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Improvement of intensive in-seam gas drainage technology at Kirova mine in Kuznetsk coal basin.

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Abstract The Kirova mine with its 3 Mt production in 2019 is one of the coal mining leaders in Russia. The available mining equipment has the potential to significantly increase the output, however, gas is a limiting factor on the way to this. The customary approaches to coal seam degassing have already been petered out. The miners and mine science are facing a challenge to validate and test an alternative technology to ensure effective in-seam gas drainage prior to vigorous mining. This article gives an account of the improvement track record of the in-seam gas drainage technology used to pre-treat coal seam for intensive and safe extraction. This technology suggests, at the first stage, hydraulic slotting of the target coal seam through wells drilled from the surface (SHS), then hydraulic fracturing of the coal seam through the boreholes drilled from underground development headings, followed by methane extraction from the created high-permeability coal-gas reservoir through standard in-seam gas drainage underground wells. Presented in this paper are the results of field testing of improved SHS technique. Findings are presented on the effective parameters of the hydraulic fracturing technology. Methodological recommendations are offered for selecting viable in-seam gas drainage technology.

Key words intensive coal mining, integrated in-seam gas drainage, hydraulic slotting through surface wells, hydraulic fracturing from underground boreholes, in-situ tests, improvement of technology.

Introduction. SUEK-Kuzbass JSC is one of the leaders in the coal industry in Russia. In 2018, the company set a world record for monthly production from one longwall face - 1.7 million tons. The Kirova mine with its 3 Mt production in 2019 is one of the key assets of the company. It is currently a single LW mine operating in 2.2 m thick Boldyrevsky Seam. The gas content in this seam averages 16 m³/t. The company management aim at further increase of production while maintaining the conditions for safe mining. The key limiting factor for further production intensification is gas factor, which sets the task of ensuring effective and early in-seam gas drainage.

Dozens of gas drainage methods and technologies are known internationally (Gas 2013; Hu at al. 2018; Karacan 2011; Kurlenya at al. 2015; Slastunov at al. 2015; Slastunov at al. 2016; Szott at al. 2018; Wu 2020; Yan 2015; Zhang at al. 2017; Zhao at al. 2014). The most effectively used methods of gas drainage are those where methane is drained from the stress-relieved coal seam. The effectiveness of these methods is over 80%, which from a cause-and-effect view is due to extraction of liberated gas. Whatever issues arising thereat do not represent conceptual scientific problems and their solution depends on competent engineering support.

The situation is different with coal seams still exposed to strata pressure, where gas drainage efficiency is significantly lower. Worldwide, a common approach to achieve high production from a face while assuring gas related safety of the mining operations is to apply the in-seam gas drainage technology operation schedules and parameters thereof are defined with due account for the properties and behaviour of the target coal seam, time allowance for its drainage and the size of "gas barrier". Yet at the depth of 400 meters and below, the effectiveness of the

in-seam gas drainage technology at SUEK-Kuzbass JSC mines is only 10÷15%. Therefore, gas factor is the obvious bottleneck in the face output and impedes more intensive mining in high-gas coal seams, hence, the challenge is to develop new effective coalbed gas drainage technologies.

In recent years experimental and implementation work at Kirova mine to substantiate effective technological gas drainage systems have been and are being carried out, at the initiative of the authors and with support of the company's management.

In this paper, we consider the experience of developing new for Russia integrated schemes for the stepwise degassing of development areas using the example of Kirova mine.

2. Methodology

2.1 Improving the in-seam gas drainage technology prior to intense underground mining.

Layout of mine workings in Boldyrevsky Seam is provided in Figure 1. The extraction blocks 2458, 2459, 2460, and 2462 were mined out in recent years; extraction blocks 2463 and 2464 have been in operation in 2019–2020. In blocks 2458, 2459, 2460 and 2462, standard technique, i.e. in-seam gas drainage from development headings, was applied as a baseline scheme since it has been well proven in the mines of Russia. The parameters of this standard technology are set out in the current guideline document – Gas Drainage Instructions (2013).

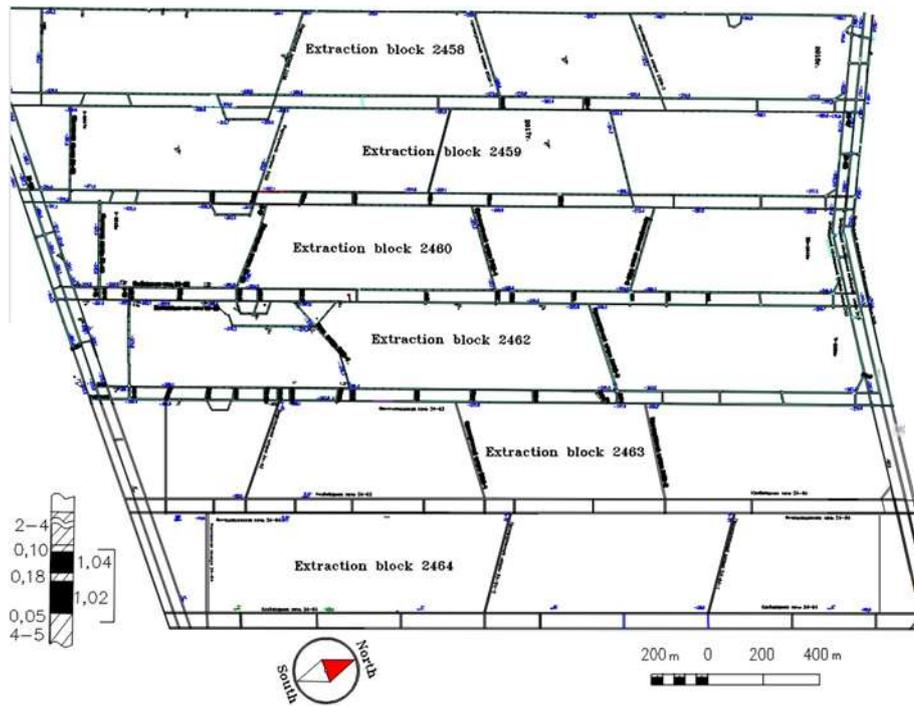


Fig. 1 Mine workings layout in Boldyrevsky Seam

In the block 2458 with intense coal production this baseline gas drainage scheme was supplemented by seam hydraulic fracturing technology. In this production block hydraulic fracturing was performed from 12 underground wells (UgHF technology). The effectiveness of this auxiliary technological scheme was evaluated during coal-face operations. Following factors were taken into account: gas emission rate, resultant quantity of methane captured from the in-seam gas drainage wells, reduced amount of gas in production workings, reduced longwall downtime due to gas factor, and increased output from the production face.

An important aspect of the work carried out on this technology was the search for effective parameters of UgHF technology, primarily the effective length of UgHF wells. So, the plan of exploratory experimental studies on in-seam gas drainage in the extraction block 2460, Boldyrevsky Seam, includes the hydraulic fracturing operations with effective lengths of hydraulic fracturing wells varying at 5, 35, 70 and 110 meters (Table 1).

Table 1 Technical specifications for extraction block 2460 in Boldyrevsky seam.

	Parameter	Unit	Hydrofracture location - vent. raise 2460
1.	Effective length of hydrofracture boreholes	m	110 (for bh.9-13) 70 (for bh.14-18) 35 (for bh.19-23) 5 (for bh.24-28)
2.	Drill bit dia	mm	93-132
3.	Casing pipe dia	mm	70
4.	Pump pressure at seam hydrofracture	MPa	12÷30
5.	Fluid pumping rate	l/s	до 10
6.	Seam hydro-conditioning radius	m	25
7.	Quantity of fluid for hydrofracture	m ³	5...50
8.	Min time of seam treatment considering varied pumping rate	min	80

As shown in Table 1, four zones were laid out in the extraction block 2460 where in-seam gas drainage was done by underground hydraulic fracturing through wells with various effective lengths (i.e. lengths of the open/uncased part of the borehole). In the first group of wells No. 60/9-60/13 (zone 1 in Fig. 2), the effective length of the hydraulic fracturing wells was 110 m; in the second group of wells No. 60/14-60/18 (zone 2 in Fig. 2) this parameter was 70 m, in the third group of wells No. 60/19-60/23 (zone 3 in Fig. 2) it was 35 meters, and in the fourth group of wells No. 60/24-60/28 (zone 4 in Fig. 2) it was 5 meters respectively.

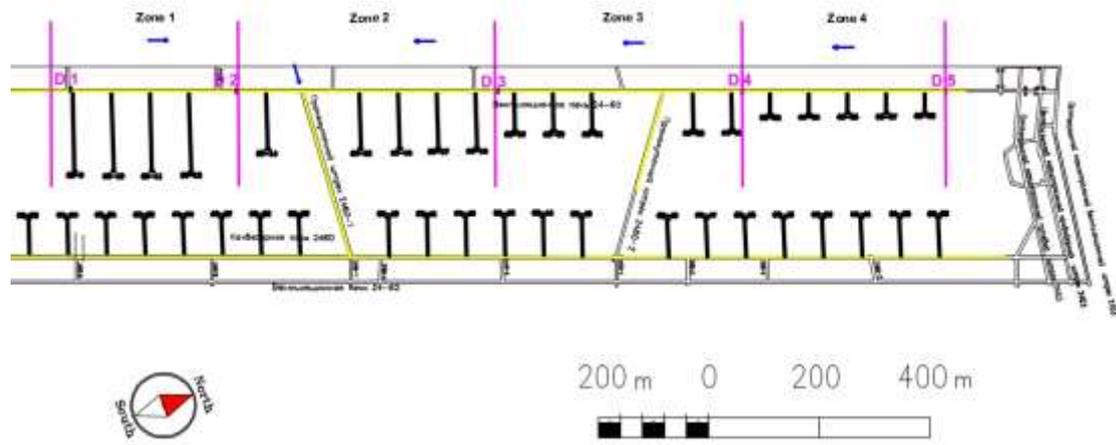


Fig. 2 Location of UHF wells of various length at extraction block 2460

The length of the uncased part increases only when hydraulic fracturing (hydraulic slotting/hydrojacking) mode is achieved, i.e. when pressure is stabilized at a certain level while working fluid is being injected into the seam.

The design amount of working fluid for injection is 50m^3 . The injection volume allowable, for various technological reasons (mainly liquid breakout into the mine working, water drip from under the roof bolts), can vary between 5 and 50m^3 .

Concurrently, the technology of auto-pneumatic impact on a coal seam was initially tested in extraction block 2455 (Slastunov and Yutyaev 2017). During auto-pneumatic impact (API) on a coal seam, the sliding valve in gas drainage well was shut off from time to time. When the valve is shut, the pressure in the well rises to the value which hypothetically levels off with that in the seam, hence increases the coal seam permeability in the near-wellbore zone.

3. Results

3.1 Results of combining in-seam gas drainage baseline scheme with seam hydrofracture technology

The very first results of underground hydrofracture technique application in intensive coal extraction block 2458 demonstrated 3 to 4-fold long-term (7-8 months prior to face breakthrough) increase in methane yield attributed to the in-

seam gas drainage holes drilled in the fracture target areas. The average value of the relative gas content at the LW face was reduced by 30%, process shutdowns due to “gas barrier” decreased by 42% and coal production was increased by 21% on average. Subsequently, the technology of underground hydraulic fracturing was successfully used in extraction blocks 2459, 2460 and 2462.

3.2 The results of the underground hydrofracture parameter optimization

One of the key parameters of the underground hydrofracture technique is the effective length of UgHF hole. The time related changes in the amount of methane removed from wells in 2460 ventilation raise with different effective lengths is shown in Figure 3.

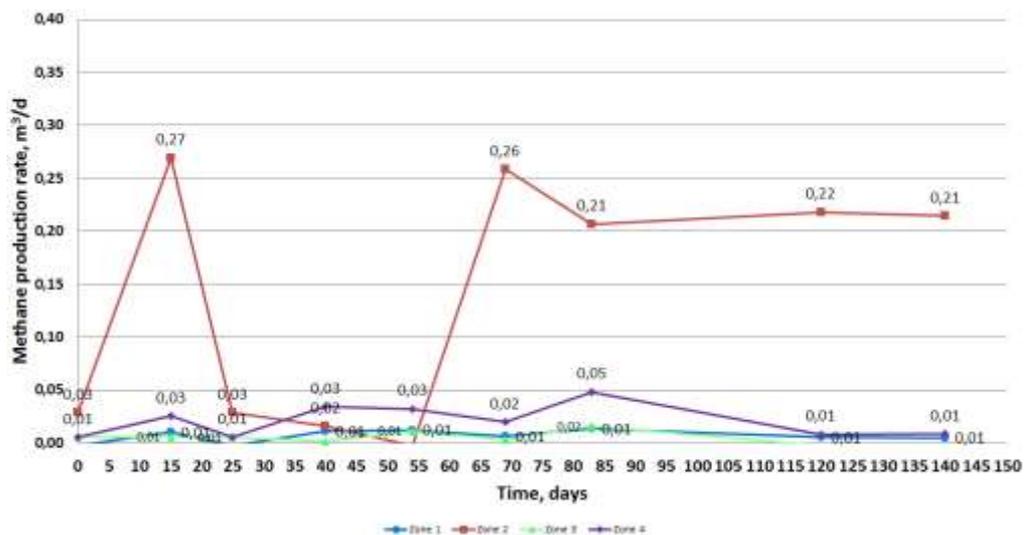


Fig. 3 Time related changing flow rate of methane from various effective length boreholes observed in ventilation raise 2460

The methane yield analysis shows that the integrated in-seam gas drainage process is most effective when the length of the wells is 70 meters (red curve in Figure 3).

At the present stage of research, our recommendation is the range of effective UgHF well lengths between 35 and 70 meters.

3.3 Results of combining in-seam gas drainage baseline scheme with the technology of pneumatic impact on a coal seam

Technological try out of seam pneumatic impact in block 2455 provided following data. In eight trial gas drainage wells, after the valve was shut off, the pressure rose to 20÷25 atmospheres, thereafter the methane flow rate increased from 3÷8 l/min to 22÷27 l/min, which significantly improved the effectiveness of in-seam gas drainage.

The pneumatic impact technology probed is recommended as a method to stimulate gas release from slow functioning typical underground wells of in-seam gas drainage.

3.4 Recommended Practice for selecting the most viable method of in-seam gas drainage for high production mining panels

Based on the results obtained, recommendations were drafted on the selection of in-seam gas drainage methods for high production mining panels, including two phases.

At the first stage of drafting recommendations, the required performance of in-seam gas drainage is determined where the predicted gas yield, the time available for in-seam gas drainage and the scheduled face output are taken into account (Fig. 4). At the second stage (Table 2), the specific integrated in-seam gas drainage technology is selected (eg: the conditions of Kirova mine with its extraction blocks 2458, 2459, 2460 and 2462).

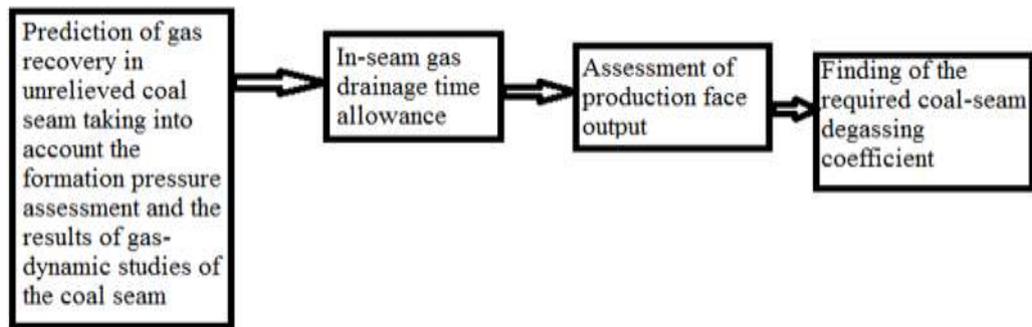


Fig. 4 Methodological approach to defining the required effectiveness of in-seam gas drainage (Phase 1)

Table 2 Recommended Practice for selecting the most viable method of in-seam gas drainage for high production mining panels (Phase 2).

Factors to be taken into account and technological operations	In-situ conditions
Drilling-in method	Boreholes drilled from development headings
Baseline scheme	In-seam gas drainage from underground workings
Support technology	Hydraulic fracturing of coal seam (UgHF)
Recommended in-seam gas drainage enhancement technique	Auto-pneumatic impact (API)

4. Discussion and further development of the integrated in-seam gas drainage technology

4.1 Justification of experimental work on testing new integrated technology for gas drainage conditioning of the coal seam

The results obtained on enhancing the effectiveness of in-seam gas drainage in hydraulically fractured zones in longwalls 2455, 2458, 2459, 2460 and 2462 served as the basis for launching a larger-scale program of gas drainage trial operations in extraction block 2463 in 2019. It is here that it became possible to implement the already proven technology of early in-seam gas drainage through wells drilled from the surface (SHS) in combination with hydrofracture of the Boldyrevsky coal seam (UgHF).

The purpose of such integration is to achieve even higher performance of gas drainage operations hence ensure intense recovery of coal seams. The main idea of this experimental technology is to improve the reservoir properties (porosity and permeability) of a coal seam by creating a network of technogenic fractures by injecting water under high pressure.

It is assumed that by way of hydraulic slotting from surface wells (SHS), in-seam fractures shall open up and integrate into a common hydraulic system, which will result in many-fold increase of the coal seam permeability in the well coverage radius. Associated with this would be replacement of part of methane in the coal sorption volume by working fluid, forcing methane off and blocking it outside the mining range of influence.

In this regard, following tasks were set during the experimental work:

- ensure radius of SHS well influence of 120-150 m and more;
- use physical properties of the coal seam (swelling, shrinkage, dissolution, creeping, plasticity) to achieve high conductivity of the fissures expanded by hydrofracture;
- use shrinkage, associated with stress relief, to achieve enhanced permeability, as well as substitution of part of methane in the coal sorption volume for subsequent profound gas drainage from the coal-bearing stratum.

Many-fold increase of permeability and gas release potential of coal seams, achieved by their hydraulic slotting is due to their changed stress-strain condition and physical properties caused by injection of working fluid in regimes exceeding natural intake capacity of the seams. Such injection results in widening of natural fissures and/or development of artificial fissures, all of them making up an integrated hydraulic system oriented towards the well, which becomes a canal for subsequent extraction of liquid and gas onto the surface.

Early gas drainage through surface wells is normally effective when methane extraction period is more than 3 years (Interim 1991; Nozhkin 1979). It is possible to reduce this time to less than 3 years, draining hydraulic slotting zone by discharge of water into the mine workings.

The coal seam gas drainage work procedure whereby hydraulic slotting is performed using surface boreholes most commonly includes three main phases: I - hydrodynamic impact; II - well completion (removal of working fluid from the seam using pumps or in-seam wells, gas extraction); III - gas extraction from the worked out space after wells have been negotiated by the longwall operations.

Surface wells are located at a distance of at least 300m from the existing workings in the direction of the main system of natural fissures in coal seams and not more than radius of faults influence with amplitudes exceeding the thickness of the target seam.

At the stage of experimental search at Kirova mine, process water shall be used as working fluid.

To make a hydraulic slotting, a well is drilled to a target depth of 600-620 m, working (ultimate) core bit diameter being 159 mm; annular space shall be overlapped and thoroughly grouted to the entire depth including overlying worked out formations. Wells are drilled from the surface, 0.5 m well depth span below the top of the seam is cased and coal seam undergoes hydraulic slotting.

4.2 Experimental site

The first experimental area within the extraction block 2463 at Kirova mine covers six seam hydraulic slotting boreholes (SHS) №№ 1-6 drilled from the

surface. Part of the program is to test a simplified SHS procedure whereby the target coal seam is not screened by a perforated pipe. After the well has been cased, the entire complex of equipment is moved down the hole and seam hydraulic slotting is performed by high pressure pumps with a total flow rate of up to 100 l/s.

Pressure and flow rate are constantly monitored by gauges capable to record and visualize data from a safe distance. The volume of water required for injection into one well is at least 500 to 1000 m³.

After hydraulic slotting is completed, the wells are left inactive for up to 8-12 months or until the approach of mining operations. At the experimental phase, it is assumed that withdrawal of working fluid will be in the form of SHS well spouting with associated gas removal, however, at a later phase, water shall be discharged into underground working.

As soon as longwall operations approach SHS well influence zone, working fluid shall be discharged into ventilation raise 2463. For this purpose, a cluster of 3 to 5 directional wells shall be drilled towards SHS well zone with water inflow control therein. If needed, the number of wells can be increased.

At the present phase of work (extraction block 2463), the plan is to apply the integrated gas drainage option based on SHS wells, whereby water shall be discharged into mine workings, with subsequent effective functioning of standard underground in-seam wells in the impact zones. The time lag between drilling advance in-seam gas drainage wells in SHS zone and those in the control area shall not exceed 2 months. The completion of both groups of wells shall be at approximately the same time, with a time lapse of no more than 2-3 weeks.

In the future, we intend to explore if it is possible to alter the grid of both SHS wells and underground gas drainage boreholes, and if it is viable to reduce the time needed for in-seam gas drainage in SHS zones.

4.3 The selection of feasible in-seam gas drainage technology for extraction block 2463

Selection of viable in-seam gas drainage technology for individual geological and mining conditions is one of the most challenging issues. The key point here is the magnitude of the “gas barrier”, hence, adequate in-seam gas drainage effectiveness shall be defined.

The nomogram on the required methane extraction as a result of in-seam gas drainage in the Boldyrevsky coal seam is shown in Figure 5 and allows to make an adequate decision about the in-seam gas drainage option depending on the required output of the production face.

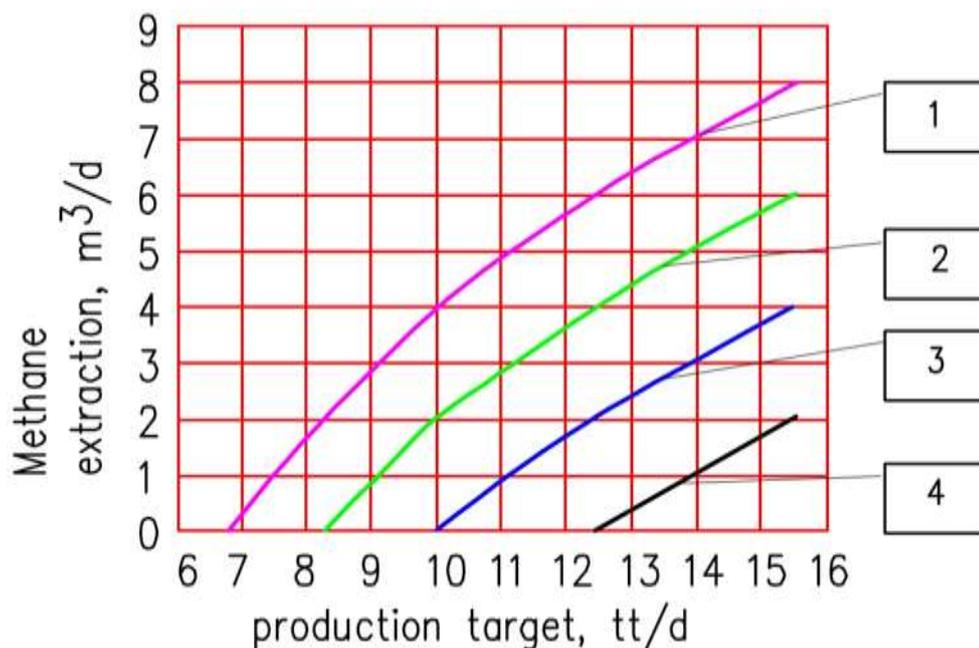


Fig. 5 Methane extraction required to enhance production output in dependence on baseline gas content of the coal seam 1) 18 m³/t 2) 16m³/t 3) 14 m³/t 4) 12 m³/t

With actual gas content at 16 m³/t in the extraction block 24-63 of the Boldyrevsky seam and estimated production target of 14,000.00 tpd, the required volume of methane removal in the process of in-seam gas drainage is 5 m³/t. Based on the available data on the actual efficiency of in-seam gas drainage, the updated technology for early degassing of coal seams through surface wells (SHS) was

advised; the proven efficiency thereof is $0.3 \div 0.5$ and it can provide methane extraction at the level of $5 \text{ m}^3/\text{t}$. The technology of in-seam gas drainage from underground development headings in SHF zones with an extended grid of in-seam wells was recommended as a support measure. The parameters of in-seam gas drainage should also take into account the availability and location of tectonically stressed and tectonically relieved zones that could be identified by geodynamic zoning (Batugina and Petukhov 1990; Yutyaev 2019). The latter aspect is the subject of additional research.

Conclusions

1. Analysis made for a number of production blocks of the Kirova mine on restrictions imposed on face output by gas factor shows that in-seam gas drainage with rated capacity of up to 0.3 (30%) is required for majority of production faces. Under favorable conditions this can be achieved by means of advance gas drainage operations carried out from development headings (in particular, the technological version of integrated degassing using underground hydraulic fracturing, shown in Table 2). This was confirmed by successful practices in the extraction blocks 2458, 2459 and 2460 at Kirova mine. (Slastunov at al. 2018; Slastunov at al. 2019).

2. Mining is currently carried out at extraction block 2462, where in-seam gas drainage facilities include UgHF and advance in-seam gas drainage wells. Gas is drained from extraction block 2463, where the in-seam gas drainage complex also includes hydraulic slotting through surface wells. Studies on the relative and absolute gas content in production faces, downtime of mining equipment due to gas factor and mining intensity will make it possible to provide adequate assessment of how viable the tested in-seam gas drainage technologies are and estimate their feasibility and scope of their application.

In conclusion, it should be noted that Kirova mine with their large-scale gas drainage project is the first ever mining company to pioneer such practice in Russia

and this practice is definitely of great interest for specialists in the field of assuring methane safety for high performing underground coal mines.

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Figures

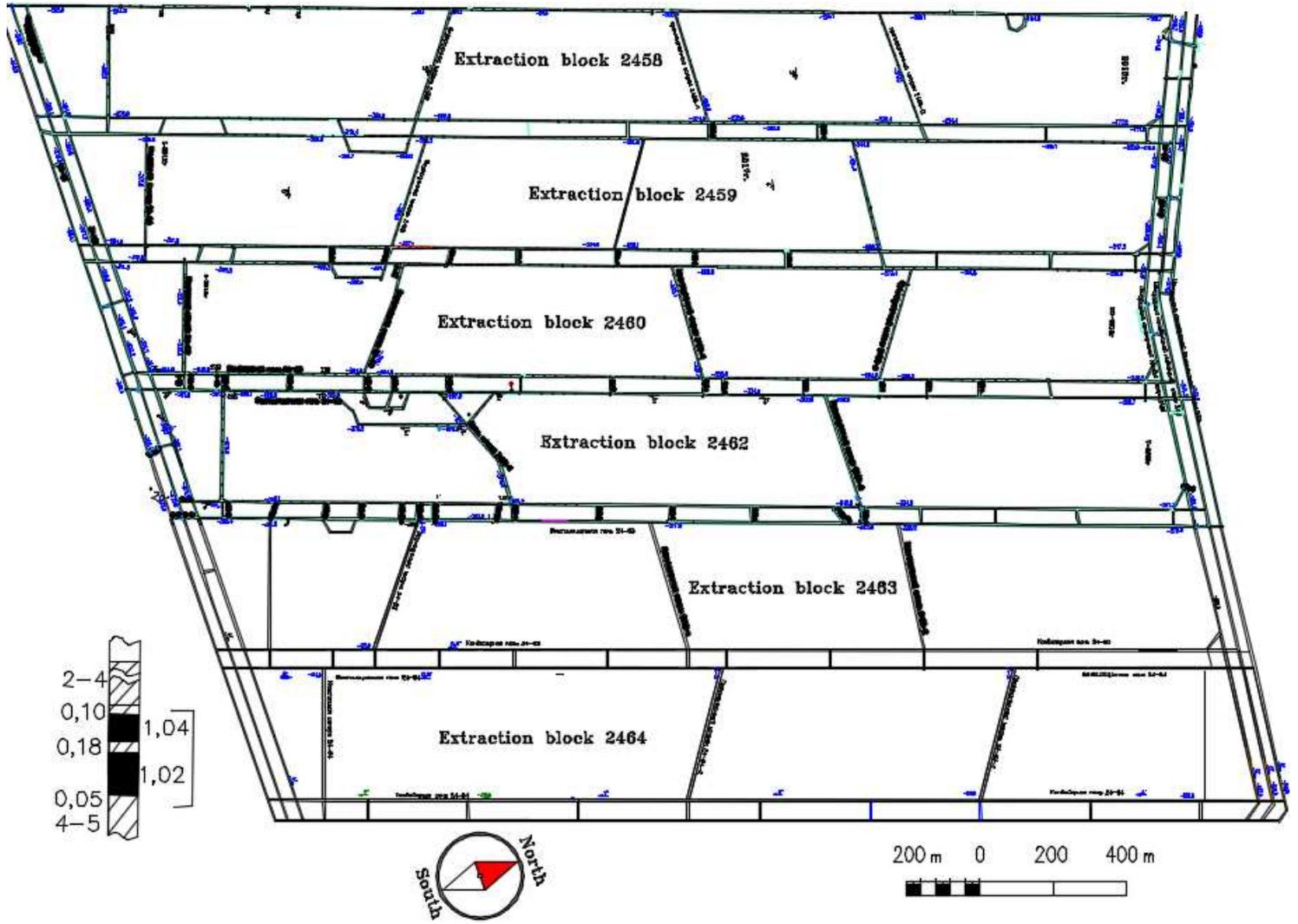


Figure 1

Mine workings layout in Boldyrevsky Seam

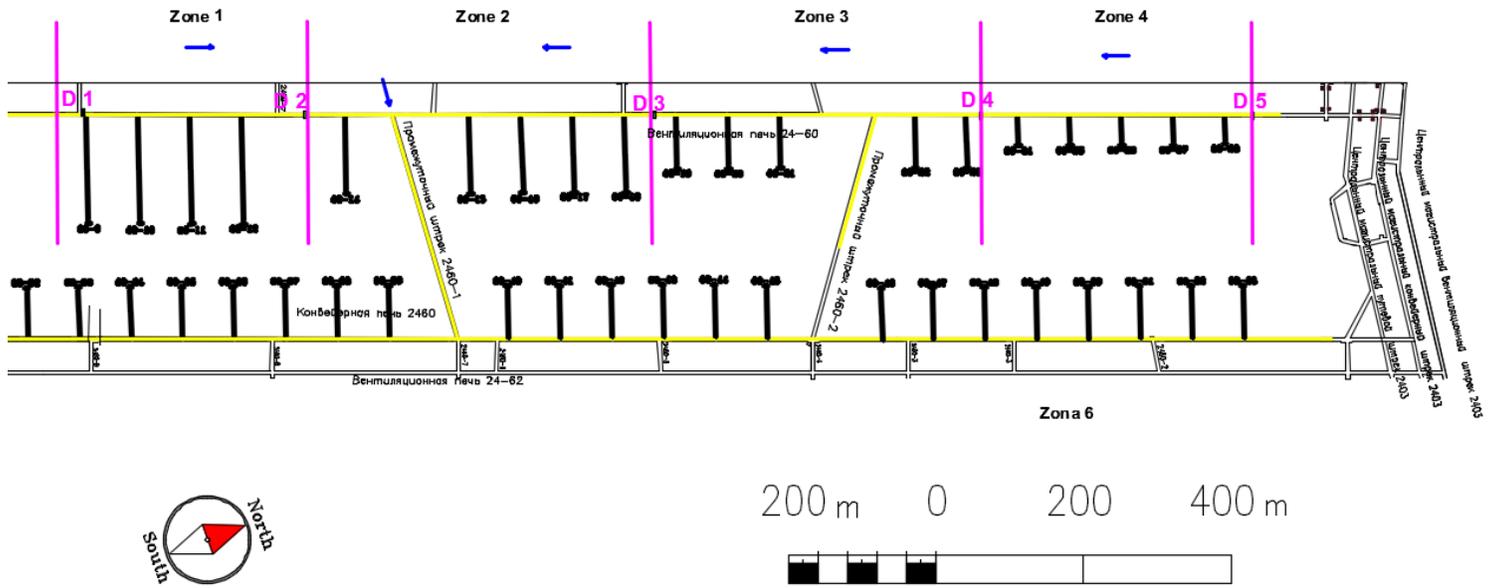


Figure 2

Location of UgHF wells of various length at extraction block 2460

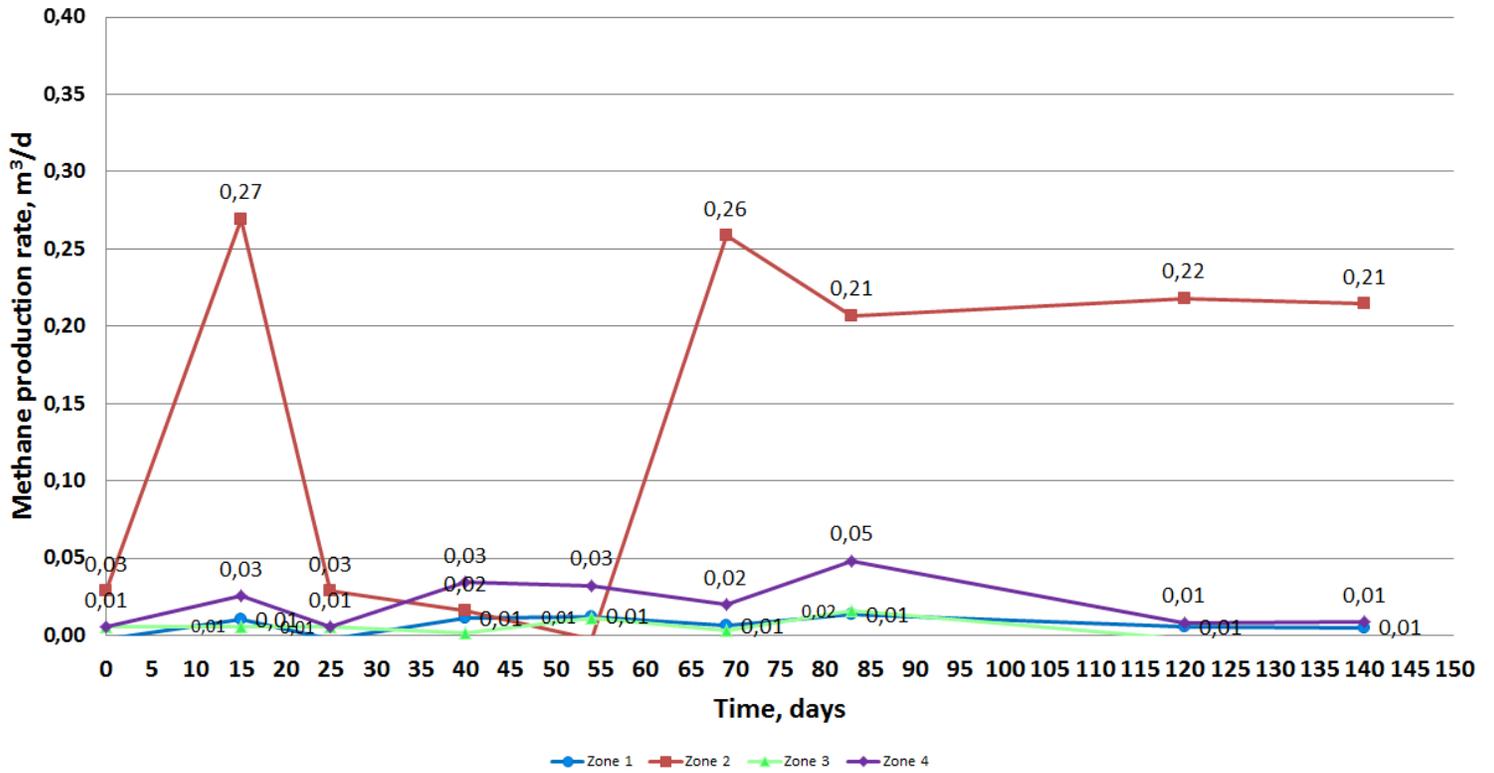


Figure 3

Time related changing flow rate of methane from various effective length boreholes observed in ventilation raise 2460

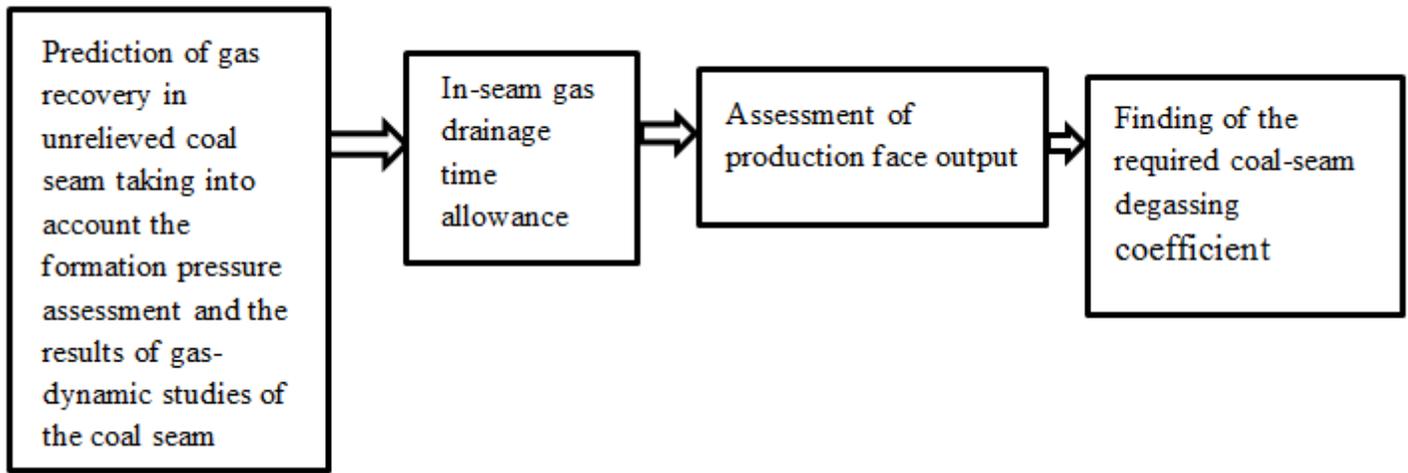


Figure 4

Methodological approach to defining the required effectiveness of in-seam gas drainage (Phase 1)

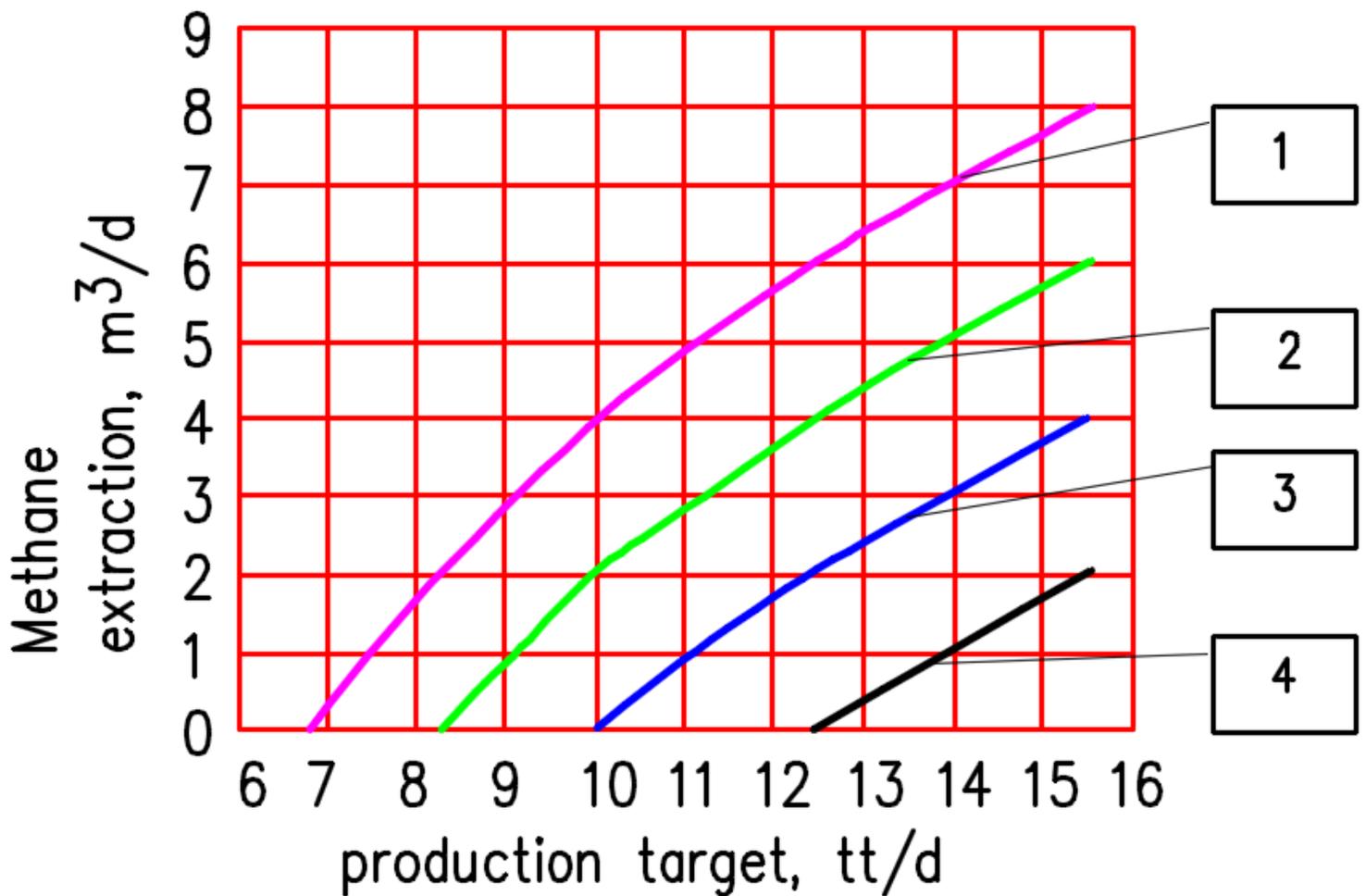


Figure 5

Methane extraction required to enhance production output in dependence on baseline gas content of the coal seam 1) 18 m³/t 2) 16 m³/t 3) 14 m³/t 4) 12 m³/t