal-bearing strata. By analogy with the earth's surface, a subsidence semi-trough is formed in it with characteristic points A_3 , B_3 , C_3 , D_3 and F_3 . Insignificant gas emission from the rock stratum is possible from zone I_3 , the dimensions of which are determined by the boundary angle and the position of the point B_3 in the undermined range. Point B_3 is located at a distance of H_p from the developed formation, which defines the boundary of the displacement zone of rocks with a break in their continuity. With the removal of the slope from the cut, H_p reaches a certain value, which remains constant as the extraction column is further worked out [8, 9, 10]. The most favorable conditions for intense gas emission appear in the zone (II_3) of active rock movement. The dimensions of this zone are determined by the section of the $B_3 - C_3 - D_3$ curve and the H_p parameter. Separate determination of gas emission from zones I_3 and II_3 experimentally in mine conditions is practically impossible due to the technical capabilities of modern measuring equipment. Based on the gas surveys in mine workings and measurements in degassing systems, it is possible to establish the total gas emission from zones I_3 and II_3 , neglecting methane emission from zone III_3 . The most accurate and accessible indicator characterizing the size of these zones is the area of the mined-out space S_r . It can be determined by the product of the parameter L_r and the length of the L_n longwall. The value of the parameter L_r is determined by the projections of points D and D_3 . For coal mines of Donbass, the L_p parameter is approximately equal to 0,466 of the depth (H) of mining [3]. Based on the above scheme (Fig. 1), it follows that all the gas emission from the undermined strata (I_v) when moving the clean face can be roughly attributed to the goaf area $S_r = L_n \cdot L_r$.

In production conditions, the value of the L_r parameter, as a rule, does not coincide with the monthly rate of movement of the clean face. If $v_{0q} < L_r$, when determining the specific gas emission from the ratio, this indicator will be overestimated. Gas emission in fact refers to the goaf area of $L_n \cdot L_r$, and it is referred, in some cases, to $S' = v'_{0q} \cdot L_n$.

It is extremely rare that the v''_{0q} values can exceed the L_r parameter, then $S'' = v''_{0q} \cdot L_n$ will exceed the $S_r = L_n \cdot L_r$ area and the specific gas emission per unit goaf area will be underestimated.

It can be assumed that, according to a similar scheme, gas emission occurs above the open cut from zones I_3 and II_3 . Their sizes are also determined by the position of the characteristic points A_p , B_p , C_p , D_p and F_p in the underworked strata and the value of the H_p parameter.

When the clean face is removed from the open-cut mine at a distance of L'_D , zone II_p is largely degassed, since it was subjected to the most intense rock movement. Some gas emission is possible from the I_p zone, in which rock displacements were insignificant.

When the clean face is removed from the open-cut mine at a distance of L'_F , zones III_p and III_3 are more

degassed. The rocks in these zones, before their compaction, successively went through all stages according to the intensity of their movement and, obviously, according to the activity of gas emission from underworked sources.

In the process of developing the scheme (Fig. 1), several assumptions were made that need to be verified and confirmed by experimental results. These include the assumption of the similarity of the gas emission processes from the undermined coal-bearing strata when the clean faces are removed from the split furnaces in the initial period of the excavation sections operation at a distance of L'_D (with the settlement of the main roof in zone II_p) and methane emission above the clean face, determined by the boundaries of zone II_3 and the goaf area S_r , calculated using the parameter L_r .

The analysis involved the results of the cleaning works development observations and gas emission at fifteen excavation areas of four mines. For these sites, in advance, considering the depth (H) of the cleaning works, the L_r parameter was determined [3]. For the conditions of the A.F. Zasyadko mine [11] (16th eastern longwall of the m_3 seam) for a depth of $H = 1195$ m, the value of L_r is 547 m.

In the conditions of the 'Sukhodolskaya - Vostochnaya' mine, during the operation of the 12th bis and 24th eastern longwall of the i_3 seam, the depths were 965 and 1016 m respectively, and they corresponded to L_r values of 450 and 474 m. For the D.F. Melnikov mine, the extraction area of the 1st northern longwall of the ℓ_6 seam was mined at a depth of 852 m, for which the parameter was 397 m. Mine in the name of the "Izvestia" newspaper mined an anthracite layer ℓ_2^6 at a depth of 300 m, and the calculated value of the L_r parameter was 140 m.

For each excavation site, monthly movements of the clean faces were pre-established and the amount of gas emission during this period was determined experimentally. After that, the movement of the clean faces (L_{0q}) was sequentially selected for a certain period (one or several months), starting from the moment of longwall operation in such a way that $L_{0q} \approx L_r$. Then, for the selected values of L_{0q} , the goaf areas $S_r = L_{0q} \cdot L_r$ were found, which corresponded to gas emission when the clean faces moved to a distance of L_{0q} . We also took into account the period of longwall operation (t) when moving the faces to a distance of L_{0q} , the average gas emission per month and the specific methane emission $\frac{I_v}{S}$ per m^2 of the goaf area when moving the clean faces at a distance of L_{0q} . This data is summarized in Table 1.

When the clean faces move in the initial period of exploitation of the extraction areas at a distance $L_{0q} \approx L_r = L'_D$ (Fig. 1, Table 1), in most cases, the indicators of the amount of gas (I_v), its average amount (\bar{I}_1) emitted in one month, as well as the specific gas emission from units of the goaf area ($\frac{I_v}{S_r}$) were less in comparison with their subsequent values when moving the clean faces at a distance of L_{0q} . This is explained by the fact that intense gas emission from the undermined coal-bearing strata does not begin immediately after the

introduction of the longwalls into exploitation, but occurs after the main roof has settled.

For example, in the conditions of the “Izvestia” mine, the sediment of the main roof occurred when removing clean face from cut workings at a distance of 80÷120 m [3]. At the same time, the peak values of methane emission when moving the clean faces on the L'_D section (Fig. 1, a), located closer to the open-cut working, were

slightly higher than the gas emissions during their subsequent moves by the value of L'_R . The total amount of gas I_v emitted during the passage of the longwall sections L'_R of the extraction pillars located far from the split furnaces, as a rule, exceeded this indicator during the operation of longwalls near the split workings.

Table 1. Information about the operating conditions of longwalls in zones of active rock movement and intense gas emission from undermined sources (L'_R).

Lawa	Face length, L_a , m	Estimated size of the gas emission zone, L'_R , m	Clean face movement, $L_{ov} \approx L'_R$, m	Goaf area, $S_R = L_{ov} \cdot L_a$, m ²	Gas emission, I_v , mil. m ³	Longwall life, t , month.	Average gas emission per month, \bar{I}_1 , mil. m ³	$\frac{I_v}{S_R}$, m ³ /m ²
1	2	3	4	5	6	7	8	9
A.F. Zasyadko mine [11]								
16th eastern	270	547	552*	149040	15,7	5	3,1	105,3
			540	145800	18,9	5	3,8	129,6
			541	146070	18,0	4	4,5	123,2
‘Sukhodolskaya - Vostochnaya’ mine								
12th bis eastern	240	450	448*	107520	14,3	16	0,9	133,0
			431	103440	20,5	20	1,0	198,2
24th eastern	240	474	455*	109200	15,7	7	2,2	143,8
			454	108960	24,8	11	2,3	227,6
			203	48720	16,0	9	1,8	328,4
D.F. Melnikov mine								
1st northern	220	397	408*	89760	2,8	12	0,2	31,2
			409	89980	2,7	9	0,3	30,0
			392	86240	5,3	30	0,2	61,5
			0	0	0,5	8	0,06	5,7
Newspaper "Izvestia" mine [12]								
1st western	185	140	143*	26455	0,9	4	0,2	34,0
	157		139	25715	1,3	5	0,3	50,6
	115		132	20724	1,7	4	0,4	62,4
	111		131	15065	1,8	6	0,3	119,5
	74		156	17316	0,4	4	0,1	23,1
1st bis western	84	140	113*	8362	0,2	4	0,05	23,9
	94		152	12768	0,5	3	0,2	39,2
	74		115	10810	0,4	8	0,05	37,0
2nd western	200	140	129*	25800	0,9	2	0,5	34,9
			107	21400	2,0	1	2,0	93,5
			143	28600	3,1	2	1,6	108,4
			86	17200	1,4	1	1,4	81,4
			133	26600	1,6	1	1,6	60,2
			139	27800	1,8	1	1,8	64,7
			127	25400	1,4	1	1,4	55,1
2nd bis western	185	140	123*	22755	1,4	4	0,4	61,5
			156	28860	3,1	10	0,3	107,4
3th western	215	140	141*	30315	1,6	2	0,8	52,8
			91	19565	1,4	1	1,4	71,6
			112	24080	1,6	1	1,6	64,4
			131	28165	1,6	1	1,6	56,8
			153	32895	2,9	2	1,5	80,2
			132	28380	1,4	1	1,4	49,3
4th western	210	140	194*	40740	0,7	2	0,4	17,2
			112	23520	3,3	2	1,7	140,3
			150	31500	2,2	2	1,1	69,8
			163	34230	2,0	2	1,0	58,4
			140	29400	1,5	1	1,5	51,0
			128	26880	2,1	1	2,1	78,4
			154	32340	1,5	1	1,5	46,4
			153	32130	1,2	1	1,2	37,3

* Note - removal of clean faces from cut workings at a distance of L_{ov} in the period before the settlement of the main roof.

Such a ratio of indicators for gas emission in the areas L'_D and L_R indicates a different course of the processes of rock displacement and gas emission when clean faces are located in different parts of the extraction pillars.

We examined in more detail the cases when mining pillars in the areas L'_D and L_R , when the indicators I_v , \bar{I}_1 and $\frac{I_v}{S_R}$ were quantitatively close to each other.

The D.F. Melnikov mine, during the operation of the 1st northern longwall of the ℓ_6 seam, the section of the pillar $L'_D=L_{ov}=408\text{m}$ near the split furnace was worked out for twelve months, and the subsequent section $L_R=409\text{m}$ after the settlement of the main roof - nine months (Table 1). During these periods, approximately the same amount of methane was emitted, respectively 2,8 and 2,7 mil m^3 . In this case, with approximately the same areas of undermined stratum (89760 and 89980 m^2), practically the same amount of gas was emitted over different periods of time when a part of the extraction pillar was worked out on segments L'_D and L_R . This indicates that the amount of methane emitted from the zone of active movement of underworked rocks depends on the time of degassing of the coal-bearing strata. The influence of the time factor on all indicators of gas emission (I_v , \bar{I}_1 и $\frac{I_v}{S_R}$) is confirmed by the experimental results obtained during the refinement of the extraction pillar of the 1st northern longwall with a length of 392 m for thirty months. During this period, 5,3 mil m^3 of gas was released, because of which the $\frac{I_v}{S_R}$ indicator also increased from 30,0 to 61,5 m^3/m^2 of methane (Table 1). The amount of methane emitted per month remained practically unchanged. After stopping the clean face ($S_R=0$), 0,5 mil m^3 of methane was emitted over eight months. The $\frac{I_v}{S_R}$ indicator must be determined according to the scheme (Fig. 1) from the $\frac{I_v}{L_R \cdot L_n} = \frac{0,5 \cdot 10^{-6}}{397 \cdot 220} = 5,7 \text{m}^3/\text{m}^2$ ratio. After stopping the clean face, its movement is absent, which caused a decrease in the specific gas emission per unit of goaf area from 61,5 to 5,7 m^3/m^2 . In this case, if the amount of emitted gas is related to the area corresponding to the monthly movement of the clean face ($S_v=0$), then the $\frac{I_v}{S_v}$ indicator tends to infinity and it has no practical value. A similar mistake is made by the methodology of regulatory framework when determining the hazardousness of mines, when the amount of emitted gas is attributed to coal production per month. In its absence, the gas content of the mine seemingly tends to infinity. The absolute gas emission when the clean face is stopped depends on the the location of sources in the undermined coal-bearing strata, which are no longer associated with coal mining [13, 14].

On the site of the 8th western longwall of the ℓ_2^B seam of the "Izvestia" mine part of the extraction column $L'_D=L_{ov}=151\text{m}$ was worked out for three months, and the next - $L_R=131\text{m}$ for one month. During the exploitation of the mining area, 1,4 and 1,2 mil m^3 of methane was emitted in the corresponding periods. Indicators \bar{I}_1 and $\frac{I_v}{S_R}$ in the corresponding periods were equal to 0,5 and 1,2 million m^3 and 43,1 and 42,6 m^3/m^2 . In this case, with the

same $\frac{I_v}{S_R}$ indicator, the average amount of gas emitted in one month significantly differed. Such a ratio of parameters in this case can be explained by the incomplete development of rock displacement processes at the initial stage of seam development at $L_{ov}=151\text{m}$. After stopping the longwall, 0,5 mil m^3 of gas was emitted in two months. For this case, $\frac{I_v}{S_R} = \frac{0,5 \cdot 10^{-6}}{140 \cdot 215} = 16,6 \text{m}^3/\text{m}^2$. This indicates a decrease in the specific gas emission per unit of goaf area in the absence of coal mining for a certain period.

After stopping the 9th western longwall, 0,3 million m^3 of methane was emitted in four months, and the specific gas emission during this period was 8,6 m^3/m^2 . This confirms the validity of the fact that when calculating the specific gas emission per unit of goaf area, the amount of emitted gas I_v must be related to the S_R area that determines the active zone of rock displacement.

If the rate of clean face movement (v_{ov}) is approximately equal to the calculated value of the size of the zone of active displacement of rocks (L_R) (Fig. 1), then it can be assumed that the values of specific methane emission per unit goaf area ($\frac{I_v}{S_v}$ and $\frac{I_v}{S_R}$) will slightly differ from each other. The closeness of the $\frac{I_v}{S_v}$ and $\frac{I_v}{S_R}$ parameters in this case also indirectly indicates the reliability of determining L_R by a calculation method.

Of the considered excavation areas, working out different seams, only in the conditions of the "Izvestia" mine for individual mining areas, in some cases, the speed of clean faces (v_{ov}) was close to the indicator $L_R=140\text{m}$. The L_R determination accuracy is about 20%. In this case, the L_R value is $140 \div 28\text{m}$ and should be in the range $112 \div 168\text{m}$.

For six excavation areas, where there were cases of approximate equality $L_R \approx v_{ov}$, we made samples according to the rate of clean faces movement in the indicated interval ($112 \div 168\text{m}$) and the corresponding amount of released gas ($I_{v_{ov}}$) and area ($S_{v_{ov}}$ and S_R) of worked-out spaces (Table 2). The graphs of the experimentally determined $\frac{I_{v_{ov}}}{S_R}$ and $\frac{I_{v_{ov}}}{S_{v_{ov}}}$ values practically coincided with the bisector (1) of the coordinate grid (Fig. 2).

This is evidenced by the closeness of the regression coefficient to unity of the averaging straight line (2) and the high value of the correlation coefficient ($r=0,97$). The established facts indicate that in order to reliably determine the specific gas emission from a unit area of the goaf, it is necessary to take into account the zones of active movement of underworked rocks.

4 Conclusions

Conducted theoretical and experimental studies of gas emission from the undermined coal-bearing stratum by workings made it possible to draw the following conclusions:

- the developed theoretical scheme for the joint formation of zones of the undermined coal-bearing stratum active movement and intense gas emission made it possible, on the basis of experimental data, to establish

a part of the goaf area, which determines the amount of methane emitted from the sources;

Table 2. Information on gas emission at the rates of clean faces (v_{ov}) is close to the size of the L_r zone of active movement of rocks in the conditions of the "Izvestia" mine.

Lawa	Face length, L_{r1} , m	Speed of face movement, v_{ov} , m/month	Average methane amount in a seam, $m^3/t.m.r.$	Amount of emitted gas, I_v , thousand. m^3	Goaf area, m^2		Gas emitted from $1m^2$ of goaf, m^3/m^2		Observation date
					$S_{v_{ov}}$	S_r	$\frac{I_v}{S_{v_{ov}}}$	$\frac{I_v}{S_r}$	
1	2	3	4	5	6	7	8	9	10
2nd western	200	133	20,4	1589,2	26600	28000	59,7	56,8	III 1979
		139	18,6	1766,9	27800	28000	63,6	63,1	IV 1979
		127	15,8	1415,1	25400	28000	55,7	50,5	V 1979
		132	12,3	933,1	26400	28000	35,3	33,3	VI 1979
3th western	215	112	26,5	1607,0	24080	30100	66,7	53,4	XI 1979
		131	26,5	1584,7	28165	30100	56,3	52,6	XII 1979
		132	25,8	1391,0	28380	30100	49,0	46,2	IV 1980
		144	24,8	866,0	30960	30100	28,0	29,4	V 1980
		130	22,4	738,7	27950	30100	26,4	24,5	VI 1980
		134	20,2	915,1	28810	30100	31,8	30,4	VII 1980
		116	15,8	709,8	24940	30100	28,5	23,6	VIII 1980
4th western	210	123	28,1	738,7	25830	29400	28,6	25,1	XI 1980
		140	29,3	1481,8	29400	29400	50,4	50,4	VI 1981
		128	28,9	2129,3	26880	29400	79,2	72,4	VII 1981
		154	28,4	1473,1	32340	29400	45,6	50,1	VIII 1981
		153	27,1	1213,9	32130	29400	37,8	41,3	IX 1981
		128	24,4	589,2	26880	29400	21,9	20,0	X 1981
5th western	216	147	31,3	1330,3	31752	30240	41,9	44,0	VIII 1982
		149	31,0	334,8	32184	30240	10,4	7,5	IX 1982
7th western	230	118	34,8	1767,7	27140	32200	65,1	54,9	VIII 1983
		116	34,3	1412,6	26680	32200	52,9	43,9	IX 1983
8th western	215	131	35,0	1160,6	28165	30100	41,2	38,6	VIII 1984
		130	34,7	1032,4	27950	30100	37,0	34,3	IX 1984

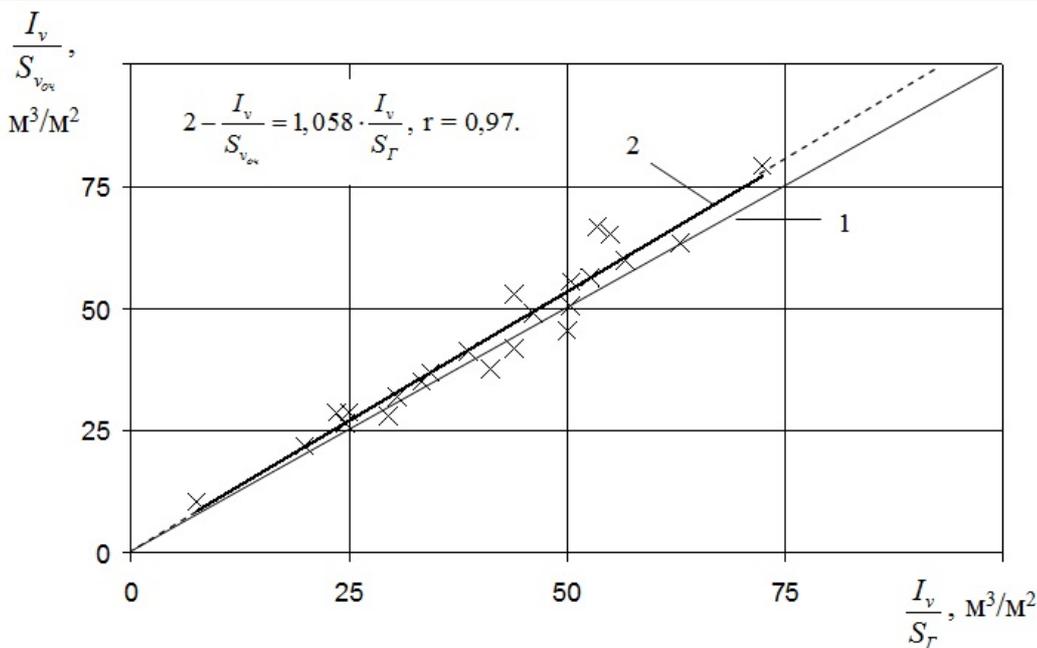


Fig. 2. Graph of the ratio of specific gas emissions per unit goaf, determined, respectively, by the monthly movement of the clean faces ($\frac{I_v}{S_{v_{ov}}}$) and the zone of active rock movement ($\frac{I_v}{S_r}$) during mining of the ℓ_2 seam by the "Izvestia" mine: 1 – grid bisector; 2 – averaging straight line; x - experimental data; r – correlation coefficient.

- in the conditions of four mines at 15 excavation areas, the distinctive features of specific gas emission (per unit of goaf area) have been established, which are determined by the development of cleaning work and the speed of moving the clean face;

- the main factors that determine the specific gas emission are the area of the goaf, which affects the active stages of rock movement and the time period required for the formation of this goaf area;

- the obtained scientific conclusions make it possible to more effectively use the results of establishing the category of gas hazards in mines in terms of relative gas emission per ton of coal production in terms of improving the forecast of gas emission from the undermined coal-bearing stratum.

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