МИСИС
УНИВЕРСИТЕТ

eISSN 2500-0632

Mining Science and Technology

Горные науки и технологии

Vol. Том 8 № 2
2023

https://mst.misis.ru/

MINING SCIENCE AND TECHNOLOGY (Russia)

Горные науки и технологии

SCIENTIFIC AND PRACTICAL E-JOURNAL

eISSN 2500-0632

2023

Vol. 8, no. 2

https://mst.misis.ru/

Activities of the *Mining Science and Technology (Russia) (Gornye nauki i tekhnologii)* international journal are aimed at developing international scientific and professional cooperation in the field of mining.

The journal target audience comprises researchers, specialists in the field of mining, representatives of academic and professional communities.

The journal publishes original papers describing research findings, experience in the implementation of projects in mining industry, review publications.

The journal seeks to develop interdisciplinary areas that contribute to progress in mining, for example, technological and environmental safety, project organization and management in mining industry, development of territories, legal aspects of natural resource use, and other areas studied by researchers and practitioners. The journal always welcomes new developments. Papers are accepted in English or Russian.

QUARTERLY

FOUNDED in 2016

REGISTRATION

The journal science and applied research journal is registered by the Federal Service for Communication, IT and Mass Communication Control on August 10, 2015.
Registration Certificate E-No. ФС77-62652

INDEXATION

Scopus, CAS, EBSCO, DOAJ, РИНЦ, ВИНИТИ РАН, Dimensions, BASE, J-Gate, Jisc Library Hub Discover.

FOUNDER AND PUBLISHER

MISIS UNIVERSITY

The National University of Science and Technology MISiS (NUST MISiS)

CONTACT

4 Leninsky Prospect, Moscow 119049, Russian Federation
Phone: +7 (495) 955-00-77
e-mail: send@misis.ru

ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ

Mining Science and Technology (Russia)

ЭЛЕКТРОННЫЙ НАУЧНО-ПРАКТИЧЕСКИЙ ЖУРНАЛ

eISSN 2500-0632

2023

Т. 8, № 2

https://mst.misis.ru/

Деятельность научно-практического журнала «Горные науки и технологии» (Mining Science and Technology (Russia)) направлена на развитие международного научного и профессионального сотрудничества в области горного дела.

Целевая аудитория журнала – исследователи, специалисты в области горного дела, представители академического и профессионального сообществ.

В журнале публикуются оригинальные статьи, описывающие результаты исследований, опыт реализации проектов в горнопромышленном комплексе, обзорные публикации.

Журнал стремится развивать такие междисциплинарные направления, как технологическая и экологическая безопасность, организация и управление проектами в горной промышленности, развитие территорий, правовые аспекты использования природных ресурсов и другие, которые способствуют прогрессу в горном деле и реализуются исследователями и практиками.

ПЕРИОДИЧНОСТЬ 4 раза в год

ОСНОВАН в 2016 году

РЕГИСТРАЦИЯ

Зарегистрирован Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций 10 августа 2015 года.
Свидетельство о регистрации Эл № ФС77-62652.

ИНДЕКСИРОВАНИЕ

Scopus, CAS, EBSCO, DOAJ, РИНЦ, ВИНИТИ РАН, Dimensions, BASE, J-Gate, Jisc Library Hub Discover.

OPEN ACCESS Журнал открытого доступа.

УЧРЕДИТЕЛЬ И ИЗДАТЕЛЬ

Национальный исследовательский технологический университет «МИСиС» (НИТУ «МИСиС»)

АДРЕС УЧРЕДИТЕЛЯ И ИЗДАТЕЛЯ

119049, г. Москва, Ленинский проспект, д. 4

КОНТАКТЫ РЕДАКЦИИ

Адрес: 119049, г. Москва, Ленинский проспект, д. 4
Телефон: +7 (495) 955-00-77
e-mail: send@misis.ru

MINING SCIENCE AND TECHNOLOGY (Russia)
Горные науки и технологии
SCIENTIFIC AND PRACTICAL E-JOURNAL
eISSN 2500-0632
2023 Vol. 8, no. 2
https://mst.misis.ru/

CONTENTS

ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ
Mining Science and Technology (Russia)
ЭЛЕКТРОННЫЙ НАУЧНО-ПРАКТИЧЕСКИЙ ЖУРНАЛ
eISSN 2500-0632
2023
Т. 8, № 2
https://mst.misis.ru/

СОДЕРЖАНИЕ

eISSN 2500-0632
https://mst.misis.ru/

GEOLOGY OF MINERAL DEPOSITS

Review paper

https://doi.org/10.17073/2500-0632-2022-11-35
UDC 662.3(510)

Chinese mining industry: state of the art review

A.K. Kirsanov ✉
Siberian Federal University, Krasnoyarsk, Russia
✉ *AKirsanov@sfu-kras.ru*

Abstract
The territory of the present-day People's Republic of China is rich in mineral and energy resources which stimulate the growth of the extractive industry in the country. China is currently the world leader in the production of 31 commodities (mineral products): molybdenum, tungsten, iron, aluminum, lead, zinc, gold, coal, gypsum, bentonite, and many others. This stimulates the development of the appropriate infrastructure and training of specialists in the mining industry, the development of international links for investment and the exchange of best production practices. The purpose of this work was to study the history of exploration and extraction of natural resources, establish a domestic strategy for the development of the mining and metallurgical sector, and review leading Chinese mining and metallurgical companies. The paper reviewed key domestic processes in China which would affect the domestic and global mining and metallurgical industry. An assessment of natural resource deposits throughout the whole territory of the country was carried out with their brief description, highlighting the prime prospects, and presenting commodity reserves. The paper presents the main challenges for the mining and metallurgical industry to be met in the 14th Five-Year Plan. The development of the industry up to 2025 implies the expansion of extractive capacities with an overall reduction in dependence on imports, enhancing exploration programs, and the reduction of harmful emissions from operating enterprises, etc. Special attention is paid to publicly traded mining and metallurgical companies in China. The leaders in each sector are presented, and their brief economic indicators are given.

Keywords
China, mineral resources, mineral products, provinces, review, extraction, consumption, analysis, yearly data, economy, industry

For citation
Kirsanov A.K. Chinese mining industry: state of the art review. *Mining Science and Technology* (*Russia*). 2023;8(2):115–127. https://doi.org/10.17073/2500-0632-2022-11-35

ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Обзорная статья

Обзор современного состояния горнодобывающей промышленности Китая

А.К. Кирсанов ✉
Сибирский федеральный университет, г. Красноярск, Российская Федерация
✉ *AKirsanov@sfu-kras.ru*

Аннотация
Территория современной Китайской Народной Республики обладает значительными запасами минеральных и энергетических ресурсов, что стимулирует рост добывающей отрасли. На текущий момент Китай является мировым лидером по добыче и производству 31 вида минерально-сырьевых продуктов: молибден, вольфрам, железо, алюминий, свинец, цинк, золото, уголь, гипс, бентонит и многие другие. Данный факт обусловливает развитие соответствующей инфраструктуры и подготовку специалистов в горнодобывающей отрасли, развитие международных связей для инвестиций и обмена передовым производственным опытом. Целью настоящей работы являлись изучение динамики разведки и добычи природных ресурсов, определение внутригосударственной стратегии развития горно-металлургического сектора, анализ передовых китайских горно-металлургических компаний. В представленной работе рассмотрены ключевые внутренние процессы в Китае, которые будут влиять на внутреннюю и мировую горно-металлургическую промышленность. Проведена оценка месторождений природных ресурсов на всей территории государства – дана их краткая

характеристика, выделены наиболее перспективные участки и показаны запасы сырья. Показаны основные задачи для горно-металлургической промышленности, которые должны быть решены в 14-м пятилетнем плане. Развитие отрасли до 2025 г. предполагает наращивание добывающих мощностей с совокупным снижением зависимости от импорта, развитие программы геологоразведки, сокращение вредных выбросов от действующих предприятий и т.д. Отдельное внимание уделено публичным горно-металлургическим компаниям Китая – представлены лидеры в каждом секторе, даны краткие экономические показатели.

Ключевые слова

Китай, минеральные ресурсы, полезные ископаемые, провинции, обзор, добыча, потребление, анализ, данные по годам, экономика, промышленность

Для цитирования

Kirsanov A.K. Chinese mining industry: state of the art review. *Mining Science and Technology* (*Russia*). 2023;8(2):115–127. https://doi.org/10.17073/2500-0632-2022-11-35

Introduction

Over the past half century, China has made a quantum leap in many economy sectors. The mining sector is no exception. Whereas in the past the country had to import resources and technologies for mining, now it is exporting itself and, in some respects, has even gained effective leverage over the world market.

In 1949, when the 22-year civil war was finally over, the newly formed People's Republic of China was in extreme decline [1]. The consequences of semi-colonialism, civil war, and Japan's occupation of parts of the Chinese territories during World War II had caused enormous economic damage to the country. However, two important factors allowed China to overcome the crisis and develop into an economic superpower.

The first is a good location of the country, encompassing different types of landscapes with diverse mineral deposits. Secondly, the confrontation between the USSR and the U.S., each of which has tried at different times to pull China on its side, helping it to gain technologies and knowledge from both sides of the Iron Curtain.

The history of mining industry of China illustrates very well the historical use of these two factors. Initially, the Soviet government actively assisted in the exploration of new mineral deposits [2]. U.S. then actively helped its businesses in founding U.S.-China joint ventures with transferring new technologies and knowledge on extracting resources [3]. Finally, China itself, having secured its economic independence, went on the offensive, launching an international expansion in resource extraction.

The mining industry is an important source of employment and income for the country, and a significant contributor to the Chinese economy. This paper provides an overview of the Chinese mining industry, including its brief history, current situation, and prospects for future development.

Assessment of natural resource deposits in the territory of China

One of the first acts of cooperation between the USSR and China in the extractive industry was the exploration, production, and refining of oil in 1935–1955. The exploration was carried out mainly in the territory of the Xinjiang Uighur Autonomous Region. Assistance was provided for exploration of other minerals too [4].

To date, China can be described as one of the leading countries in the world mining industry. The country has the world's largest reserves of coal, iron ore, copper, tin, lead, zinc, tungsten, gold, molybdenum, rare earth minerals, etc.

According to the U.S. Geological Survey (USGS), China invested about $14.4 billion in exploration and $173 billion in mining in 2019, an increase of 23 % and 24 % from 2018, respectively. In 2019, China ranked first in the world in coal production, fifth in natural gas production and seventh in crude oil production. China was the world's leading producer and consumer of primary energy.

Table 1 shows the reserves of the main mineral products extracted in the territory of the People's Republic of China. The data is for 2020.

Since the country has huge reserves of natural resources, the issue of training specialists for the relevant industries is also urgent.

According to China's National Bureau of Statistics, about 5.3 million people were employed in the mining sector in 2020. This includes personnel engaged in the extraction of coal, crude oil, natural gas, and other mineral products.

In terms of training, many mining industry employees in China receive on-the-job training through internships and other programs offered by employers. There are also a number of mining schools and institutes which offer specialized training in mining and related fields.

The list of key mining institutes (universities) in China include: China University of Mining and

Technologies (Xuzhou, Jiangsu Province), being one of the oldest and most prestigious mining universities in China; Northeastern University: (Shenyang, Liaoning Province); Central South University (Changsha, Hunan Province); China University of Geosciences (campuses in Beijing, Wuhan and other cities); Shandong University of Science and Technology (Qingdao, Shandong Province).

These are just a few examples of many mining institutes and schools in China offering mining education and training.

On the whole, almost all elements of the Mendeleev periodic system are extracted in the country now (Fig. 1). However, the most important mineral products include coal, oil and gas, and rare earth metals [5–8].

Coal is one of the main resources produced in the country. It is used as the main fuel for thermal power plants (60 % of the country's electricity is provided by coal), steel production, and the production of hydrogen (so-called “brown hydrogen” is obtained in the process of coal gasification) [9-13].

Coal is produced in all provinces of the country, but the main deposits are located in the north. The leader in the production is Shanxi province, where up to 50 % of all coal reserves in the country are assumed to be located. Other important coal provinces are Inner Mongolia, Liaoning, Heilongjiang, Hebei, Shandong, and Jilin.

The most common types of coal in the country are lignite and bituminous coal. The first has a low calorific value (up to 7,700 kcal/kg), high moisture content (30 to 70 %), unlimited volatile-matter yield. Bituminous coal has a higher calorific value (7,700–8,800 kcal/kg), up to 10 % moisture content, and a limited volatile-matter yield.

The highest quality type of coal, anthracite, which has calorific value of 8000–8500 kcal/kg, moisture content up to 5 %, and volatile-matter yield up to 14 %, is produced in China in very limited amounts. This requires the government to import it additionally.

The history of coal production in China is shown in Fig. 2.

The main sources of oil, as with coal, are the northern regions of the country. The largest reserves are located in Heilongjiang Province (Daqing oil field), Xinjiang Uygur Autonomous Region (Tarim Basin), Qinghai and Gansu. Individual deposits were found in Sichuan, Henan, Shandong, Liaoning, and Guangdong provinces [14–17].

Most of China's “black gold” deposits can be roughly divided into two types: light high-quality oil and shale oil. The first type (light oil) is refined at refineries, and its production is quite easy. In contrast, shale oil is more difficult to process and extract. In most cases it occurs in deep horizons and requires special technologies for its extraction, such as hydraulic fracturing. Shale oil production is often low-profitable.

Table 1

Reserves of key minerals and indicators of their extraction in PRC according to USGS и World Mining Data for 2020

Metal/Mineral/Natural gas	Reserves		Production volume	
	Mtpa	share in world reserves, %	kt	share in world production, %
Tungsten	1.9	51.4	71.4	81.7
Iron ore	20000	11.1	225.4*	14.8
Gold	2.0	3.7	365.3	11.4
Cobalt	80.0	1.0	2,2	1.7
Lithium	1.5	6.8	28.8	15.5
Copper	26.0	2.9	1.72*	8.3
Molybdenum	8.3	51.8	95.9	33.4
Nickel	2.8	2.9	105.0	4.2
Tin	1100	22.4	94.5	34.1
Fluorspar	42.0	13.1	4.3*	56.7
Natural gas	5.4	n/a	192.5**	4.8
Rare Earth Elements	44.0	36.6	140.0	62.1
Lead	18.0	20.0	1.97	41.5
Talc	82.0	n/a	2.0*	26.2
Uranium	0.25	4.0	2,2	3.9
Zinc	44.0	17.6	4.0*	32.2
Zircon	n/a	n/a	140.0	11.3

* – data in mln t; ** – data in bln m^3; n/a – data are not available.

Fig. 1. Mineral map of China

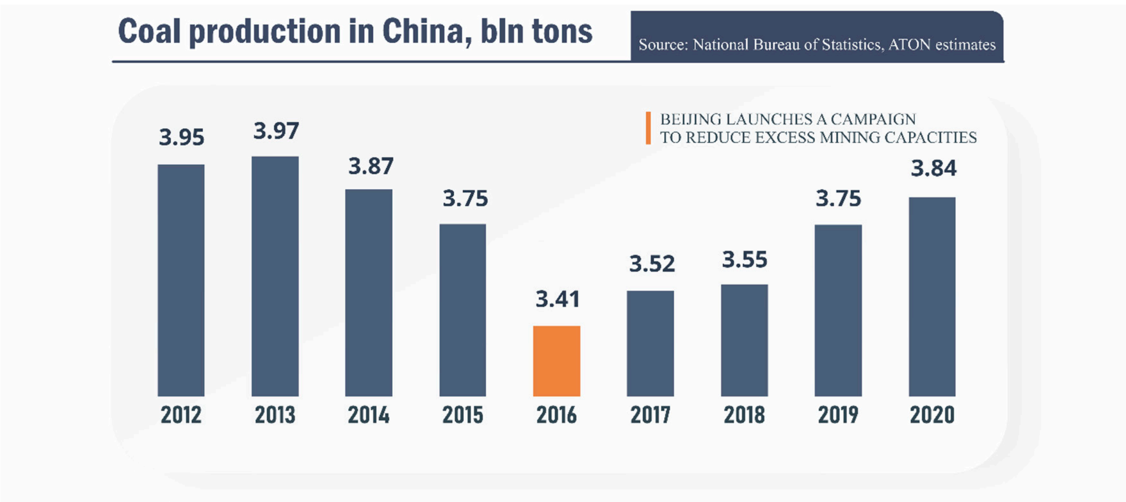


Fig. 2. Coal production history in China

The exploration of natural gas in China has been very underdeveloped for a long time, for which reason the potential of this resource in the country is still unknown. In addition, oil production is often accompanied by the extraction of associated natural gas, such as with Daqing. For this reason, prospecting for natural gas fields for a long time was a low-demand activity. To date, almost half of the explored natural gas reserves belongs to Sichuan Province. Other fields are located in Inner Mongolia, Shanghai, Shaanxi, Hebei, Jiangsu, Zhejiang, and near Hainan Island [18–21].

China has vast iron ore reserves: rich deposits are located in Sichuan, Gansu, Guizhou, Guangdong, and Hainan provinces. Antimony, tungsten, tin, and bauxite reserves are considered to be some of the largest in the world [22]. There are rich deposits of gold and lithium [23–25]. Pyrite explored in Shanxi, Hebei, Shandong, and Liaoning provinces is also one of the most important resources [11].

One more important mineral product are rare-earth elements: 17 metals that are used today in microelectronics, instrumentation, chemical industry, metallurgy, and the nuclear industry. Their peculiarity is that in spite of their occurrence all over the world, they are very rarely found in the form of deposits. This makes their extraction extremely unprofitable, except for some places where their concentration is very high. One such place is Bayan Obo in Inner Mongolia province. This deposit accounts for more than half of the world's rare earth element production and about 70 % of domestic production. According to various estimates, the ore reserves of this deposit are estimated at more than 50 million tons [26–29].

The presence of such a developed mineral resource base also implies a well-developed and up-to-date infrastructure in this sector. The country produces a wide range of mining equipment and machinery, from simple hand tools to modern machinery such as excavators, bulldozers, and cranes. China also has a wide range of options for transporting produced minerals. An extensive network of roads, railroads, and waterways ensures efficient transportation of the extracted resources. China has a well-developed energy infrastructure with a wide range of energy sources, including coal, oil, gas, and hydroelectric power. The country is investing heavily in research and development to improve the efficiency and safety of its mining operations. All of these factors have enabled China to become one of the world's leading producers of minerals and other natural resources.

Development of mining and metallurgical industry in the country

While the Soviet Union mainly helped China in prospecting, exploration, and primary development of minerals, since the late 1970s the U.S. began actively investing in the creation of joint U.S.-Chinese companies. The basis for such business was laid by Deng Xiaoping, the "father" of modern Chinese economy.

At that time, the country was facing major deficiencies in modern technologies, and Deng Xiaoping found an interesting solution in joint ventures. The essence of the proposal was that foreign investors paired with Chinese investors, in order to create a joint business. Foreigners transferred technologies and provided financing, while the Chinese side provided tax incentives and access to a market of 1.4 billion people. This practice soon spread throughout the country and still exists today.

This strategy gave rise to the rapid growth of many companies. The mining sector was no exception, so when we consider Chinese companies hereinafter, we have to remember that some of them are essentially foreign.

It is also important to remember that, unlike American and European companies, Chinese mining companies have a number of key differences that directly affect their day-to-day operations.

In addition to the creation of joint ventures, a key difference is the great influence of the state on the development strategy of companies. This translates into regulation and "recommendations". For example, in the 14th Five-Year Plan, covering the period of 2021–2025, there is an entire section devoted to the mining and metallurgical industry (Fig. 3) [30].

14th Five-Year Development Plan: Key Points

→ Reduce dependence on imports of iron-containing raw materials (ores);
→ Invest in foreign mining assets;
→ Launch a new exploration program to discover new mineral deposits;
→ Reduce CO_2 emissions through modernizing production facilities;
→ Continue consolidation of the steel industry;
→ Increase mining capacities;
→ Increase the workload of scrap collecting points

Fig. 3. Key points of development of the PRC's mining and metallurgical industry from 2021 to 2025

A more detailed description of the main tasks presented is given below:

Reduce dependence on imports of iron-containing ores. The reason for this task was the critical dependence on Australia, which accounts for 80 % of Chinese imports of these raw materials. However, since 2020, relations between the two countries have become increasingly tense, and the PRC is trying to secure itself ahead of time. It plans to resolve the problem through several steps:

- Launch a new exploration program to discover new deposits.
- Increase the workload of scrap collecting points. The country currently produces just over 1 billion tons of steel per year. With a recycling target of 30 %, the total amount of scrap for recycling would be 300 million tons, which would be 40 % more than 216 million tons recycled in 2019.
- Increase investment in foreign assets. In particular, the government plans to develop up to two world-class iron mines. One of the most likely sites will be the Simandou mine in Guinea (contains about 2 billion tons of high-grade iron ore graded at 65 % Fe).
- Increase domestic production. China ranks 4th in iron ore reserves, but the grade of the resource is quite low which makes it less profitable and also increases CO2 emissions (the higher grade of iron ore, the easier its processing and the lower total CO_2 emissions per ton of steel) [31].

Reduce harmful emissions. Mining and steel industries are a major source of carbon emissions. In the current conditions, the government demanded to improve the environmental situation by:

- implementing new techniques for carbon capture, use, and storage at new mining facilities, as well as modernization of existing ones;
- increasing the share of renewable energy sources and nuclear power in the structure of energy consumption.

Consolidate the steel sector by merging existing companies and reduce excess steelmaking capacities. China's ongoing gradual consolidation of the steel industry should increase government control over pollution and, in the long term, lead to a reduction in excess capacities. In addition, it will give the major industry players more powerful leverage over leading producers of imported iron ore resources during the negotiations on pricing.

The "recommendations" include silent government regulations. In particular, as of November 6, 2020, it was "recommended" that coal, copper ore, and a number of other commodities no longer be bought from Australia. The main reason was the tense relations between the two countries: Australia was supporting the U.S. in a trade war against China, as well as repeatedly hinting at the guilt of the PRC in the spread of the coronavirus infection COVID-19. In order to understand the scale of the silent regulations, it is enough to cite just a couple of figures: before the embargo, China was the largest importer of Australian commodities, buying up to 60 % of coking coal and 25 % of steam coal, which constituted 21 % of total Australian exports of this commodity. In addition, copper ore and concentrates (which covered 5 % of China's demand), as well as a number of other commodities were banned. A little later the embargo was officially imposed.

Chinese publicly traded mining and metallurgical companies

Another difference is the constant tendency to merge an increasing number of companies, and thus create huge industrial corporations. This often makes it very difficult to judge profitability. Certain subsidiaries are clearly unprofitable, but at the expense of other more profitable ones. In this way the corporation's overall income is almost always in the black. In our case, certain Chinese mining companies are being merged with manufacturing companies. This is particularly evident in the steelmaking sector. Therefore, this paper looks at Chinese companies which belong to two industries simultaneously, mining and metallurgy. This will allow confusion about financial indicators and main characteristics of companies to be avoided.

In absolute terms, the mining and metallurgical industry in China is huge. Its market capitalization is estimated at $477 billion. Of these, $197 billion are available to investors in the form of free-floating shares (Fig. 4) [30].

The largest sectors in the industry are steelmaking and coal production, with market capitalizations of $126 billion and $98 billion, respectively. They are followed by the precious metals sector, lithium and cobalt production, base metals and aluminum, rare earth elements, etc. [30].

Let's take a closer look at each sector:

Steel sector. Out of 23 public companies, only three are large: Baoshan Iron&Steel (capitalization of $27 billion), China Steel Corp ($20 billion) and Inner Mongolia Baotou Steel Union ($11 billion). Their average EBITDA margin (an analytical indicator of a company's earnings before interest, taxes, depreciation, and amortization) was 9 % in 2020. On the whole, this is at the level of Japan and North America, but lower than in Russia (27 %) and India (23 %). Large dividend payments, despite the debt burden of the sector, should be also noted: the average projected dividend yield is 5 % for 2022, second only to Russia with 10 % [30].

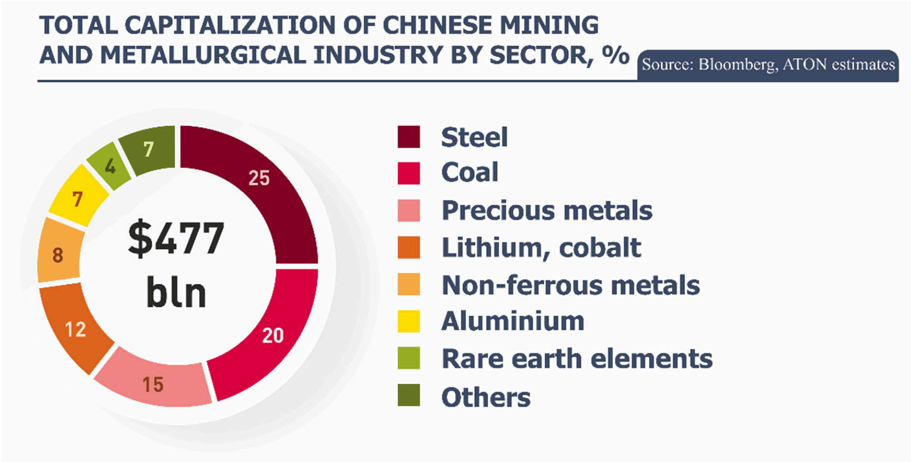


Fig. 4. Total capitalization of Chinese mining and metallurgical industry by sector

It is worth noting that the main iron ore reserves exploited are located north of the Yangtze River and supply neighboring metallurgical plants. However, China has to permanently import raw materials to meet its production needs. Australia accounts for the largest share of Chinese iron ore imports (60 %). This type of resources is not embargoed.

Coal sector. The sector is represented by five companies, four of which are traded on the Shanghai Stock Exchange. The largest of these is China Shenhua Energy. Its capitalization is more than half of the whole sector, $58 billion. It is followed by Shaanxi Coal and Chemical Industry with a capitalization of $17.5 billion and China Coal Energy ($12 billion). The average EBITDA margin in 2020 was 23 %, the highest in whole mining and metallurgical industry. The projected dividend yield in 2022 will be 6 %, also the highest in the industry [30].

A total of 3.9 billion tons of coal were produced by Chinese companies in 2021. This was 2.5 % more than in 2020. The production growth of coal due to the gradual cancellation of quarantine measures and the energy crisis in the EU. The growth rates are expected to be 1.1 %, reaching a production of 4.1 billion tons in 2025. However, due to the government's initiative to decommission obsolete coal extraction facilities [32], the growth rate of coal production will decrease in the near term.

Here we should also note the government's strong regulation of coal production — previously thousands of small mines were established across the country to provide coal for local needs. They account for 40 % of the total domestic production, and most of them are low-margin. However, such an initiative allowed reducing the volumes of coal transportation – the transport network suffered from the excessive load of coal exports from Shanxi Province.

Precious metals sector. It includes six publicly traded companies with a total capitalization of $70 billion. The largest of these are Zijin Mining (capitalization of $42 billion), Shandong Gold Mining ($14 billion) and Zhongjin Gold ($7 billion), as well as private China National Gold and Zhaojin Gold. The average EBITDA margin in the sector in 2020 was 12 %, against 50 % for global gold producers [30].

Lithium and cobalt production sector. It consists of four publicly traded companies: Tianqi Lithium, Ganfeng Lithium, GME, and Zhejiang Huayou Cobalt. The average EBITDA margin in the sector for 2020 was 21 % [30].

Base metals and aluminium sector. Five base metals producing companies (Jiangxi Copper, Tongling Nonferrous, Chihong Zinc, China Molybdenum, and Tibet Huayu Mining) and four aluminum companies (China Zhongwang, Aluminium Corp, China Hongqiao, and Shandong Nanshan) represent this sector. The total market capitalization of the sector is $74 billion. The average EBITDA margin in the sector in 2020 was 7 % for the base metals producers (vs. 37 % for global producers) and 21 % for the aluminum producers (higher than that of global producers). This sector has the highest debt burden in the industry [30].

It should be taken into account that many base metal producing companies possess mines for the extraction of ores of cobalt, molybdenum, rare earth elements, etc.

Rare earth elements sector. It includes 34 producers, of which only five can be considered relatively large. The largest of these is China Rare Earth (capitalization of $11.4 billion), followed by China Northern, Xiamen Tungsten, China Minmetals, and JL Mag. The average EBITDA margin in the sector in 2020 was 10 % [30].

MINING SCIENCE AND TECHNOLOGY (RUSSIA)
ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ
2023;8(2):115–127
eISSN 2500-0632
https://mst.misis.ru/

It should be noted that some companies, in addition to mining REE resources, are engaged in production of other products, for instance, lithium, tungsten, potassium, etc.

On the whole, as can be seen, in terms of financial indicators, Chinese companies do not appear very attractive to investors. In most cases, foreign companies, unconstrained by the political plans of a country government, demonstrate a much higher performance (Fig. 5). On the other hand, the government promotes new programs for discovering new mineral deposits and actively encourages increased production.

However, despite the development of Chinese companies and the build-up of efforts to increase the production of minerals, the country is unable independently to satisfy domestic demand. This forces China to permanently import resources from other countries and engage in international expansion.

Trade in minerals

Mineral resources play an important role in China's economic power. Over the past decades, the country has emphasized the development of its own industry, producing all kinds of goods, from bicycles to spacecraft. However, despite numerous domestic mineral reserves, Chinese industry became so large that the country was forced to start importing mineral products from other countries.

According to the World Trade Organization, China's fuel and mineral imports in 2021 were $789.255 billion, second only to the European Union at $987.763 billion. In recent years, China, like the EU, has been actively increasing imports (Table 2). The slowdown in 2018–2019 was due to the trade war with the U.S., when both countries imposed customs duties on a number of goods and commodities. The slight decline in 2020 was due to the consequences of coronavirus restrictions.

It is also interesting to note that China actively buys mineral products, but has little to sell. For example, Chinese fuel and mineral exports in 2021 were only $87.871 billion, ranking only 13th among the largest exporters. However, the upward trend in China's mineral product exports can be seen here too, as well as the drop in 2019 and 2020, for the above reasons.

Key import and export indicators for key mineral products will be presented in more detail below.

Mineral product imports

A noticeable characteristic feature of China's imports of mineral products is that the Chinese importers are looking for suppliers with the lowest prices, not allowing the international political agenda to influence their purchases. Nevertheless, in some cases the country refuses favorable terms if the Communist Party of China "silently" recommends stopping trade with a particular country.

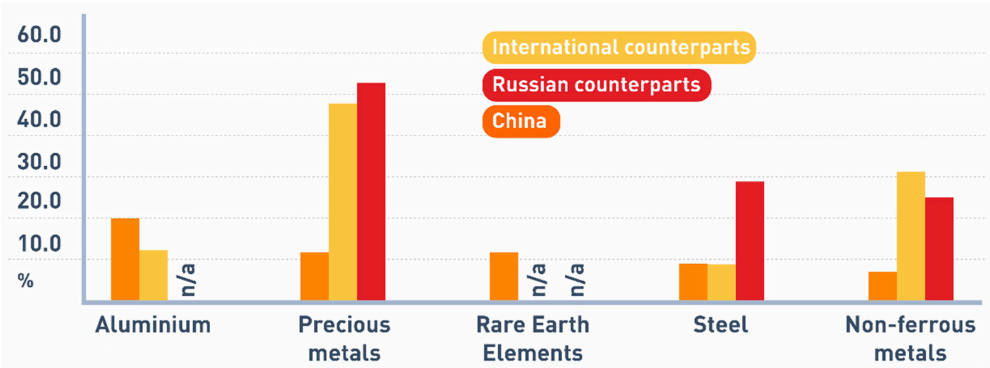


Fig. 5. Average EBITDA margin of some mining and metallurgical sectors in 2020 (comparison of China with global and Russian counterparts)

Table 2

World leaders in mineral product imports for 2016–2021 (according to World Trade Organization)

Region	Amount of mineral product imports by year, $ billion/year					
	2016	2017	2018	2019	2020	2021
European Union	569.917	716.361	883.131	788.515	573.823	987.763
China	326.216	444.767	560.913	580.577	541.761	789.255
USA	205.737	257.850	300.582	265.652	185.778	307.856
Japan	146.164	184.213	222.842	201.620	151.774	227.103
Germany	117.119	140.207	168.694	157.057	125.779	202.784
India	108.092	148.150	198.755	177.565	123.616	201.546

The main items in the imports of mineral products are coal, crude oil, iron ore, and copper ore (Fig. 6).

Let us now consider these import items in more detail:

Iron ore. Traditionally, the main supplier of iron ore to China was Australia. However, due to the country's U.S.-oriented political course, the Chinese government has in recent years been actively developing supplies from other countries, primarily Brazil. For instance, in the third quarter of 2022, imports from Brazil increased, first of all, because of good weather conditions, allowing increased iron ore production in the country. However, the very price of iron ore is on a permanent decline. Over the same period, the IODEX index fell 25 percent to $95.95 (as of September 30, 2022). This is due to the fact that China, acting as one of the main world importers of iron ore, is experiencing a crisis in the real estate market, due to which the demand for steel for construction has fallen.

Copper ore. In this sector, Australia is the main exporter to China. In November 2020, a silent ban on copper ore and coal imports from Australia was imposed due to the Australian government's demand for an international investigation into the origins of COVID-19. In November 2022, after the meeting of the leaders of China and Australia at the G-20 summit, the silent embargo was lifted.

Table 3

World leaders in mineral product exports for 2016–2021 (according to World Trade Organization)

Region	Amount of mineral product exports by year, $ billion/year					
	2016	2017	2018	2019	2020	2021
European Union	340.330	430.396	510.980	465.947	359.363	589.889
USA	129.247	177.683	238.025	243.141	201.283	305.067
Russia	163.989	209.142	263.390	248.032	171.033	248.868
Australia	112.245	142.277	170.951	184.308	169.108	241.301
UAE	55.423	72.285	132.631	223.881	181.802	233.014
China	50.524	62.657	79.447	78.357	60.493	87.871

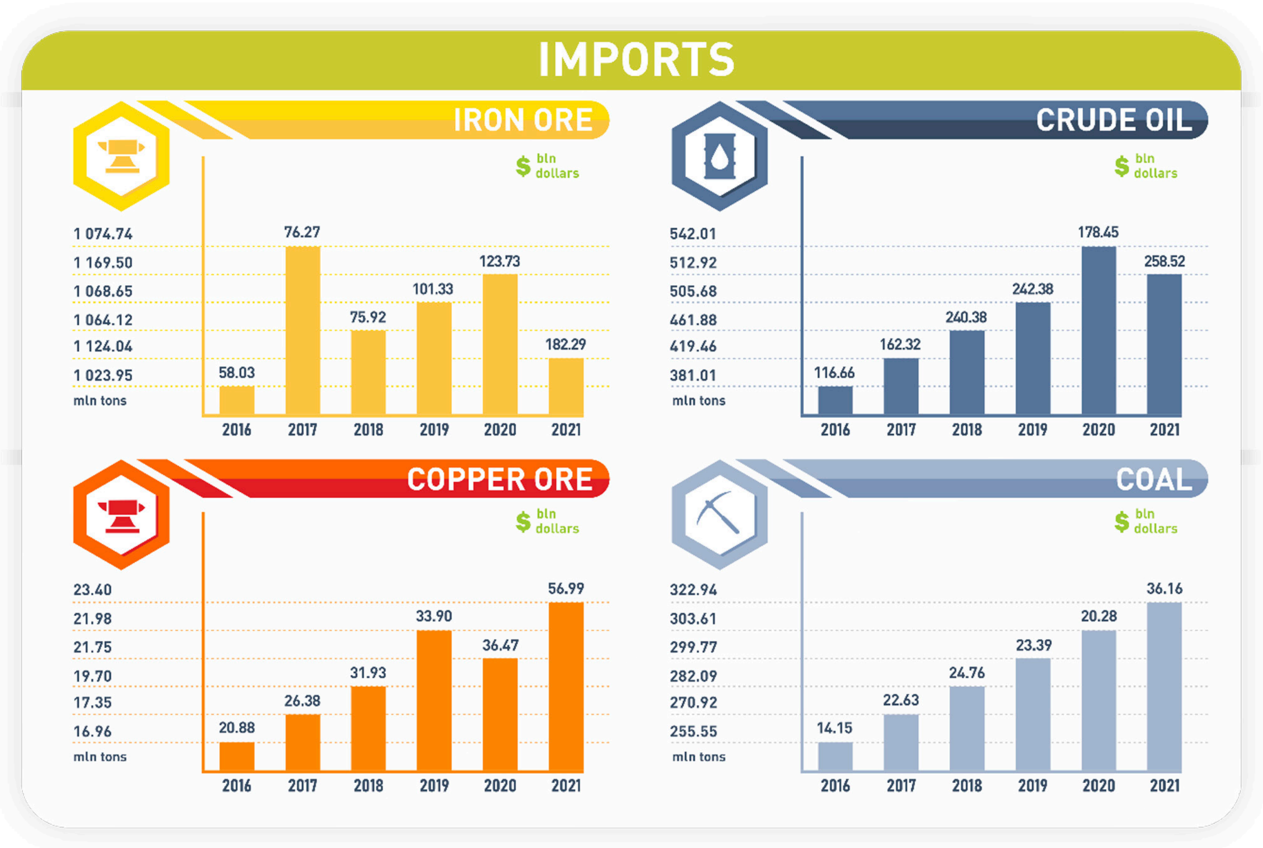


Fig. 6. Imports of major mineral products into China between 2016 and 2021 (according to the National Bureau of Statistics of China and UN Comtrade Database)

MINING SCIENCE AND TECHNOLOGY (RUSSIA)
ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ
2023;8(2):115–127
eISSN 2500-0632
https://mst.misis.ru/

Coal. In February 2023, the first two ships carrying coal from Australia arrived in China and several more are en route, thus breaking a two-year embargo. However, on February 16, 2023, the customs office did not let one ship with 12,000 t coal pass. For five days the ship tried to pass customs inspection, but failed to do so. So it had to change its route and deliver coal to Vietnam. The event itself suggests that the Chinese government has not yet fully taken a decision whether to completely lift the embargo on Australia's exports of certain minerals. In addition, China actively is increasing its coal imports from Russia. Due to the EU's and British embargoes on Russian coal, Russia has begun to redirect coal exports to Asia. However, the main problem of the exports is overloaded railways which limits Russia's ability to supply coal.

Crude oil. The main suppliers are Russia and Saudi Arabia. Notice that Russian oil is most often purchased for subsequent resale to Western countries because of international sanctions imposed on Russia, while oil from Saudi Arabia satisfies domestic demand of China.

Export of mineral products

China is one of the world's leading exporters of natural resources with a wide range of minerals, agricultural products, and fossil fuels offered. The country exports a variety of mineral products and metals, including iron ore, copper, oil, aluminum, and manganese, and is a leading global producer of rare earth elements, which are used in many industries, including electronics, automotive, and renewable energy. Fig. 7 presents some of the main exports.

China exported a total of 6.08 billion tons of mineral products in 2019, including iron ore, copper, aluminum, manganese, and rare earth elements, according to China's National Bureau of Statistics. The iron ore exports account for the largest share of the mineral product exports, with 2.82 billion tons exported in 2019, followed by copper (1.08 billion tons), aluminum (0.72 billion tons), manganese (0.48 billion tons), and rare earth elements (0.35 billion tons).

Over the past few years, China's mineral product exports have been growing steadily. In 2018, China exported 5.9 billion tons of mineral products, and, in 2017, 5.4 billion tons. This increase in the exports was due to a combination of factors, including increased demand from China's trading partners, as well as increased production capacities in the country.

While importing resources, the Chinese government and business are actively trying to expand the number of suppliers, in order to buy minerals at lower prices. In the case of exports, China is actively using

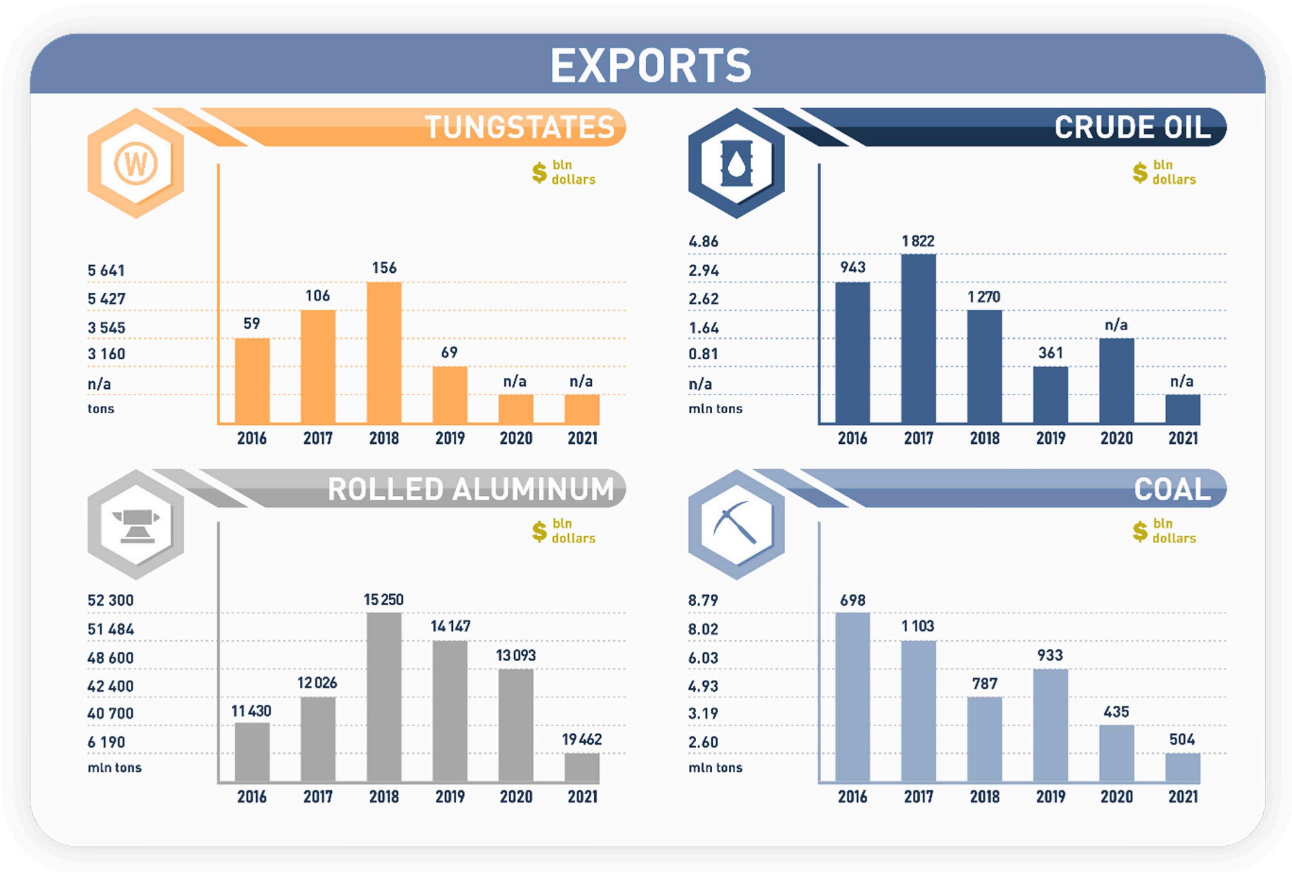


Fig. 7. Exports of major minerals from China between 2016 and 2021
(according to the National Bureau of Statistics of China and UN Comtrade Database)

eISSN 2500-0632
https://mst.misis.ru/

its influence to raise prices or seek political concessions. For example, in 2010, China reduced its supplies of rare earth elements to Japan amid a scandal with a fishing vessel. In 2019, due to a trade war with the United States, the country threatened to raise duties on the same resources. In December 2021, China even temporarily excluded Lithuania from its customs register, blocking the ability of Lithuanian businesses to clear their goods.

Another feature of the exports is the country's extreme reluctance to sell minerals in their raw form. Instead, China prefers to sell finished products or at least perform primary processing. For example, among the country's largest export items there are no iron, copper, or aluminum ores, but there are pig iron, aluminum, steel, and copper rolled products and downstream products (nails, bolts, etc.). China produces almost 60 % of all types of rare earth elements, but exports beneficiated REE, or metal REE, or even products based on them.

The main country-importers of these mineral products from China are the United States, Japan, South Korea, and the European Union. Some resources are supplied by sea (oil and petroleum products) and some by rail (rare earth elements, coal).

International expansion in exploration and development of old and new mineral deposits

The trade war with the U.S. in 2018, the embargo on Australian resources in 2020, and the preparation of new U.S. sanctions in 2022 have forced the Chinese authorities to think about new threats to current commodity supplies, while the embargo on Russian energy resources forced to start acting in advance.

Since imports could suddenly decline, the Chinese government has begun actively to pursue international expansion, in order to discover new deposits and develop old and new ones. In the first place, preference is given to geographically closest projects. For example, China has actively invested in coal and copper ore mining projects in Mongolia. Moreover, the investment concerns not only companies working directly in these sectors, but also companies involved in the development of transport infrastructure that allows the volume of supply to increase.

Despite increasing tensions with the U.S., Chinese companies are actively cooperating with Western partners, conducting joint exploration of new oil fields in Yellow Sea, South China Sea, Gulf of Tonkin, and Bohai Gulf. Some promising areas fall within the zone of economic interests of Vietnam, North and South Korea, Taiwan.

China is paying special attention to developing countries in Africa and South America. According to a report by the Shanghai University of International Business and Economics, from 2000 to 2019, the PRC invested in 52 of 54 countries on the African continent. The amount of investment has increased from $210 million to $47.3 billion. In 2021, the amount of investment was $49 billion.

However, this figure does not include lending to individual states by Chinese companies. Therefore, it is very difficult to determine how much money has gone into the development of the mining industry. This can only be judged by circumstantial data, such as the growth of trade turnover up to $254 billion in 2021, and reports on individual investment projects. Such projects include the development of the Simandou iron ore deposit in Guinea. A Chinese company as a part of the Winning Consortium Simandou and Australian-British Rio Tinto have agreed to invest more than $15 billion in the mine. Part of the money is earmarked for the creation of infrastructure for the convenient export of the resources from the continent.

In addition, there is information about the acquisition of two African gold mining companies Guyana Goldfields and Continental Gold by the Chinese company Zijin Mining. In 2019, Chinese businesses spent a total of $750 million in buying gold mining assets abroad [30].

In South America, China has become a major trading partner for countries such as Brazil, Peru, Uruguay, and Chile. Most other countries have China in the second place. In exchange for the purchase of commodities, China often offers investments in major infrastructure projects and loans to individual companies for some mining enterprises. The total trade in 2020 was $315 billion, and the loans to the mining industry were $2.1 billion [33].

It is especially important to emphasize Venezuela's role in supplying oil to China. The country provides 13 % of China's oil imports (40 % of Venezuela's oil exports).

It should be noted, however, that Chinese mining companies are increasingly facing competition with U.S. companies. In addition to traditional competition in the form of buying-out companies or obtaining licenses, in some situations companies are engaged in "black PR". For example, the Chinese news agency Xinhua in January 2022 published a rebuttal to a report by the British "Guardian" newspaper. The latter reported that two Chinese mining companies, Jinding Mining Zimbabwe and Shanghai Haoyun, were paying low wages and forcing local workers to work overtime.

Conclusion

China has a huge impact on the whole Asian region: the country has the status of an emerging economy and is the world leader in the extraction of a long list of different mineral products.

This study demonstrates the impact of the mining sector on the country's economy. Based on the findings of the review performed in this study, it can be concluded that the prospects of the Chinese mining industry are gradually stabilizing after the COVID-19 pandemic. For instance, following the development of the Chinese economy and the growth of foreign investment, a number of Chinese companies have become widely known in the global mining sector.

In recent years, China has become increasingly dependent on imported natural resources. This is due to a combination of factors, including population growth, rapid economic growth, and a shift in the country's energy balance from coal to renewables. As a result, China is now the world's largest net importer of natural resources, with the imports of minerals, agricultural products, and fossil fuels steadily increasing in recent years.

In order to achieve the goals of the 14th Five-Year Plan, China must focus on the more active development of clean energy, including wind power, photovoltaics, hydropower, and nuclear power, carry out structural reform and eliminate obsolete facilities in high energy-intensive industries (steel, petrochemical, and chemical industries).

As a continuation of this study, future work will focus on an in-depth study of each mining sector in the PRC, discussed in this paper, and its detailed review.

References

1. Cucchisi J.L. *The causes and effects of the Chinese Civil War, 1927–1949.* South Orange, New Jersey: Seton Hall University. 84 p. URL: https://scholarship.shu.edu/cgi/viewcontent.cgi?article=3416&context=dissertations (Accessed: 01.11.2022)

2. Pu J. Soviet assistance to Chinese industry in the 1950s. *Manuscript*. 2018;(5):45–49. (In Russ.) https://doi.org/10.30853/manuscript.2018-5.9

3. Muromtseva Z.A. Reform of the public sector in china: improving the system of modern state-owned enterprises. In: *40 years of economic reforms in the PRC*. Moscow, April 01–02, 2019. Moscow: Institute of the Far East of the Russian Academy of Sciences; 2020. Pp. 76–89. (In Russ.)

4. Yevdoshenko Yu.V. Foreign economic projects of the Stalin era: Xinjiang oil and the Soviet Union, 1935–1955. *Economic History: a Yearbook*. 2021;2020:264–318.

5. Zhang B., Yao J., Lee H.-J. Economic impacts and challenges of Chinese mining industry: an input–output analysis. *Frontiers in Energy Research*. 2022;10:784709. https://doi.org/10.3389/fenrg.2022.784709

6. Hu R., Liu J., Zhai M. *Mineral resources science in China: A roadmap to 2050*. Beijing, Berlin: Science Press Springer; 2010. 86 p.

7. Zhai M.G., Hu R.Z., Wang Y., et al. Mineral resource science in China: review and perspective. *Geography and Sustainability*. 2021;2(2):107–114. https://doi.org/10.1016/j.geosus.2021.05.002

8. Balaram V. Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers*. 2019;10(4):1285–1303. https://doi.org/10.1016/j.gsf.2018.12.005

9. Xu M. *Analysis: Quantity over quality – China faces power supply risk despite coal output surge*. Reuters. June 21, 2022. URL: https://www.reuters.com/markets/commodities/quantity-over-quality-china-faces-power-supply-risk-despite-coal-output-surge-2022-06-21/ (Accessed: 01.11.2022)

10. China Energy Portal. *2021 electricity & other energy statistics (preliminary)*. 2022. URL: https://chinaenergyportal.org/en/2021-electricity-other-energy-statistics-preliminary/ (Accessed: 01.11.2022)

11. Britannica. *Minerals of China.* URL: https://www.britannica.com/place/China/Minerals (Accessed: 01.11.2022)

12. Kondratiev V.B. Situation on the global coal market during the recovery of the world economy after the COVID-19 crisis. *Russian Mining Industry*. 2021;(4):84–92. (In Russ.) https://doi.org/10.30686/1609-9192-2021-4-84-92

13. Tzian Ch., Prokofieva L.M. “Black Gold” of China. *Asia and Africa Today*. 2011;(3):42–47. (In Russ.)

14. Yuan S., Wang Q. New progress and prospect of oilfields development technologies in China. *Petroleum Exploration and Development*. 2018;45(4):698–711. https://doi.org/10.1016/S1876-3804(18)30073-9

15. Evdoshenko Yu.V. Xinjiang oil and the “Dushantsi” oil processing plant. Oil production and processing in northwest China in 1938–1943. *Oil Industry*. 2020;(2):108–112. (In Russ.) https://doi.org/10.24887/0028-2448-2020-2-108-112

16. Korzhubaev A.G. Cooperation prospects of Russia and China in oil and gas industry. *Problems of Economics and Management of Oil and Gas Complex*. 2011;(5):32–36. (In Russ.)

17. Nikitina M.G. Petroleum diplomacy of the People's Republic of China. *Uchenyye Zapiski Tavricheskogo Natsional'nogo Universiteta imeni V.I. Vernadskogo. Seriya: Ekonomika i Upravleniye*. 2014;27(1):94–100. (In Russ.) URL: http://sn-ecoman.cfuv.ru/wp-content/uploads/2017/04/010nikitina.pdf

18. Li J., She Y., Gao Y., et al. Natural gas industry in China: development situation and prospect. *Natural Gas Industry B*. 2020;7(6):604–613. https://doi.org/10.1016/j.ngib.2020.04.003

19. Zhen W., Yinghao K., Wei L. Review on the development of China's natural gas industry in the background of "carbon neutrality". *Natural Gas Industry B*. 2022;9(2):132–140. https://doi.org/10.1016/j.ngib.2021.08.021

20. Wang J., Feng L., Zhao L., Snowden S. China's natural gas: resources, production and its impacts. *Energy Policy*. 2013;55:690–698. https://doi.org/10.1016/j.enpol.2012.12.034

21. Zhang J., Meerman H., Benders R., Faaij A. Potential role of natural gas infrastructure in China to supply low-carbon gases during 2020–2050. *Applied Energy*. 2022;306(A):117989. https://doi.org/10.1016/j.apenergy.2021.117989

22. In the world "Tungsten Capital" – Jiangxi Province – exploration at a new large tungsten deposit produced good results. *Rénmín Rìbào*. 2013. URL: http://russian.people.com.cn/31518/8271841.html (Accessed: 01.11.2022)

23. Polevanov V.P. China's Golden Path. *Gold and Technology*. 2016;(2):30–34. (In Russ.)

24. Wang D.-H., Dai H.-Z., Liu S.-B., et al. Research and exploration progress on lithium deposits in China. *China Geology*. 2020;(3):137–152. https://doi.org/10.31035/cg2020018

25. Lightfoot P.C., Bagas L., Nie F.J. Gold deposits of China: a special issue of ore geology reviews. *Ore Geology Reviews*. 2016;73(2):175–178. https://doi.org/10.1016/j.oregeorev.2015.07.025

26. Mitchell J. China's stranglehold of the rare earths supply chain will last another decade. *Mining Technology*. April 26, 2022. URL: https://www.mining-technology.com/analysis/china-rare-earths-dominance-mining/ (Accessed: 01.11.2022)

27. What are rare earth elements and why are they so important in the us-china trade war? *Euronews*. (In Russ.) URL: https://ru.euronews.com/2019/08/16/rare-earth-elements-ru (Accessed: 01.11.2022).

28. Li H.-T., Yang K.-F., Gao Y.-P., et al. Age and origin of the H9 member from the Bayan Obo Group: Implications for the genesis of the giant Bayan Obo Fe-Nb-REE deposit, China. *Ore Geology Reviews*. 2022;146:104927. https://doi.org/10.1016/j.oregeorev.2022.104927

29. Fan H.R., Yang K.F., Hu F.F., et al. The giant Bayan Obo REE-Nb-Fe deposit, China: Controversy and ore genesis. *Geoscience Frontiers*. 2016;7(3):335–344. https://doi.org/10.1016/j.gsf.2015.11.005

30. Lobazov A., Fedorova M. *China. Forge of global metallurgical trends*. Moscow: LLC "Aton"; 2021. 24 p. (In Russ.)

31. China to boost coal output, reserves to ensure power supply – NDRC. *Reuters*. March 7, 2022. URL: https://www.reuters.com/business/energy/china-boost-coal-output-reserves-ensure-power-supply-ndrc-2022-03-05/ (Accessed: 01.11.2022)

32. Top five coal producing countries (million tonnes, 2021). *GlobalData*. 2021. URL: https://www.globaldata.com/data-insights/mining/the-top-five-coal-producing-countries-million-tonnes-2021/ (Accessed: 01.11.2022)

33. Mamysheva D.K. Key aspects of China – Latin America cooperation in the energy sector. *Innovation &* Investment. 2021;(3):72–75. (In Russ.)

Information about the author

Aleksandr K. Kirsanov – Cand. Sci. (Eng.), Senior Lecturer of the Department of Mine and Underground Construction, Siberian Federal University, Krasnoyarsk, Russian Federation; ORCID 0000-0001-7977-4954, Scopus ID 56825475600, ResearcherID A-7720-2016; e-mail AKirsanov@sfu-kras.ru

Received 22.11.2022
Revised 27.02.2023
Accepted 13.03.2023

eISSN 2500-0632
https://mst.misis.ru/

GEOLOGY OF MINERAL DEPOSITS

Review paper

https://doi.org/10.17073/2500-0632-2023-02-83
УДК 622.3:546.831:339.13

Russian zirconium industry: current issues in raw material supply

V. Yu. Khatkov[1], **G. Yu. Boyarko**[2] ✉, **L. M. Bolsunovskaya**[2], **A. M. Dibrov**[3], **Yu. A. Dibrova**[2]

[1] *PJSC «Gazprom» Russia, St. Petersburg, Russian Federation*
[2] *National Research Tomsk Polytechnic University, Tomsk, Russian Federation*
[3] *Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russian Federation*
✉ *gub@tpu.ru*

Abstract

The relevance of the research is connected with Russia's long-term import dependence on zirconium raw materials.
Goal of this research: to study the dynamics of commodity flows (production, import, export, consumption) of Russian zirconium raw materials; its prices (world and Russian); the raw material base of zirconium in Russia and the prospects for national production of its extraction and processing.
Methods: statistical, graphic, logical.
Results: Russia imports the vast majority (3.5–14.9 kt/year or 98–100 % of consumption) of consumed zircon concentrate. At the same time, almost all of the baddeleyite mined in Russia (4.0–9.3 kt/year or (96–100 % of production) is exported. Since 2018 has there been a decrease in its export supplies and an increase in the national consumption (up to 60 % of production).
Russia has existing deposits, including a useful zirconium component, but all are connected with a certain economic and technological complexity in their development.
In 2022, the national production of selective zircon concentrate began during the development of the Tugan titanium-zirconium deposit. This deposit covers up to 30 % of Russia's demand for zirconium raw materials up to 2023. Furthermore, the construction of the 2-nd stage of the Tugan mining and processing plant will increase its supply to 15 kt/year. This will completely cover Russian demand for zirconium raw materials. Work is in progress on Zashikhinsky field preparation, where, in the course of enrichment of tantalum-rare-earth ores, up to 8 kt/year of zircon concentrate will be additionally extracted. The emerging trend of reducing Russia's import dependence on zirconium raw materials, and in the future its complete elimination will allow consumption of zircon and zirconium oxides to be increased in the most demanding area of their use – for dampening the glaze of ceramic tiles. The presence of an independent and sufficient national mining base of zirconium raw materials will allow Russian production of metal zirconium, zirconium refractory and abrasive products, solid fuel energy cells and other zirconium-containing applications to be developed.

Keywords

strategic raw materials, import dependence, zircon, baddeleyite, metal zirconium, zirconium oxides, export, national projects

Acknowledgements

The article was written as part of a grant from the Russian Science Foundation on the topic "Critical Mineral Products in the Russian and World Economy" for 2022–2023. (Project No. 22-28-01742).

For citation

Khatkov V. Yu., Boyarko G. Yu., Bolsunovskaya L. M., Dibrov A. M., Dibrova Yu. A. Russian zirconium industry: current issues in raw material supply. *Mining Science and Technology* (*Russia*). 2023;8(2):128–140. https://doi.org/10.17073/2500-0632-2023-02-83

eISSN 2500-0632
https://mst.misis.ru/

ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Обзорная статья

Обзор циркониевой отрасли России: состояние, проблемы обеспечения сырьем

В.Ю. Хатьков[1], **Г.Ю. Боярко**[2] ✉, **Л.М. Болсуновская**[2], **А.М. Дибров**[3], **Ю.А. Диброва**[2]

[1] *ПАО «Газпром», г. Санкт-Петербург, Российская Федерация*

[2] *Национальный исследовательский Томский политехнический университет, г. Томск, Российская Федерация*

[3] *Томский государственный университет систем управления и радиоэлектроники, г. Томск, Российская Федерация*

✉ *gub@tpu.ru*

Аннотация

Актуальность работы обусловлена наличием в течение длительного времени импортозависимости России по циркониевому сырью, осложняемой встречными потоками тотального импорта цирконового концентрата и экспорта значительной доли бадделеитового концентрата.

Цель: изучение динамики товарных потоков (производства, импорта, экспорта, потребления) циркониевого сырья в России, его цен (мировых и российских), сырьевой базы циркония России и перспектив национального производства ее добычи и переработки.

Методы: статистический, графический, логический.

Результаты: Россия импортирует подавляющее количество (98–100 %) потребляемого цирконового концентрата (3,5–14,9 тыс. т/год). Лишь в 2022 г. началось массовое национальное производство селективного цирконового концентрата при разработке Туганского титан-циркониевого месторождения, что позволит уже в 2023 г. закрыть до 30 % потребности России в циркониевом сырье, а дальнейшее строительство 2-й очереди Туганского ГОКа приведет к увеличению его предложения до 15 тыс. т/год, что полностью перекроет российские потребности в циркониевом сырье. В то же время концентрат бадделеита (природный оксид циркония), извлекаемый попутно при обогащении апатит-магнетитовых руд на Ковдорском ГОКе, до 2017 г. практически весь (96–100 %) отправлялся на экспорт (4,0–9,3 тыс. т/год) и лишь с 2018 г. наметилось снижение экспортных поставок и увеличение его национального потребления (до 60 % от производства).

В 2022 г. прекратился импорт цирконового концентрата с Украины и осложнились его поставки из недружественных стран. Для покрытия временного дефицита российского потребления цирконового концентрата (3–5 тыс. т/год) возможны поставки от независимых производителей из дружественных стран, в том числе и по схеме параллельного импорта. Снижение временного дефицита циркониевого сырья возможно также переориентированием части экспортного потока бадделеитового концентрата на российские нужды.

На территории России имеются подготовленные месторождения, включающие полезный циркониевый компонент, но для всех них имеются экономические и технологические сложности их освоения. Это Лукояновское, Бешпагирское, Туганское, Центральное и Тарское титан-циркониевые погребенные россыпные месторождения, Катугинское, Улуг-Танзегское, Зашихинское и Сахарйокское комплексные рудные цирконсодержащие редкометалльно-редкоземельные месторождения, участок эвдиальтовых руд Аллуайв на Ловозерском редкометалльном месторождении.

Кроме развития уже организованных добычных работ на Туганском титан-циркониевом месторождении, ведутся работы по подготовке Зашихинского месторождения, где при обогащении тантал-редкоземельных руд будет дополнительно извлекаться до 8 тыс. т/год цирконового концентрата.

Возможно также создание зарубежных совместных предприятий по добыче циркониевого и титанового сырья в дружественных странах (во Вьетнаме и ЮАР) для последующих поставок добытого сырья в Россию.

Наметившийся тренд снижения импортозависимости России по циркониевому сырью, а в дальнейшем и полная ее ликвидация позволят нарастить потребление циркона и оксидов циркония в самом емком направлении их использования – для глушения глазури керамической плитки. Наличие независимой и достаточной национальной добывающей базы циркониевого сырья позволит развивать российское производство циркония металлического, циркониевых огнеупорных и абразивных продуктов, твердотопливных энергетических элементов и других цирконийсодержащих приложений.

Ключевые слова

стратегическое сырье, импортозависимость, циркон, бадделеит, цирконий металлический, оксиды циркония, экспорт, национальные проекты

Благодарности
Статья написана в рамках выполнения гранта Российского научного фонда по теме «Критические минеральные продукты в российском и мировом хозяйстве» на 2022–2023 гг. (проект № 22-28-01742).

Для цитирования
Khatkov V. Yu., Boyarko G. Yu., Bolsunovskaya L. M., Dibrov A. M., Dibrova Yu. A. Russian zirconium industry: current issues in raw material supply. *Mining Science and Technology* (*Russia*). 2023;8(2):128–140. https://doi.org/10.17073/2500-0632-2023-02-83

Introduction

At the present time, the situation regarding the manufacture and consumption market of zirconium raw materials in Russia is challenging. The situation is burdened with high risks of failures to ensure the movement of commodity flows.

In world zirconium production, the main uses of zirconium are the production of ceramic products (54 %), non-stick coatings (14 %) and refractory products (13 %) in the foundry industry [1]. In Russia over 60 % of zirconium mineral raw materials is used in the nuclear industry for the production of metallic zirconium [1, 2]. Zirconium is included in the national list of the main types of strategic mineral raw materials (Order of the Russian Federation Government as at 16 January, 1996, №. 50-r). In the Strategy for the Development of the Mineral and Raw Material Base of Russia until 2030, it belongs to the problematic third group of scarce minerals, internal consumption of which is largely provided by enforced imports (Decree of the Government of the Russian Federation of December 22, 2018, № 2914-r).

The greatest difficulties for the Russian zirconium industry arose after the collapse of the USSR, when the main supplies of zirconium raw materials were provided from the existing mining and processing complexes (MPC) (Volnogorskiy, Irshinskiy, Streminogorskiy, Mezhdurechenskiy) located on the territory of Ukraine. In the 80 years of the XX century in the USSR, up to 40 kt of *zircon concentrate* (containing 65 % ZrO2) was mined and processed annually. Since 1991 it was imported into Russia, and by 2000 Russian consumption decreased to 9 kt/year [2].

At the same time, at the Kovdorsky mining plant in the Murmansk region, during the apatite-magnetite development of the same-named deposit, 4–9.3 kt/year of associated minerals is mined – baddeleyite concentrate (natural zirconium oxide) [2]. Most (2.4–9.3 kt/year or 40–100 %) is exported.

There is an overall zircon raw material shortage for the needs of Russian industrial production which is covered by imports. There is also a contradiction between the benefits of exporting Russian baddeleyite concentrate and the problems of domestic Russian demand for this product.

Given the risks of the consequences of anti-Russian economic sanctions by the EU and the USA, the real current state of the Russian zirconium industry needs to be determined.

Methodology

In order to study the Russian market of zirconium raw materials, data was collected on the global and Russian production of zirconium raw materials for the period 1996–2020, as well as the dynamics of Russian and world prices for zirconium products for the period 1996–2022. Sources of information were: Bulletins and survey reports of the Russian Ministry of Natural Resources and Environment[1], data of foreign trade of the Federal Customs Service of Russia[2], data of the British Geological Surveys[3] and the United States Geological Surveys[4], data of the UN Information Service and reviews[5] of marketing companies[6]. Mining, production, imports, exports and consumption are reported in metric tons. Prices for zirconium products are quoted in USD per metric ton of the specific commodity. When calculating the sum of zirconium products of different qualities, they are given in terms of 100 % ZrO_2 in metric tons.

Condition of the Russian zirconium industry

Mining. In world practice, the main source of zircon concentrate is titanium-zirconium coastal marine alluvial deposits. These are very technologically advanced in terms of mining and enrichment of ore sands. The world leaders in zircon mining are: Australia (400–620 kt/year); South Africa (320–390 kt/year); USA (70–100 kt/year); and Sene-

[1] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[2] Federal Customs Service of Russia. URL: http://stat.customs.ru/analytics/

[3] US Geological Survey. URL: National Minerals Information Center | U.S. Geological Survey (usgs.gov)

[4] Britain Geological Surveys. URL: Commodities & statistics | MineralsUK (bgs.ac.uk)

[5] UNdata. A world of information. URL: https://data.un.org/Default.aspx

[6] TrendEconomy. URL: https://trendeconomy.ru/

gal (50–100 kt/year)[7]. In Russia, despite a sufficiently established resource base for explored titanium-zirconium sand deposits, the extraction of zircon (zirconium silicate containing 65 % ZrO_2) has not been carried out due to the presence of a stable zircon import flow (together with ilmenite and rutile) concentrate from Ukraine. In 2007–2015, the pilot operation of the Tugan titanium-zirconium deposit in the Tomsk region was carried out with an annual zircon concentrate output of 79–936 t/year [2, 3]. In 2022, the construction of the 1st stage of the Tugansky GOK of JSC Ilmenit was completed (Fig. 1). This provided production of 410 tons of zircon concentrate by the end of the year and expected output of 3.5–3.7 kt in 2023. This meets 30–35 % of Russian demand for this product. The construction of the 2-nd stage of the Tugansky GOK planned for 2025 will increase the zircon concentrate output to 14.7 kt/year. This will completely cover Russian demand for zirconium raw materials [3].

Baddeleyite (zirconium natural oxide) is a rare industrial type of mineral raw material, periodically mined in the weathering crusts of carbonatites of the Poços de Caldas deposit in Brazil (1940–1950s). It has also been extracted during beneficiating of apatite-copper ores of the Palabora carbonatite deposit in South Africa (1964–2001). In Russia, starting from 1975, baddeleyite has been extracted during beneficiating of baddeleyite-apatite-magnetite ores of the Kovdor carbonatite deposit and the Kovdorskiy GOK of MCC EuroChem (see Fig. 1) [2, 4]. Since baddeleyite concentrate is an associated useful component, its production volumes are practically not regulated. This is due to the variability in the quality of the composition of ores (containing only 0.13–0.16 % ZrO_2), controlled to optimize the production of the main commodity component – iron ore concentrate. Accordingly, the production volumes of baddeleyite concentrate are variable over time (4.0–9.3 kt/year). They show trends of initial increase from a local minimum of 4.0 kt in 1999, to a maximum of 9.3 kt in 2010 and a subsequent downward trend in supply down to 6.0 kt in 2020 (Fig. 2).

[7] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

Fig. 1. Enterprises mining, processing and consuming zirconium raw materials, Metallogenic provinces of the location of zircon-bearing placers and the actual zirconium deposits:
1 – metallogenic provinces of location of zircon-bearing placers (I – Unecha-Krapivnenskaya; II – Central Chernozem; III – Penza-Murom; IV – Lukyanovskaya; V – North Caucasus; VI – Timan; VII – Zauralye; VIII – Tara; IX – West Siberian-Khatanga); *2* – titanium-zirconium placer deposits; *3* – zircon-bearing complex rare-metal deposits; *4* – baddeleyite deposits in carbonatites; *5* – baddeleyite deposits in the weathering crusts of carbonatites; *6* – enterprises extracting zirconium raw materials; *7* – metallurgical enterprises for the production of metallic zirconium; *8* – other enterprises consuming zirconium raw materials

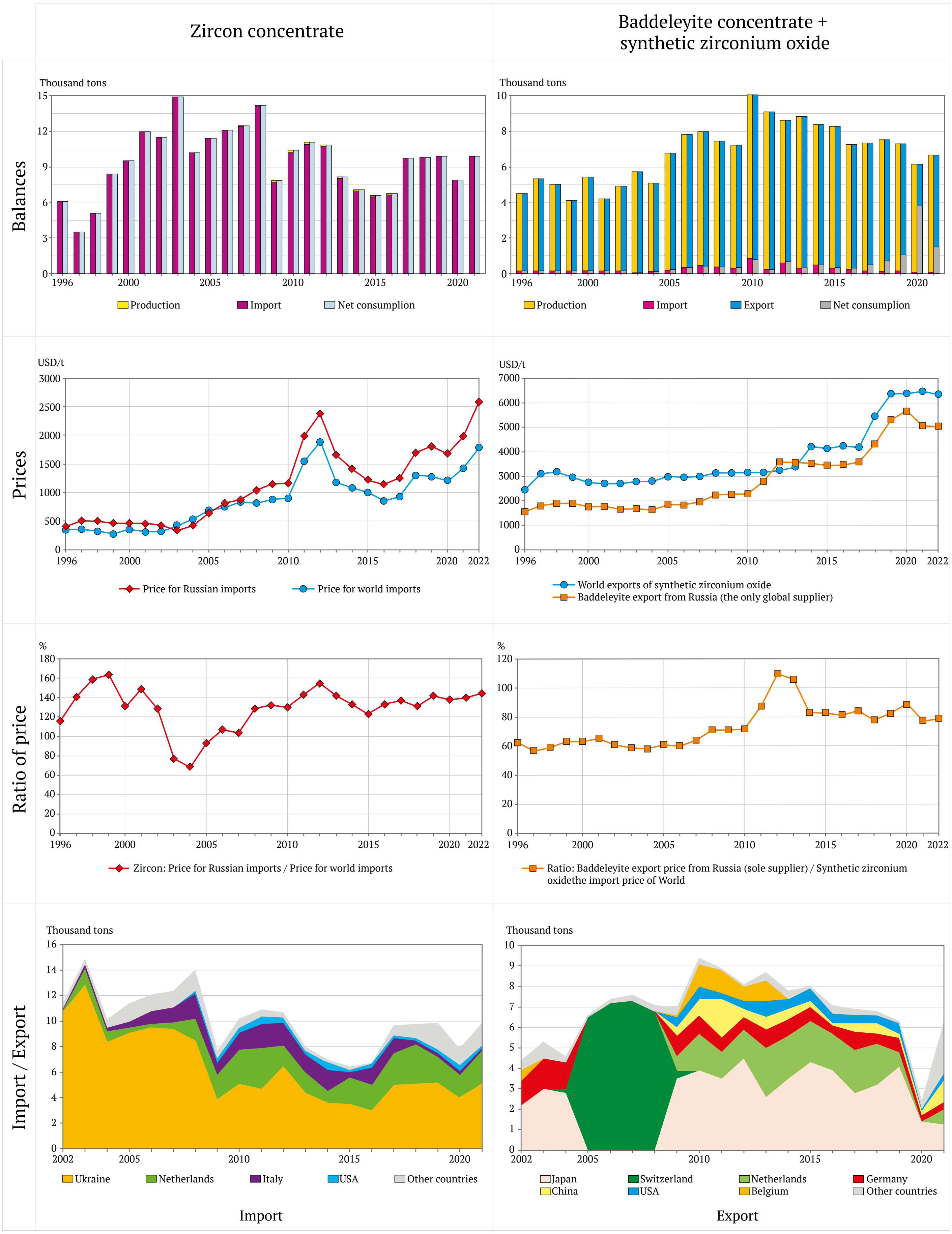


Fig. 2. Dynamics of indicators of zircon and baddeleyite concentrates commodity flows for 1996–2021(2022)

Baddeleyite makes up 99–100 % of total zircon raw materials production in Russia. The share of zircon production does not exceed 1.4 %. In relation to world production of zirconium raw materials, the share of Russian supply is 0.6–1.1 %. This figure fluctuates relative to the average level of 0.8 % (Fig. 3) – a very small contribution to the volume of world consumption of zirconium products (528–1127 kt/year in terms of 100 % ZrO_2).

Import. The vast majority of *zircon concentrate* (98–100 %) prior to 2021 inclusive was supplied to Russia by import (3.5–14.9 kt/year), see Fig. 2. The main commodity flow of zircon was from Ukraine (3.0–12.9 kt/year or 43–94 %). This was due to the traditional nature of the usual commodity flows of zircon and, in particular, its lower radioactivity when compared to zircon concentrate from South Africa and the USA [5]. However, if in the 1990s and 2000s, the overwhelming share of imports of zircon concentrate came from Ukraine (75–94 %), then in the 2010s, supplies from the Netherlands (up to 32 %), Italy (up to 24 %) and the USA increased (up to 9 %), see Fig. 2. There were small import inflows of zircon concentrate from Indonesia, China, Kazakhstan. In 2022, the import of zircon concentrates from Ukraine stopped and its supplies from unfriendly countries became more complicated.

Average world import prices for zircon concentrate in 1996–2002 were at the level of 310–360 USD/t. In 2003, their growth began against the background of increased consumption in China (20 % of world demand in 2002 and 60 % in 2012) up to 1534 USD/t in 2012. The global economic crisis of 2008–2009 years affected the growth of zircon price trend only by slowing down its increase (see Fig. 2). Subsequently, against the background of a decrease in the volume of consumption of zircon concentrate in China, its average world prices decreased to 860 USD/t in 2016. Later, with a resumption in demand, their growth resumed up to 1780 USD/t in 2020.

The price of imported zircon concentrate only in 2003–2005 (during the initial period of growth in its consumption in China) was lower than the average world export prices by –24 ...–32 % (see Fig. 2). There was an excess of the price of Russian imports over world prices by +20...+60 % over the years. This can be explained by the declared higher quality of Ukrainian zircon concentrate [5]. In general, against the backdrop of the general global price increase, the cost of Russian imports of zircon concentrate increased from USD 2.6 million in 1996 to USD 25.4 million in 2012. Subsequently, against the backdrop of a decline in import volumes, this amounted to USD 8–18 million, USD/year.

There are also small volumes of imported synthetic *zirconium oxide* (analogous to natural baddeleyite) – 51–852 t/year (see Fig. 2), mainly of high-quality varieties. 96–172 tons/year of *metallic zirconium* are also imported.

Export. Prior to 2017, almost all of the *baddeleyite concentrate* produced at Kovdorsky mining and processing complex was exported (96–100 %), see Fig. 2. This was facilitated by a high level of world prices and limited volumes of world trade in natural and synthetic *zirconium oxide*. The dynamics of export supplies of baddeleyite concentrate almost completely mirror the trends in the production of baddeleyite. There was an initial increase from a local minimum

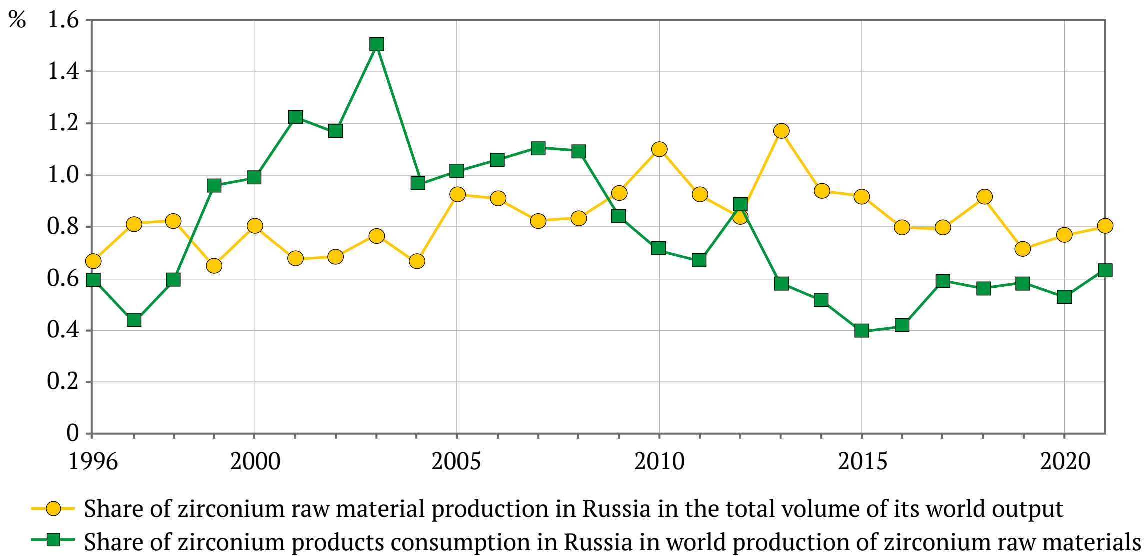


Fig. 3. Shares of the Russian production and consumption of zirconium raw materials in terms of its global output for 1996–2021 (in recalculation on 100 % ZrO_2)

of 4.0 kt in 1999 to a maximum of 9.3 kt in 2010 to a subsequent trend of decreasing exports up to 6, 9 kt in 2017, and then their sharp reduction to 2.6 kt in 2020 (40 % of production), see Fig. 2. The main buyers of Russian baddeleyite concentrate were: Japan (up to 65 % of Russian supply); the Netherlands (up to 30 %); and Germany (up to 28 %), see Fig. 2. In 2005–2008 the export flow of baddeleyite concentrate from Russia passed through intermediary companies in Switzerland, see Fig. 2.

In general, the market for zirconium oxide international trade (natural + artificial) is relatively small – (29–52 kt/year). It corresponds to 3.9–6.3 % of the world production / consumption of zirconium raw materials (in terms of on ZrO_2), see Fig. 4. The share of Russian exports of baddeleyite (4.8–9.3 kt) in the world trade of zirconium oxides is 12–22 % (see Fig. 4).

For a long period (1996–2013), world trade prices for synthetic zirconium oxide remained approximately at the same level of 2700–3350 USD/t. Subsequently, there have been jumps in price growth with a subsequent stability of their level of 4200–4300 USD/t in 2014–2017 and 6400–6500 USD/t in 2019–2022 (see Fig. 2). The 2008–2009 global economic crisis did not affect the dynamics of prices for zirconium oxides. The price rises for zirconium oxide in 2013 and 2018 fell at the moments of decrease in the volumes of Russian production and, accordingly, export of baddeleyite concentrate.

The export price of Russian baddeleyite concentrate in 2002–2010 was below the average world import prices of synthetic zirconium oxide by −28, ...−48 % with a downward trend over time (see Fig. 2). Between 2012–2013, there was only one period when the prices of Russian exports exceeded average world prices by 6–10 %. This was due to a larger share of the output of ceramic varieties of baddeleyite produced at that time. Between 2014–2022, Russian baddeleyite concentrate was again sold at a discount of +10...+22 %. The value of the Russian baddeleyite concentrate export increased from USD 6.8 million in 1996 to a maximum of USD 33.5 million in 2019. However, it dipped sharply with the fall of export volumes to USD 13.7 million in 2020.

Consumption. The main consumer of imported and domestic *zircon concentrate* in Russia is SC Chepetsky Mechanical Plant (ChMP) in Glazov (Republic of Udmurtia). It produces metallic zirconium and products for the needs of the nuclear industry, as well as synthetic zirconium dioxide. ChMP in the 2010s produced up to 3000 tons of metal zirconium [2] annually, obtained by processing up to 5000 tons of zircon concentrate[8] [5].

LLC Kerama Marazzi at the Orlovsky plant of ceramic tiles, produces zircon concentrate to muffle the enamel of ceramic tiles. Consumption is 0.8–1.3 kt/year[9].

JSC Klyuchevskoy Ferroalloy Plant (settlement Dvurechensk, Sverdlovsk region), annually produces up to 150 tons of ferrosilicon zirconium for deoxidi-

[8] Federal Customs Service of Russia. URL: http://stat.customs.ru/analytics/

[9] I bid.

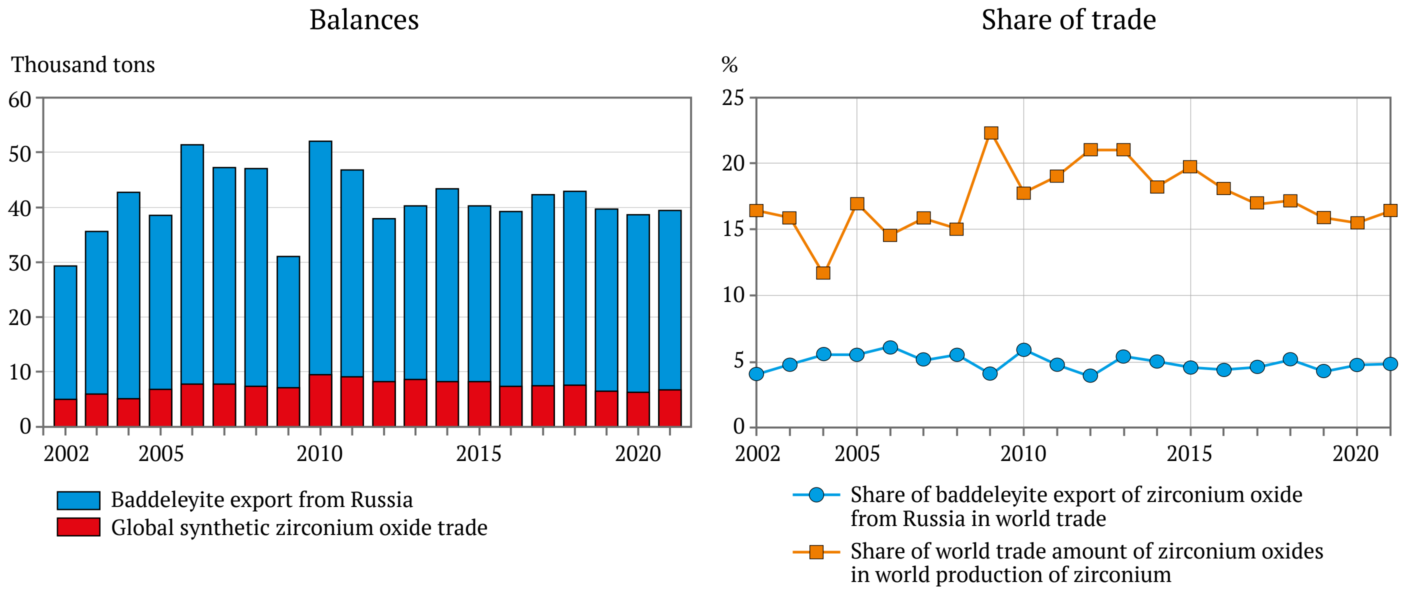


Fig. 4. Dynamics of world trade balances of natural and synthetic zirconium oxides, as well as the share of baddeleyite export from Russia of the total zirconium oxide world trade and the share of zirconium oxide world trade in the world production of zirconium raw materials for 2002–2021 (in terms of 100 % ZrO_2)

zing steel and increasing its strength. Consumption is up to 250 tons of zircon concentrate [6].

Zircon concentrate is also used for the manufacture of anti-burning paint for coating crucibles and molds directly at ferrous and non-ferrous metallurgy enterprises [7]. However, there are no statistics on the volume of this use.

A significant part of imported zircon concentrate (3–5 kt/year) is processed into zirconium dioxide for use in the production of refractory materials and ceramics.

The processing of zircon concentrate for zirconium dioxide (including doping with calcium or yttrium) is carried out at Russian enterprises: ORPE Technologiya named after A.G. Romashin and LLC Technokeramika (Obninsk, in the Kaluga region), JSC DINUR (Pervouralsk, Sverdlovsk region).

LLC Technokeramika, in addition to zirconium oxides, produces abrasive materials from zirconium oxides (Zirco+).

ORPE Technologiya named after A.G. Romashin produces refractory materials based on zirconium oxides: zirconium dioxide ceramic film; porous elements and diaphragms for electrochemical water purification; layered structures with zirconium dioxide coatings for insulating or sealing elements for electrochemical devices; nozzles and bushings for metal melt spraying installations; solid electrolytes of electrochemical solid oxide fuel cells and oxygen pumps; oxygen concentration sensors in metal melts; crucibles for ferrous and non-ferrous metallurgy for heat treatment of various materials; electrochemical elements in dynamic oxygen sensors of on-board security and life support systems; and in nuclear power engineering.

STC Bakor (Moscow), EFR Sherbinka (Shcherbinka, the Moscow region) and JSC Borovichi Refractories Plant (BRP) in Borovichi (the Novgorod region) produce corundum oxide zirconium refractory products and mortars (bulk refractories) for the glass industry. They also produce products for continuous casting of steel based on zirconium dioxide, or with the addition of zircon.

According to the dynamics of Russian consumption of zircon concentrate, there has been a significant increase in consumption from 3.5 kt in 1997 to 15 kt in 2004. There was stabilization at the level of 10–12 kt/year until 2012 with a crisis drawdown of up to 7.7 kt in 2009, after which the consumption of this marketable product has fluctuated in the range of 8–11 kt/year (see Fig. 2). In terms of 100 % ZrO_2, the minimum annual consumption of zircon was 3.2 kt in 1997, the maximum was 9.7 kt in 2003, and the most recent in 2020 was 6.4 kt (see Fig. 1).

In terms of the dynamics of the Russian primary supply of zirconium oxides (baddeleyite + imports of synthetic zirconium oxide), there has been an increase in consumption from 0.15 kt in 1996 to 3.8 kt in 2020 (see Fig. 2).

In terms of the processing of imported zircon into oxides at Russian enterprises, another 2–3.5 kt are sent for sale. Thus, if by 2010 the total consumption of zirconium oxides in Russia by 2010 was up to 1 kt [8], then in 2020 it was 7.3 kt/year.

In general, in terms of domestic and imported zirconium raw materials, 30–60 % of consumed raw materials are used for the production of metallic zirconium. 40–60 % are used for refractory products, up to 20 % for ceramics, up to 5 % for abrasive materials, and for ferroalloys. up to 2 %.

In world practice, more than 50 % is used in the production of mass-produced ceramic products for silencing enamel, in order to increase its strength and reducing thermal conductivity [9]. This use is constrained in Russian conditions by the total import dependence on zirconium raw materials [10]. However, the experience of creating a large-scale production of ceramic tiles at the Orel plant of LLC Kerama Marazzi. This has led to an explosive growth in the volume of its production and consumption in Russia in 2013–2015, testifying to the urgent demand for these products and, accordingly, the increase in demand for zircon and baddeleyite raw products.

The total import dependence of Russia on zirconium raw materials also constrains other areas of zirconium product use:

– production of powders of zirconium carbide [11] and zirconium diboride [12] for the manufacture of abrasive materials, wear-resistant coatings and as part of hard alloys;

– use of zirconium oxides (doped with yttrium or scandium) as solid electrolytes, stable at high temperatures in solid fuel cells for converting the chemical energy of hydrocarbon fuel into electricity and heat [13];

– hydrochemical production of magnesium-stabilized zirconium oxide powders for the manufacture of heat-resistant composite ceramic material [14].

Mineral raw material base. Globally, only one type of zirconium deposits is currently being developed: modern coastal-marine titanium-zirconium placers with minimal overburden volumes. *Titanium-zirconium placers* are also known on the territory of Russia. However, almost all of them are buried and with epigenetic changes in the properties of useful minerals [15]. This complicates their development and reduces investment attractiveness. The most attractive of them in terms of quality and quantity of zirconium raw materials are[10] [2]:

– Lukoyanovskoye deposit in the Nizhny Novgorod region, containing an average of 13 kg/м³ of zircon in sands, reserves of 389 kt of ZrO_2;

– Beshpagir deposit in the Stavropol Territory, 7.84 kg/м³, 166 kt;

– Tugan deposit in the Tomsk region, 7.65 kg/м³, 1007 kt;

– Central deposit in the Tambov region, 6.7 kg/м³, 830 kt;

– Tarskoye deposit in the Omsk region, 6.37 kg/м³, 181 kt.

At present, the construction of the 1st stage of the Tugansky GOK of JSC Ilmenit has been completed. The commercial operation of the Tugan titanium-zirconium deposit has begun with an annual output of up to 3.7 kt of zircon concentrate, 11.4 kt of ilmenite concentrate, 0, 8 kt of rutile concentrate and up to 220 thousand m³ of construction sand [3]. The Lukoyanovskoye, Beshpagirskoye and Tsentralnoye deposits are currently in unallocated subsoil.

There are also possible development projects of titanium-zirconium placer deposits in friendly countries: Vietnam (deposits Cam-Hoa, Qui-Ninh, Ke-Sung, etc.) [16], and in South Africa, where there is experience in creating Russian-African mining enterprises (importing manganese ores to Russia) [17].

Baddeleyite ores in carbonatite deposits, the only deposit is being developed in Russia – Kovdorskoye in the Murmansk region[11], including significant reserves of zirconium (2182 kt ZrO_2). They are also developed as an associated component of complex apatite-magnetite ores (average content of 0.15 % ZrO_2) [2]. Moreover, due to the status of associated raw materials for baddeleyite, there are low rates of extraction into concentrate (30–40 %) and the formation of tailings rich in this mineral. At Kovdorsky GOK, a technogenic deposit has now been formed, including 34 kt of ZrO_2. Technology needs to be developed for the enrichment of baddeleyite-containing ores with an increase in its extraction into concentrate.

A pure baddeleyite deposit is also known in Russia: Algama in the Khabarovsk region. This is a genetic analogue (carbonatite weathering crust) of the Posos de Caldas deposit in Brazil [18]. However, the Algaminskoye deposit is located in a remote area outside transport communications, has not been explored. It is unlikely to be of industrial interest in the near future.

Other types of *complex ore deposits have previously been explored, including significant mineralization of zircon* in Russia[12]. Among the most notable of these are:

– Katugin zircon-pyrochlore-cryolite deposit in the Trans-Baikal region, with reserves of 3086 kt of ZrO_2 with an average content of 1.6 % ZrO_2;

– Ulug-Tanzek zircon-pyrochlore-columbite deposit in the Republic of Tyva, 2900 kt, 0.4 % ZrO_2;

– Zashikhinsky zircon-pyrochlore-columbite deposit in the Irkutsk region, 282 kt, 0.46 % ZrO_2;

– Sakharjok deposit in the Murmansk region with resources of 1625 kt of ZrO_2.

Complex deposits can be challenging in terms of enrichment of their ores, selectivity in the extraction of useful minerals and components. A particular risk is managing the individual commercial product output, especially in the context of increasing prices. The main commercial product which is the focus of the main technological enrichment process with its optimal yield in terms of quality and quantity is singled out. This is also the case for all other mineral products which are accounted for upon their release as associated components. In the Katuginsky and Ulug-Tanzegsky deposits, niobium is the main attractive component of complex ores, for the Zashikhinsky – tantalum. Thus, the zirconium product for these objects is a minor associated mineral.

Currently, the Zashikhinskoye deposit (the owner of the license for subsoil use is JSC Technoinvest Alliance)[13] is at the stage of development and design of the mining enterprise. Moreover, the main attractive component of the complex ores of this project is tantalum (average grade in ores is 0.03 % Ta_2O_5). It is planned to produce annually 8.2 kt of zircon concentrate and 6 kt of pyrochlore concentrate containing 220 tons of Ta_2O_5 and 2.5 kt of Nb_2O_5 [19]. The Katuginskoye and Ulug-Tanzegskoye deposits are located in remote areas and, due to the low investment attractiveness and the difficulty of ore enriching, are in unallocated subsoil.

Outside the Russian Federation, zircon-containing complex ore deposits have also become the objects of investment attractiveness. This is especially the case against the background of the depletion of most developed titanium-zirconium placers. However, the same problem exists in terms of

[10] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[11] I bid.

[12] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[13] I bid.

the multiplicity of marketable product output, and linking production planning to the main mineral or marketable product. Projects for field development are being prepared for implementation, including the extraction of zircon concentrate: Thor Lake [20] and Strange Lake [21] in Canada, Bear Lodge in the USA [22], as well as Zandkopsdrift in South Africa [23] and Tunbreeze in Greenland [24] with the main components in the form of rare earth metals.

Eudialyte ores, an unconventional type of zirconium raw material known at the Alluive site of the developed Lovozero rare metal deposit, are also becoming attractive. The resources of zirconium in eudialyte ores at this deposit are 7275 kt of ZrO_2 with a cut-off grade of 2.5 % ZrO_2. The main component extracted from the eudialyte concentrate here is zirconium, and rare earth materials – associated useful components [25]. A positive aspect of the Alluive site development of eudialyte ores is the presence of an existing mining complex near the infrastructure. The risk factors are the absence of an enterprise for processing eudialyte concentrate and the likelihood of declaring specially protected geological natural monuments on the territory of the mining allotment of the deposit (pegmatite bodies "Shkatulka" and "Yubileinaya"). This followe the example of the Pilanesberg eudialyte deposit in the national park of the same name in South Africa.

Eudialyte ore deposits are being prepared for development abroad: the Durbo project at the Tungi deposit in Australia (the main component is zirconium) [26]; the Nechalacho project in Canada [27]; and the Kwan Fjeld project in Greenland [28] (the main components are rare earths).

Discussion and Conclusions

Since 1992 in Russia, the zirconium market has had a completely import-dependent zircon concentrate flow and a predominantly export-oriented baddeleyite concentrate flow. Only in 2022, did mass national production of selectively extracted zircon concentrate begin during the development of the Tugan titanium-zirconium deposit.

In the list of recent political sanctions, there is no reference to a trading ban with Russia for zirconium ores and concentrates. However, supplies from Ukraine have stopped, and the main world producers of zirconium raw materials are either unfriendly (USA, Australia) or controlled by the latter (operators Namacwa Sands and KZN Sands in South Africa by the American company Tronox, QMM in Madagascar by the Australian Rio Tinto, Tizir in Senegal by the French Eramet and the Australian MDL, Moma Titanium Minerals in Mozambique by the Irish Kenmare). Nevertheless, in order to cover the temporary shortage of Russian consumption of zircon concentrate (3–5 kt/year), supplies from independent producers from friendly countries are possible. Volumes of deliveries of zircon concentrate from Indonesia need to be increased, and new flows of its import from Vietnam, Sri Lanka, India, Brazil, Namibia, Kenya, Tanzania and other countries, including need to be coordinated through parallel import schemes.

It is also possible to cover the temporary zirconium raw material shortage for Russian needs by reorienting the baddeleyite concentrate commercial flow produced by Kovdorsky GOK. The needs of metallic zirconium production, for example, are 2.2–3.3 kt/year instead of 3.3–5 000 t/year of zircon concentrate [5]. The Chepetsk Metallurgical Plant has already started using baddeleyite concentrate since 2022.

When considering new projects for the zirconium raw material production, there are three groups of proposed development objects: 1) traditional placer of titanium-zirconium deposits; 2) complex ore rare-metal deposits, including the extractable useful mineral – zircon, 3) complex rare-metal deposits of eudialyte, the processing of which extracts the main useful component – zirconium.

As already noted, the development of complex deposits is planned. This is based on the release of the main useful component, and the fact that volumes of production of associated zircon concentrate have become uncontrollable. Nevertheless, the ongoing project for the development of the Zashikhinsky deposit with tantalum as the main component is feasible due to the extreme shortage (complete import dependence) of this product, Thus an additional 8 kt/year of zircon concentrate will be supplied for sale. As for the eudialytic Lovozerskoye deposit (Alluaive site), despite the high content of zirconium (the main component), the issue of development remains open. Currently there are no examples of industrial processing of such ores, but only projects and intentions to develop such deposits.

The most promising direction for the development of the national production of zirconium raw materials is the development of prepared titanium-zirconium alluvial deposits. The commissioning of the 1st stage of the Tuganskiy GOK will allow from 2023, up to 3.5 kt of zircon concentrate to be produced (30 % of the Russian demand for this product). The further construction of the 2nd stage of mining and processing complex will lead to an increase in its supply to 15 kt/year, This will completely cover the Russian demand for zirconium raw materials. Due to the increase in Russian demand for zirconium raw materials, projects may be implemented to develop the Central, Lukyanovskoye, Beshpagirskoye and Tara alluvial titanium-zirconium deposits. However, at the same time, the main components of their output will be ilmenite and rutile concentrates with a subordinate value of associated zircon concentrate. The main problem in the development of Russian placer titanium-zirconium deposits is the difficulty in ensuring the satisfactory quality of the resulting commercial concentrates. One of the reasons for the low quality of concentrates is the presence of newly formed films of limonite, kaolin and other exogenous minerals on zircon, ilmenite and rutile grains. This problem needs to be solved through the development and application of new technologies for the enrichment of concentrates, which will increase the economic efficiency of the development of Russian alluvial deposits.

The creation of foreign joint ventures for the extraction of zirconium and titanium raw materials in Vietnam and South Africa for subsequent supplies of the extracted raw materials to Russia is possible. However, the influence of the time factor arises in coordination with the commissioning of new national production of zirconium and titanium raw materials. Nevertheless, the issue remains relevant, and the implementation of these projects should be aimed not only at Russian demand for this raw material, but also at world markets.

The emerging trend of reducing import dependence on zirconium raw materials, and in the future its elimination will allow the consumption of zircon and zirconium oxides to be increased in the most capacious direction of their use: dampening the glaze of ceramic tiles. The presence of an independent and sufficient national mining base of zirconium raw materials will allow the development of the Russian production of metal zirconium, zirconium refractory and abrasive products, solid fuel energy cells and other zirconium-containing applications.

References

1. Fedoseev S., Tcvetkov P., Sidorov N. Development potential of Russian zirconium industry on world markets. *Journal of business and retail management research*, 2017;12(1):41–48. URL: https://jbrmr.com/cdn/article_file/content_50624_17-10-04-21-28-12.pdf

2. Bykhovsky L.Z., Remizova L.I., Chebotareva O.S. Zirconium resources of Russia: current state and prospects of the mineral resource base development. *Mineral resources of Russia. Economics and Management*. 2017;(2):11–18. (In Russ.)

3. Kabanov A.A., Akhmadshchin N.Yu. Tuganskoye deposit is the first–born industrial development of titanium-zirconium placers in Russia. *Gornyi Zhurnal*. 2021;(10):54–64. (In Russ.)

4. Larichkin F.D., Vorobyev A.G., Novoseltseva V.D., et al. Zirconium: resources, markets, prospects. *Cvetnye Metally*. 2013;(11):17–21. (In Russ.)

5. Shatalov V.V., Nikonov V.I., Kotsar M.L. Prospects for zirconium and hafnium supplies for nuclear power in Russia up to 2030. *Atomic Energy*. 2008;105(4):242–247. https://doi.org/10.1007/s10512-009-9092-7 (Orig. ver.: Shatalov V.V., Nikonov V.I., Kotsar M.L. Prospects for zirconium and hafnium supplies for nuclear power in Russia up to 2030. *Atomic Energy*. 2008;105(4):190–194. (In Russ.))

6. Boyarko G.Yu., Khatkov V.Yu., Bolsunovskaya L.M. The dynamics of ferroalloys commodity flows within Russia. *CIS Iron and Steel Review*. 2021; 21: 23–33. https://doi.org/10.17580/cisisr.2021.01.04

7. Vdovin K.N., Pivovarova K.G., Ponamareva T.B., Feoktistov N.A. Improved parting composition of zircon paint for steel casting. *Liteyshchik Rossii*. 2018;(6):14–17. (In Russ.)

8. Petrov I.M. Consumption of zirconium dioxide to produse high-tech ceramics. *Prospect and protection of mineral resources*. 2011;(6):90–92. (In Russ.)

9. Perks C., Mudd G. Titanium, zirconium resources and production: A state of the art literature review. *Ore Geology Reviews*. 2019;107:629–646. https://doi.org/10.1016/j.oregeorev.2019.02.025

10. Zagainov S.V., Reynbakh O.E. Ceramic industry as the main industry of zircon consumption. *Russian Economics Online Journal*. 2017;(1):1–9. (In Russ.)

11. Alekseeva T.I., Galevsky G.V., Rudneva V.V., Galevsky S.G. Application of zirconium carbide: Assessment, determination of dominant trends and prospects. In: *20th International Scientific and Research Conference – Metallurgy: Technologies, Innovation, Quality, metallurgy. iop Conference Series: Materials Science and Engineering*. 15–16 November, 2017. Novokuznetsk, Russia. 2018;411(119):012007. https://doi.org/10.1088/1757-899X/411/1/012007

12. Portnova E.N. Methods to improve mechanical characteristics of ceramics on the basis of zirconium and hafnium diborides (Review). *Bulletin of Perm University. Series: Chemistry*. 2020;10(2):180–190. https://doi.org/10.17072/2223-1838-2020-2-180-190 (In Russ.)

13. Ahunova D.R., Popova N.A., Lukin E.S., Pashkov O.D., Kucheryaev K.A. Composite ceramics based on zirconium dioxide for solid fuel elements (review). *Advances in Chemistry and Chemical Technology*. 2022;36(3):13–15. (In Russ.)

14. Kharitonov D.V., Shinkevich A.I., Malysheva T.V. The potential of the Russian raw material base of zirconium for production of ZrO2-based refractory materials. *Chernye Metally*. 2022;(8):17–21. https://doi.org/10.17580/chm.2022.08.03

15. Patyk-Kara N.G., Bochneva A.A., Chizhova I.A., et al. Mineral assemblages of titanium-zirconium sands at the central deposit, the East European platform. *Geology of Ore Deposits*. 2008;50(3):218–239. https://doi.org/10.1134/S1075701508030045 (Orig. ver.: Patyk-Kara N.G., Bochneva A.A., Chizhova I.A., et al. Mineral assemblages of titanium-zirconium sands at the central deposit, the East European platform. *Geologiya Rudnykh Mestorozhdeniy*. 2008;50(3):246–270. (In Russ.))

16. Quy N.C.T., Kirichenko Yu.V. Mineral potential of subsea deposits in Vietnamese part of South China Sea. *Russian Mining Industry*. 2020;(1):140–143. http://doi.org/10.30686/1609-9192-2020-1-140-143 (In Russ.)

17. Boyarko G.Yu., Khatkov V.Yu. Critical commodity flows of manganese raw materials in Russia. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*. 2020;331(4):38–53. https://doi.org/10.18799/24131830/2020/4/2592 (In Russ.)

18. Bagdasarov Yu.A., Pototskiy Yu.P., Zinkova O.N. Baddeleyite-containing stratiform bodies in old carbonate sequences. A possible new genetic type of zirconium deposits. *Transactions of the USSR Academy of sciences. Earth science sections*. 1990;315(6):144–148.

19. Seleznev A.O. Current status of development of the Zashikhinsky deposit: problems and prospects. Moscow: *JSC "Tekhnoinvest Alyans"*; 2021. 12 p. URL: https://vims-geo.ru/documents/515/15.20_Селезнев_Презентация_ТЕХНОИНВЕСТ_АЛЬЯНС_ВИМС.pdf (In Russ.)

20. Sheard E.R., Williams-Jones A.E., Heiligmann M., et al. Controls on the concentration of zirconium, niobium, and the rare earth elements in the Thor Lake rare metal deposit, Northwest Territories, Canada. *Economic Geology*. 2012;107(1):81–104. https://doi.org/10.2113/econgeo.107.1.81

21. Gysi A.P., Williams-Jones Anthony E., Collins P. Lithogeochemical vectors for hydrothermal processes in the Strange Lake peralkaline granitic REE-Zr-Nb deposit. *Economic Geology*. 2016;111(5):1241–1276. https://doi.org/10.2113/econgeo.111.5.1241

22. Moorea M., Chakhmouradiana A.R., Marianob A.N., Sidhua R. Corrigendum to "Evolution of rare-earth mineralization in the Bear Lodge carbonatite, Wyoming: Mineralogical and isotopic evidence". *Ore Geology Reviews*. 2015;64:499–521. https://doi.org/10.1016/j.oregeorev.2014.03.015

23. Riesgo García M.V., Krzemień A., Sáiz Bárcena L.C., et al. Scoping studies of rare earth mining investments: Deciding on further project developments. *Resources Policy*. 2019;64:101525. https://doi.org/10.1016/j.resourpol.2019.101525

24. Schønwandt H.K., Barnes G.B., Ulrich T. A description of the world-class rare earth element deposit, Tanbreez, South Greenland. *Rare Earths Industry: Technological, Economic, and Environmental Implications*. 2015:73–85. https://doi.org/10.1016/B978-0-12-802328-0.00005-X

25. Chanturiya V.A. Cientific substantiation and development of innovative processes for the extraction of zirconium and rare earth elements in the deep and comprehensive treatment of eudialyte concentrate. *Journal of Mining Institute*. 2022;256:505–516. https://doi.org/10.31897/PMI.2022.31

26. Spandler C., Morris C. Geology and genesis of the Toongi rare metal (Zr, Hf, Nb, Ta, Y and REE) deposit, NSW, Australia, and implications for rare metal mineralization in peralkaline igneous rocks. *Contributions to Mineralogy and Petrology*. 2016;171(121):104. https://doi.org/10.1007/s00410-016-1316-y

27. Möller V., Williams-Jones A.E. Magmatic and hydrothermal controls on the mineralogy of the basal zone, Nechalacho REE-Nb-Zr deposit, Canada. *Economic geology*. 2017;112(8):1823–1856. https://doi.org/10.5382/econgeo.2017.4531

28. Riesgo García M. V., Krzemień A., Manzanedo del Campo M.Á., et al. Rare earth elements mining investment: It is not all about China. *Resources Policy*. 2017;53:66–76. https://doi.org/10.1016/j.resourpol.2017.05.004

Information about the authors

Vitaly Yu. Khatkov – Head of Department, PJSC "Gazprom" Russia, St. Petersburg, Russian Federation; ORCID 0009-0002-0313-9166, Scopus ID 10046552700; e-mail V.Khatkov@adm.gazprom.ru

Grigory Yu. Boyarko – Dr. Sci. (Econ.), Cand. Sci. (Geol. and Min.), Professor, National Research Tomsk Polytechnic University, Tomsk, Russian Federation; ORCID 0000-0002-0715-7807, Scopus ID 56350674500; e-mail gub@tpu.ru

Liudmila M. Bolsunovskaya – Cand. Sci. (Philolog.), Assistant Professor, National Research Tomsk Polytechnic University, Tomsk, Russian Federation; ORCID 0000-0002-1499-8970, Scopus ID 56350747600; e-mail bolsunovskl@tpu.ru

Artem M. Dibrov – Senior Lecturer, Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russian Federation; ORCID 0000-0002-2954-9422; e-mail dibrov5@yandex.ru

Yulia A. Dibrova (Bolsunovskaya) – expert, National Research Tomsk Polytechnic University, Tomsk, Russian Federation; ORCID 0000-0003-4203-1609, Scopus ID 56350806400; e-mail: juliadib@yandex.ru

Received 13.02.2023
Revised 16.03.2023
Accepted 17.03.2023

eISSN 2500-0632
https://mst.misis.ru/

MINING ROCK PROPERTIES. ROCK MECHANICS AND GEOPHYSICS

Research paper

https://doi.org/10.17073/2500-0632-2023-01-97
УДК 622.276

Estimation of multistage hydraulic fracturing parameters using 4D simulation

I.I. Bosikov[1], R.V. Klyuev[2], I.V. Silaev[3], D.E. Pilieva[1]
[1] *North Caucasian Mining and Metallurgical Institute, Vladikavkaz, Russia*
[2] *Moscow Polytechnic University, Moscow, Russia*
[3] *North Ossetian State University named after K. L. Khetagurov, Vladikavkaz, Russia*
✉ *kluev-roman@rambler.ru*

Abstract
At the present stage, most oil and gas condensate fields in the southern part of the East Siberian oil and gas province are characterized by an increasing proportion of difficult oil reserves in tight reservoirs. Multistage hydraulic fracturing (MHF) is proposed for the offshore Challenger Sea field (Southeast Dome). The implementation of this technique at a shelf will be a source of additional risks. For example, the properties of the RR-2 overlying seal have not been unambiguously assessed, and there are a number of geological uncertainties, such as the tectonic regime. However, there are a number of arguments in favor of MHF: heterogeneity of the reservoir; low permeability; low water cut of the field; sufficient thickness of the pay zone; and the overlying seal. One more positive factor is that sand ingress is not observed in the process of oil production. The selection of a principal well completion scheme on the eastern side of the RR-7 formation is aimed at effectively recovering the remaining reserves. The objectives of the study performed are: to create a geological and hydrodynamic model of the Challenger Sea (Southeast Dome); develop 1D and 3D geomechanical models; evaluate oil production forecasts based on fundamentally different well completion schemes; and determine the optimum parameters for multistage hydraulic fracturing. The research methods included: petrophysical methods; logging methods; core studies; drilling reports and formation testing data; and 3D, 4D geomechanical simulation. Other geophysical methods included acoustic logging, density logging, and gamma-ray logging. After building a geomechanical model of the reservoir at the beginning of drilling, a hydrodynamic calculation was performed. This established the reservoir pressures and saturations at certain points in time. The results made it possible for the principal stress directions, the values of effective and principal stresses, and the values of elastic strains to be determined. In order to assess MGF process efficiency, production forecasts were made using a hydrodynamic model for an exploration well with conventional completion (perforated liner) and with five-stage MGF. In the first case, the accumulated production was 144 kt over 15 years, and in the second case, 125 kt over 17 years. The difference in cumulative production is due to different initial well flow rates, as well as the rate of oil withdrawal during the first few years of development. Thereafter, the production and daily flow rate curves showed similar behavior. In order to select the most effective option, an economic analysis of the efficiency was performed.

Keywords
oil and gas condensate field, oil, well, core, porosity, geological model, geomechanical model, geological and hydrodynamic model (reservoir simulation model), acoustic logging, density logging

For citation
Bosikov I. I., Klyuev R. V., Silaev I. V., Pilieva D. E. Estimation of multistage hydraulic fracturing parameters using 4D simulation. *Mining Science and Technology (Russia)*. 2023;8(2):141–149. https://doi.org/10.17073/2500-0632-2023-01-97

СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Оценка параметров многостадийного гидравлического разрыва пласта с помощью 4D моделирования

И.И. Босиков[1], Р.В. Клюев[2], И.В. Силаев[3], Д.Э. Пилиева[1]
[1] *Северо-Кавказский горно-металлургический институт (ГТУ), г. Владикавказ, Российская Федерация*
[2] *Московский политехнический университет, г. Москва, Российская Федерация*
[3] *Северо-Осетинский государственный университет им. К. Л. Хетагурова, г. Владикавказ, Российская Федерация*
✉ *kluev-roman@rambler.ru*

Аннотация
На современном этапе большинство нефтегазоконденсатных месторождений южной части Восточно-Сибирской нефтегазоносной провинции характеризуется ростом доли трудноизвлекаемых запасов нефти в плотных коллекторах. В акватории моря на месторождении Челенджер-море (Юго-Вос-

точный купол) предлагается применить многостадийный гидравлический разрыв пласта (МГРП). Внедрение этой технологии на шельфе станет источником дополнительных рисков. Например, однозначно не оценены свойства покрышки RR-2, есть ряд геологических неопределенностей, например, тектонический режим. Однако есть ряд аргументов в пользу МГРП – неоднородность коллектора, небольшая проницаемость, низкая обводненность месторождения, достаточная мощность продуктивного пласта и покрышки. Также хорошим фактором является то, что в процессе добычи не наблюдается пескопроявлений. Выбор принципиальной схемы заканчивания скважин на восточном борту пласта RR-7 производится с целью эффективного извлечения остаточных запасов. Задачи проведенной работы заключаются в создании геолого-гидродинамической модели Челенджер-море (Юго-Восточный купол); разработке 1D и 3D геомеханических моделей; оценке прогнозов по добыче с использованием принципиально разных схем заканчивания скважин; определении оптимальных параметров многостадийного гидравлического разрыва пласта. Методы исследований включают в себя петрофизические методы; методы ГИС; керновые исследования; буровые сводки и данные об испытаниях пластов; 3, 4D геомеханическое моделирование; геофизические методы: акустический каротаж, плотностной каротаж, гамма-каротаж. После построения геомеханической модели пласта на начало бурения производится гидродинамический расчет, по итогам которого определены кубы пластовых давлений и насыщений на определенные моменты времени. Полученные результаты позволили определить направления главных напряжений, значения эффективных и главных напряжений, а также величины упругих деформаций. Для оценки технологической эффективности МГРП были произведены прогнозы добычи на гидродинамической модели по разведочной скважине с традиционным заканчиванием (перфорированный хвостовик) с пятью стадиями МГРП. В первом случае накопленная добыча составила 144 тыс. т за 15 лет, во втором – 125 тыс. т за 17 лет. Разница в накопленной добыче обусловлена разными стартовыми дебитами скважин, а также темпами отбора в первые несколько лет разработки, а в дальнейшем кривые добычи и суточных дебитов демонстрировали схожее поведение. Для выбора наиболее эффективного варианта выполнен экономический анализ эффективности.

Ключевые слова

нефтегазоконденсатное месторождение, нефть, скважина, керн, пористость, геологическая модель, геомеханическая модель, геолого-гидродинамическая модель, акустический каротаж, плотностной каротаж

Для цитирования

Bosikov I.I., Klyuev R.V., Silaev I.V., Pilieva D.E. Estimation of multistage hydraulic fracturing parameters using 4D simulation. *Mining Science and Technology* (*Russia*). 2023;8(2):141–149. https://doi.org/10.17073/2500-0632-2023-01-97

Introduction

At the present stage, most oil and gas condensate fields in the southern part of the East Siberian oil and gas province are characterized by an increasing number of difficult oil reserves in tight reservoirs [1, 2].

Multistage hydraulic fracturing (MHF) is an effective method of enhancing oil recovery and production in terrigenous sediments all over the world [3, 4].

In the offshore area of the Challenger Sea field (Southeast Dome), the application of MHF is proposed. The implementation of this technique at a shelf will be a source of additional risks. For example, the properties of the RR-2 overlying seal have not been unambiguously assessed, and there are a number of geological uncertainties, such as the tectonic regime. However, there are arguments in favor of MHF: heterogeneity of the reservoir [7, 8]; low permeability; low water cut of the field; sufficient thickness of the productive formation and the overlying seal. Another positive factor is that sand ingress is not observed in the process of oil production.

General information about the field

The Challenger Sea oil and gas condensate field (Southeast Dome) is located in the territory of Stoykovsky District of Primorsky Region, 40 km southeast of the town of Serov on the Southeast Stoykovsky shelf, at a latitude of the southern end of the Starkovsky Bay.

The Challenger Sea field was discovered in 2011. The field is multilayer and contains gas-condensate and oil-gas-condensate pools of different types, such as lithological, and layer-arch. In terms of structure, the field is very complex, and large in terms of the size of its reserves [11, 12].

Geographically, the area under consideration is confined to the southern range of the East Siberian ridge. The terrain is hilly, the landscape is partly forested and partly marshy. The maximum altitude does not exceed 200 m above sea level. The bottom relief in the area of the field is poorly dissected. The climate of the area is typical of Primorye: winters are harsh, snowy, windy, with frequent snowstorms.

Tectonically, the Challenger Sea field (Southeast Dome) is confined to a large megantycline located in the northern part of the eponymous anticlinal zone, extending for more than 200 km on the shelf of the East Siberian Ridge in the northwestern direction [13, 14].

The southeastern shelf sequence is composed of Mesozoic and Cenozoic sediments, forming two structural levels. The lower level, basement, is composed of faulted and folded metamorphic rocks of Cretaceous age. The sedimentary cover (section) consists exclusively of Cenozoic sediments of Neogene age. In the sedimentary section, Ust-Davydovsky and Prikhankaisky horizons can be found. The latter, in turn, is subdivided into Lower Prikhankaisky and Upper Prikhankaisky subhorizons. The thickness of the Prikhankaisky horizon ranges 2000 to 3000 m, increasing from northeast to southwest. The Lower Prikhankaisky horizon is composed of gray sandstone, often silty and clayey, with interlayers of siltstone and clay. The Upper Prikhankaisky horizon is composed of sandstone and siltstone in the lower part, and loose sands with interlayers of clays in the upper part.

The productive (pay) oil and gas reservoirs are confined to the Upper Prikhankaisky subhorizon. The main productive formations in the Challenger Sea field (Southeast Dome) are RR-2, RRI-1, RRI-2 formations.

Research techniques

The research methods and information sources included petrophysical methods: logging methods; core studies; drilling reports and formation testing data; and 3D, 4D geomechanical simulation. The geophysical methods included acoustic logging, density logging, gamma-ray logging.

Technical part

The research was conducted with the RR-2 formation. The pay formation is characterized by lateral heterogeneity. The permeability and porosity at the eastern edge are significantly worse than those at the western edge, so an MHF option was considered for effective recovery of residual oil reserves.

Construction of a 3D geomechanical model of the Challenger Sea field (Southeast Dome)

Core Studies. The core is the only direct source of information about a pay zone and an overlying seal used in both geological-and-hydrodynamic and geomechanical simulations [15, 16]. Special studies were carried out on core samples from wells drilled at the Challenger Sea field (Southeast Dome). Aimed at clarifying the mechanical properties of rocks and to build a reliable geomechanical model.

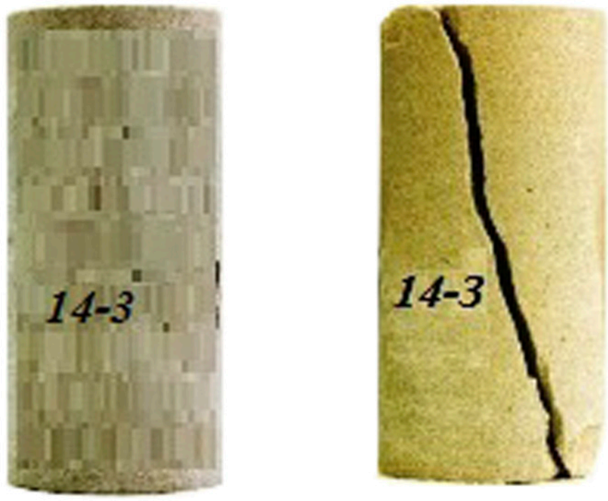


Fig. 1. Cylindrical core sample before and after a test to determine ultimate compressive strength

Core from wells 88-R and 120-R (at Challenger Sea field, only within RR-2 formation) was used in the studies. The reservoir characterization by core is poor, and rock material was sampled in only two wells from the upper and middle parts of the reservoir. When selecting samples, the lithological features of the rocks were taken into account. Before selecting the samples, the core was examined, the primary description of a rock was studied, and the thin sections were viewed under a microscope (Fig. 1). A total of 87 samples were examined.

Construction of one-dimensional geomechanical models

A one-dimensional geomechanical model is a set of elastic and strength properties, and principal stresses curves along a well path. These properties are: pore pressure; vertical stress (rock pressure); maximum and minimum horizontal stress; static and dynamic Young's modulus; Poisson's ratio; ultimate compressive strength; ultimate tensile strength; and internal friction angle.

This data set allows for permissible drilling fluid parameters to be determined, in order to prevent problems during drilling, prevent sand ingress during production well operation, and plan hydraulic fracturing in horizontal and inclined wells [17, 18]. An 1D geomechanical model for one of the key wells is shown in Fig. 2.

When creating the geomechanical model, a variety of data, including well logging methods, core studies, drilling reports, and formation testing data was used [19, 20]. The required amount of methods is presented in Table 1.

eISSN 2500-0632
https://mst.misis.ru/

Geological model and hydrodynamics

Construction of a 3D geomechanical model at the beginning of drilling was made on the basis of a geological model. The change in the stress-strain state of a formation over time is taken into account through using hydrodynamic simulation results.

Geomechanical simulation places stringent requirements on a geologic model. Therefore a new geologic model was built for this project taking into account all of the geologic information as well as the technical characteristics required for successful geomechanical calculations.

The model was built based on a 100×100 m grid, the thickness of cells was 1 m on average, and the total number of cells did not exceed 300 thousand. Such parameters were selected empirically, as geomechanical and hydrodynamic calculations require large computing power. In addition, the RR-2 reservoir overlying seal was superimposed in the geological model to simulate the strength properties of the seal rock in detail. All disjunctive dislocations were included in the model.

3D geomechanical model: at the beginning of drilling

A 3D geomechanical model at the beginning of drilling was constructed by reconstructing a stress-strain state on a relatively large fragment of the Earth's crust. For this purpose, additional cells with rocks were added to the top, bottom, and sides of a geomechanical model, which "pressed" on the cells in the model itself and thus formed stresses [21]. In addition, all cells were filled with elastic and strength properties of rocks and faults in accordance with those permeability and porosity dependences that were obtained at the one-dimensional simulation stage (Fig. 3). In Fig. 3, a rectangle marks the area where the geological model of the reservoir was built.

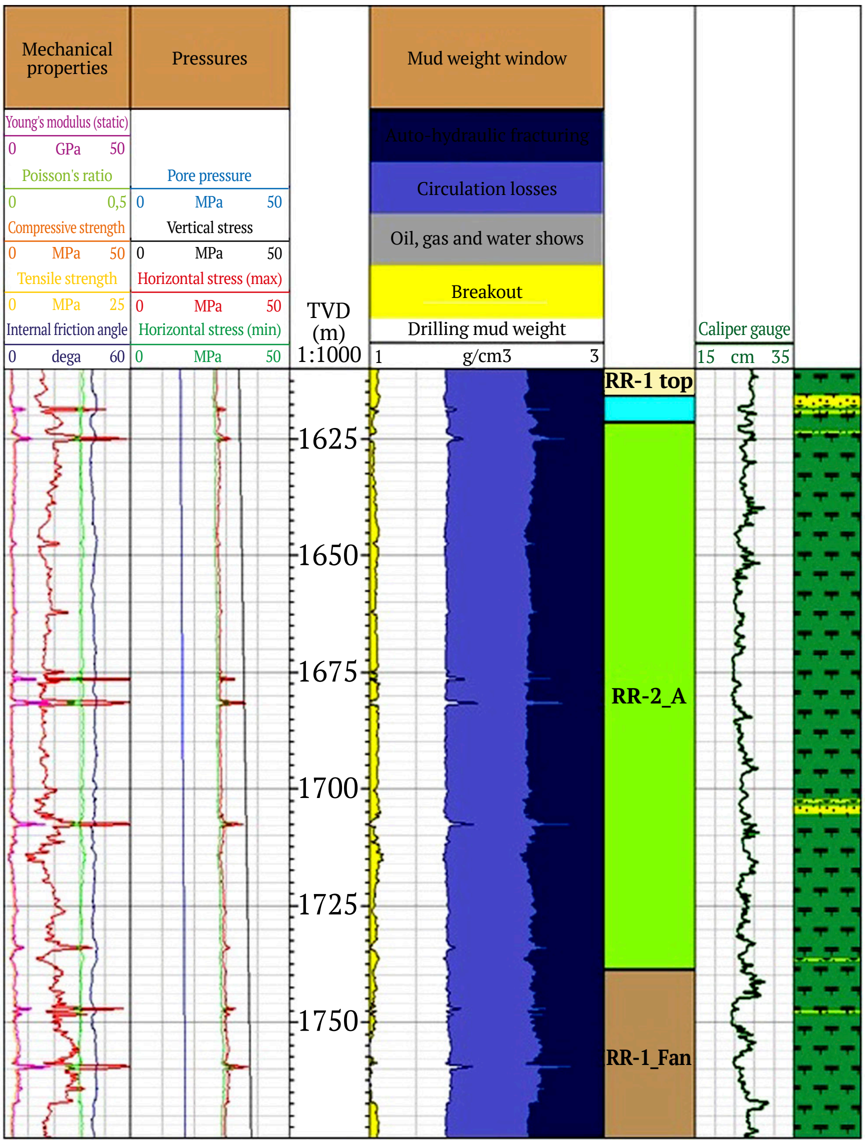


Fig. 2. 1D geomechanical model for 22-R well at the Challenger Sea field (Southeast Dome)

Table 1

Assessment of the completeness of initial data on the studies performed

Data type	Data source	Applications	Degree of confidence
Geomechanical logging			
Acoustic logging	A set of exploration well logging methods	Geomechanical model construction – elastic properties	Low
Density logging	Recorded in the majority of wells in the field	Geomechanical model construction – elastic properties and vertical stress	High
Gamma-ray logging	Recorded in all wells	Calculation of internal friction angle	
Core			
Young's modulus (dynamic)	Laboratory research	Calculation of strength properties	Medium — new laboratory tests; core characterizes only the productive part of the reservoir
Poisson's ratio		Calculation of horizontal stresses	
Young's modulus (static)		Calculation of horizontal stresses	
Ultimate compressive strength		Evaluation of wellbore stability	
Tensile strength			
Other data			
Information about drilling problems	Drilling reports	Geomechanical model calibration	Medium - no drilling problems in the formation interval
Initial reservoir pressure information	Sampling and dynamic well test data	Geomechanical model calibration and pore pressure assessment	High
Stratigraphic picks	Diagram of detailed correlation from the geomechanical model	Applied in the construction of permeability and porosity dependencies, prediction of properties	High
Sequence lithology	Core description, well log interpretation data		High

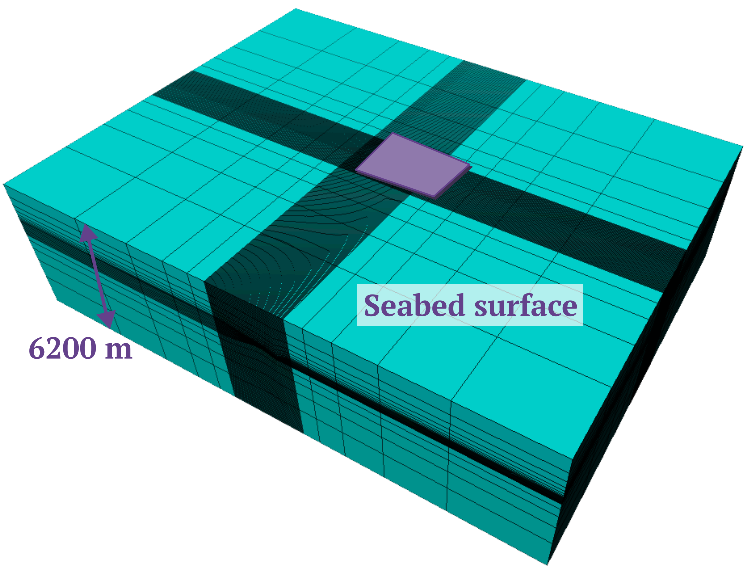


Fig. 3. General view of geomechanical grid

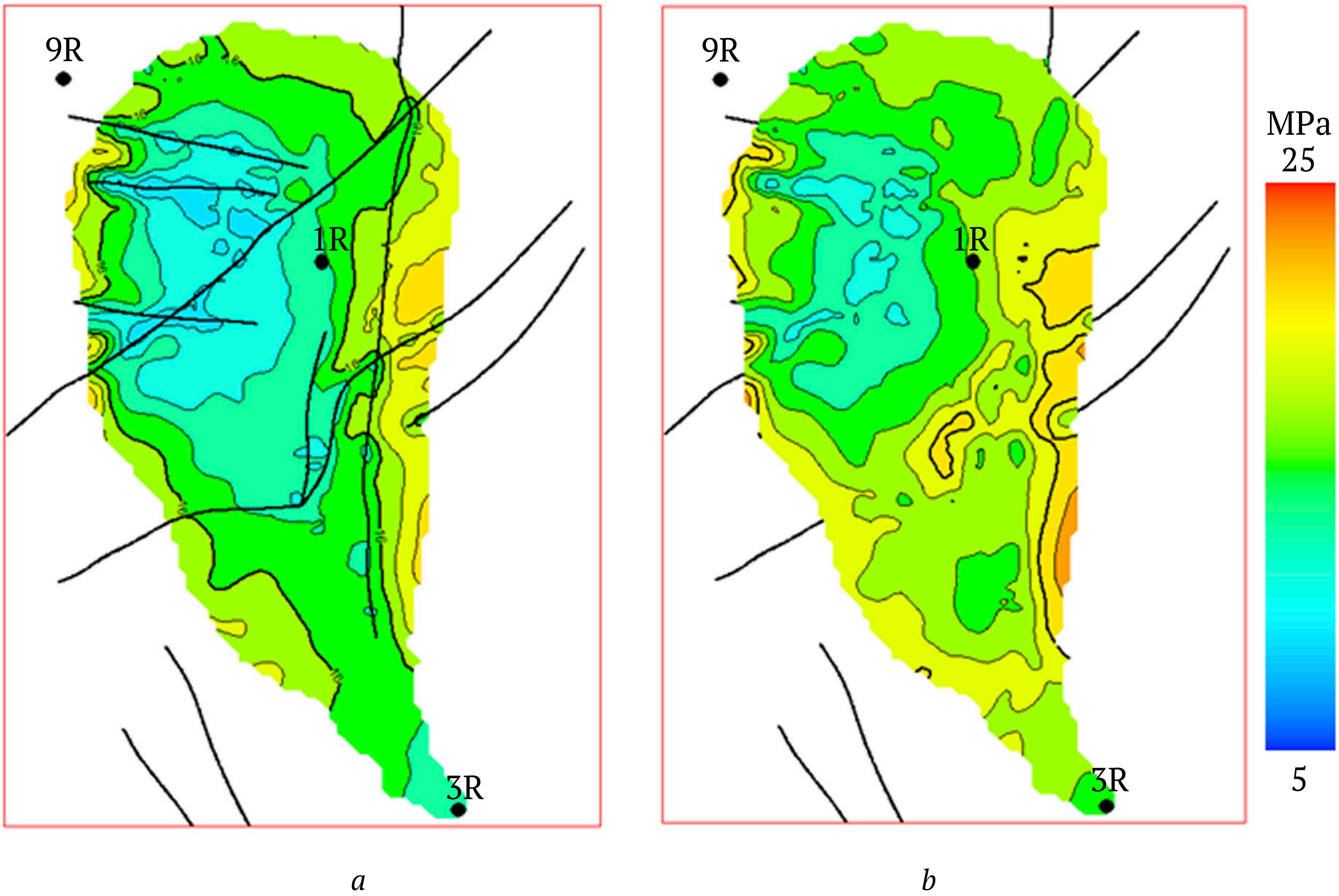


Fig. 4. Comparison of effective stress maps as of 01.01.2015 (*a*) and 01.01.2022 (*b*)

Discussion: the author's point of view and direct research

In this paper, we calculated the state change over time (4D geomechanical model). After building a geomechanical model of the reservoir at the beginning of drilling, a hydrodynamic calculation was performed. This established the reservoir pressures and saturations at certain points in time. These were the input parameters for calculating a stress-strain state at these points in time. As a result of the calculation, the following was obtained: the directions of principal stresses; the values of effective and principal stresses (Fig. 4); as well as the values of elastic strains. In addition, Mohr's circles can be used to estimate how close the rock is to fracture under reservoir conditions. In Figure 4, the fracture line is shown in dark green, and the ratios of normal and tangential stresses in a single cell are shown in the form of a classic Mohr circle. When a stress circle touches the fracture line, this leads to rock continuity failure and a fault or fracture is formed. In the case of the RR-2 reservoir, the rocks are in a stable state at this point in time and during the development period for which the model was built.

A one-dimensional post-drilling geomechanical model allows multi-stage hydraulic fracturing to be planned. This includes the number of stages, positioning multi-stage hydraulic fracturing ports and packers.

The economic efficiency of the two options is presented in Table 2.

Table 2

Performance (efficiency) indicators

Indicator	Values	
	Option 1	Option 2
Internal rate of return (IRR), %	15	22
Accumulated production, kt	165	212
Net present value (NPV), million rubles	327	612
Payback period, year	7.5	5

In order to assess the process efficiency of MGF, production forecasts were made using a hydrodynamic model for an exploration well with conventional completion (perforated liner) and with five-stage MGF. In the first case, the accumulated production was 165 kt over 15 years, and in the second case, 212 kt over 17 years. The difference in the cumulative production is due to the different initial well flow rates, as well as the rate of oil withdrawal during the first few years of development. Thereafter, the production and daily flow rate curves showed similar behavior. An economic analysis of the efficiency was performed, in order to select the most effective option.

A positive economic effect is the most important indicator of the success of the methods used and a prerequisite for their implementation. As part of the research, the economic effect of drilling of a new extended-reach exploration well with conventional completion and that of drilling the same well with MHF were evaluated and compared. Such economic indicators as costs, revenue, depreciation and residual value of a well, net profit (cash flow) were calculated, including with discounting (E = 10 %). This also took into account: income tax, export duty, mineral extraction tax, and property tax. The cost-effectiveness was assessed by three indicators: NPV, IRR, and payback period.

Conclusion

When assessing the parameters of multistage hydraulic fracturing using 4D simulation, the following tasks were addressed:

1. The advantages and disadvantages of the parameters of the MHF technique on a shelf were analyzed.

2. A preliminary 4D geomechanical model of RR-2 reservoir of the Challenger Sea field (Southeast Dome) was built.

3. 1D and 3D geomechanical models were developed and additional core studies were conducted at Odoptu Sea, taking into account RR-2 reservoir features to refine the geomechanical model.

4. Production forecasts were assessed with the use of fundamentally different well completion schemes.

5. The optimal parameters of multistage hydraulic fracturing were determined.

6. Based on the hydrodynamic model, the predicted production from a design well with conventional completion (perforated liner in a horizontal wellbore) and with multistage hydraulic fracturing (5 stages) were calculated.

7. The economic efficiency of the development options without and with MHF was evaluated. The base case (option) is economically viable, IRR is 15 %, NPV is 327 mln rubles. The second option is economically viable at discount rate of 22 %; NPV is 612 mln rubles.

8. Applying MHF (5 stages) will almost double NPV and increase the cumulative production by 30 %.

References

1. Gayduk V.V. The nature of the oil and gas potential of the Tersko-Sunzhensky Oiland Gas-Bearing Region. *Geology, Geophysics and Development of Oil and Gas Fields*. 2019;(2):40–46. (In Russ.) https://doi.org/10.30713/2413-5011-2019-2-40-46

2. Danilov V.N. Formation of thrusts and hydrocarbon potential of Urals Foredeep. *Russian Oil and Gas Geology*. 2021;(1):57–72. (In Russ.) https://doi.org/10.31087/0016-7894-2021-1-57-72

3. Vishkai M., Gates I. On multistage hydraulic fracturing in tight gas reservoirs: Montney Formation, Alberta, Canada. *Journal of Petroleum Science and Engineering*. 2018;174:1127–1141. https://doi.org/10.1016/j.petrol.2018.12.020

4. Wasantha P.L.P., Konietzky H., Xu C. Effect of in-situ stress contrast on fracture containment during single- and multi-stage hydraulic fracturing. *Engineering Fracture Mechanics*. 2019;205:175–189. https://doi.org/10.1016/j.engfracmech.2018.11.016

5. Liu Y., Ma X., Zhang X. et al. 3D geological model-based hydraulic fracturing parameters optimization using geology–engineering integration of a shale gas reservoir: A case study. *Energy Reports*. 2022;8:10048–10060. https://doi.org/10.1016/j.egyr.2022.08.003

6. Yaghoubi A. Hydraulic fracturing modeling using a discrete fracture network in the Barnett Shale. *International Journal of Rock Mechanics and Mining Sciences*. 2019;119:98–108. https://doi.org/10.1016/j.ijrmms.2019.01.015

7. Ouchi H., Foster J.T., Sharma M.M. Effect of reservoir heterogeneity on the vertical migration of hydraulic fractures. *Journal of Petroleum Science and Engineering*. 2017;151:384–408. https://doi.org/10.1016/j.petrol.2016.12.034

8. Li J.-Ch., Yuan B., Clarkson Ch.R., Tian J.-Q. A semi-analytical rate-transient analysis model for light oil reservoirs exhibiting reservoir heterogeneity and multiphase flow. *Petroleum Science*. 2022;20(1):309–321. https://doi.org/10.1016/j.petsci.2022.09.021

9. Liu P., Wang Zh., Lu K., Zhang Zh. Effect of sandstone and mudstone thickness on artificial fracturing for hydrocarbon extraction from low-permeability reservoirs. *Natural Gas Industry B*. 2022;9(4):411–425. https://doi.org/10.1016/j.ngib.2022.08.001

10. Mohamad-Hussein A., Mendoza P.E.V., Delbosco P.F. et al. Geomechanical modelling of cold heavy oil production with sand. *Petroleum*. 2021;8(1):66–83. https://doi.org/10.1016/j.petlm.2021.02.002

11. Bosikov I.I., Klyuev RV., Gavrina O.A. Analysis of geological-geophysical materials and qualitative assessment of the oil and gas perspectives of the Yuzhno-Kharbizhinsky area (Northern Caucasus). *Geology and Geophysics of Russian South*. 2021;11(1):6–21. (In Russ.) https://doi.org/10.46698/VNC.2021.36.47.001

12. Klyuev R.V., Bosikov I.I., Mayer A.V., Gavrina O.A. Comprehensive analysis of the effective technologies application to increase sustainable development of the natural-technical system. *Sustainable Development of Mountain Territories*. 2020;12(2):283–290. (In Russ.) https://doi.org/10.21177/1998-4502-2020-12-2-283-290

13. Manikovsky P., Vasyutich L., Sidorova G. Methodology for modeling ore deposits in the GIS Micromine. *Vestnik Zabaykalskogo Gosudarstvennogo Universiteta*. 2021;27(2):6–14. (In Russ.) https://doi.org/10.21209/2227-9245-2021-27-2-6-14

14. Lyashenko V.I., Khomenko O.E., Golik V.I. Friendly and resource-saving methods of underground ore mining in disturbed rock masses. *Mining Science and Technology* (*Russia*). 2020;5(2):104–118. https://doi.org/10.17073/2500-0632-2020-2-104-118

15. Tyulenev M.A., Markov S.O., Gasanov M.A., Zhironkin S.A. Numerical modeling in the structural study of technogenic rock array. *Geotechnical and Geological Engineering*. 2018;36(5):2789–2797. https://doi.org/10.1007/s10706-018-0501-3

16. Tretiakova O.G., Tretiakov M.F., Sofronov G.V. Modeling of terrigenous collectors and assessment of forecast resources of placer diamond potential on Khanninsky site with the Mining-and-Geological Information System (GGIS) Micromine. *Vestnik of North-Eastern Federal University. Earth Sciences*. 2019;(4):20–30. (In Russ.) https://doi.org/10.25587/SVFU.2020.16.49722

17. Saveliev D.E., Makatov D.K., Portnov V.S., Gataullin R.A. Morphological, textural and structural features of chromitite deposits of Main ore field of Kempirsay massif (South Urals, Kazakhstan). *Georesursy*. 2022;24(1):62–73. (In Russ.) https://doi.org/10.18599/grs.2022.1.6

18. Stolyarenko V.V., Minakov A.V., Ryaboshapko A.G. Mineral potential modelling for gold mineralization within the Mesozoic depressions in the Central-Aldan ore-placer area (on the example of the Upper Yakokutsk ore field). *Ores and Metals*. 2022;(1):44–76. (In Russ.) https://doi.org/10.47765/0869-5997-2022-10003

19. Bosikov I.I., Klyuev R.V. Assessment of Berezkinskoye ore field prospectivity using Micromine software. *Mining Science and Technology* (*Russia*). 2022;7(3):192–202. https://doi.org/10.17073/2500-0632-2022-3-192-202

20. Khan R.A., Awotunde A.A. Determination of vertical/horizontal well type from generalized field development optimization. *Journal of Petroleum Science and Engineering*. 2018;162:652–665. https://doi.org/10.1016/j.petrol.2017.10.083

21. Rybak Y., Khayrutdinov M.M., Kongar-Syuryun C.B., Tyulyayeva Y.S. Resource-saving technologies for development of mineral deposits. *Sustainable Development of Mountain Territories*. 2021;13(3):405–415. (In Russ.) https://doi.org/10.21177/1998-4502-2021-13-3-406-415

Information about the authors

Igor I. Bosikov – Cand. Sci. (Eng.), Head of the Oil and Gas Department, North Caucasian Mining and Metallurgical Institute, Vladikavkaz, Russian Federation; ORCID 0000-0001-8930-4112, Scopus ID 56919738300

Roman V. Klyuev – Dr. Sci. (Eng.), Professor of the Department of the Technique of Low Temperature named after P.L. Kapitza, Moscow Polytechnic University, Moscow, Russian Federation; ORCID 0000-0003-3777-7203, Scopus ID 57194206632; e-mail kluev-roman@rambler.ru

Ivan V. Silaev – Cand. Sci. (Eng.), Head of the Department of Physics and Astronomy, North Ossetian State University named after K.L. Khetagurov, Vladikavkaz, Russian Federation; ORCID 0000-0003-2490-1578, Scopus ID 57189031683

Dina E. Pilieva – Cand. Sci. (Sociol.), Associate Professor of the Department of Philosophy and Social and Humanitarian Technologies, North Caucasian Mining and Metallurgical Institute, Vladikavkaz, Russian Federation; ORCID 0000-0002-6712-6789, Scopus ID 57201777149

Received 15.01.2023
Revised 02.04.2023
Accepted 16.04.2023

SAFETY IN MINING AND PROCESSING INDUSTRY AND ENVIRONMENTAL PROTECTION

Research paper

https://doi.org/10.17073/2500-0632-2022-10-13
УДК 622.4

Parameterization of a ventilation network model for the analysis of mine working emergency ventilation modes

M.O. Perestoronin ✉, **O.S. Parshakov**, **M.D. Popov**
Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation
✉ *per.maks1m.97@gmail.com*

Abstract
Digital simulation of mine fires and explosions is an important stage in the process of developing technical solutions and measures aimed at improving the safety of personnel involved in underground mining. Correct simulation results determine the effectiveness of decisions in the event of an actual emergency situation. In this regard, due attention should be paid to each stage of the simulation, and especially to the initial stage of model parameterization. This study formulates a general principle for determining the parameters of mine fire and explosion models, in order to assess their development using the AeroNetwork analytical package. Such parameters in the event of a fire are heat and gas (afterdamp) releases. In the event of an explosion, excessive pressure at the shock front in the explosion origin. It has been established that when simulating a fire, it is advisable to use equivalent heat and gas releases determined by the content of combustible components in the combustion origin. In the event of burning mining equipment, these parameters can be calculated on the basis of the technical characteristics of a machine. Furthermore, when simulating an unauthorized explosion of explosives, the excess pressure determined by the dimensionless length of the active combustion area is calculated taking into account the weight and specific heat of an explosive, as well as the geometric parameters of a mine working. When simulating an explosion of a methane-air mixture (firedamp), the excess pressure is calculated taking into account the gas content of rocks in terms of free combustible gases, the length of a blast cut, the size of the area of increased fracturing, and the lower explosive limit of methane. Based on the proposed principle of the parameterization of emergency models, as an example, a model of fire and explosion development in existing extended dead-end workings (more than 1000 m long) passing coaxially to each other at different heights was developed. The numerical simulation of different emergency situations in workings was carried out, taking into account performing mining in difficult mining conditions.

Keywords
mine, underground fire, explosion, emergency, shock wave, simulation, AeroNetwork, parameterization, safety

Acknowledgments
The study was carried out with the financial support of the Russian Science Foundation as part of Project No. 20-35-90072.

For citation
Perestoronin M.O., Parshakov O.S., Popov M.D. Parameterization of a ventilation network model for the analysis of mine working emergency ventilation modes. *Mining Science and Technology (Russia)*. 2023;8(2):150–161. https://doi.org/10.17073/2500-0632-2022-10-13

ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Параметризация модели вентиляционной сети при анализе аварийных режимов проветривания систем горных выработок

М.О. Пересторонин ✉, **О.С. Паршаков**, **М.Д. Попов**
Горный институт Уральского отделения Российской академии наук (ГИ УрО РАН), г. Пермь, Российская Федерация
✉ *per.maks1m.97@gmail.com*

Аннотация
Численное моделирование развития рудничных пожаров и взрывов является важным этапом в процессе разработки технических решений и мероприятий по повышению безопасности персонала, задействованного на подземных работах. От корректности результатов моделирования зависит, насколько принятые решения будут эффективны в случае возникновения реальной аварийной ситуации. В связи с этим долж-

ное внимание необходимо уделять каждой стадии моделирования, и в особенности начальной – стадии параметризации модели. В настоящем исследовании сформулирован общий принцип определения параметров моделей рудничных пожаров и взрывов для оценки их развития при помощи аналитического комплекса «АэроСеть». Такими параметрами в случае пожара являются тепло- и газовыделения, а в случае взрыва – избыточное давление на фронте ударной волны в очаге взрыва. Установлено, что при моделировании пожара целесообразно использовать эквивалентные тепло- и газовыделения, определяемые содержанием горючих компонентов в источнике горения. В случае горения горнопроходческой техники данные параметры возможно рассчитать на основании технических характеристик машины. В свою очередь, при моделировании несанкционированного взрыва взрывчатых материалов избыточное давление, определяемое безразмерной длиной активного участка горения , рассчитывается с учетом массы и удельной теплоты сгорания взрывчатого вещества, а также геометрических параметров выработки. При моделировании взрыва метановоздушной смеси избыточное давление рассчитывается с учетом газоносности пород по свободным горючим газам, длины буровзрывной заходки, размеров области повышенного трещинообразования, а также нижнего предела взрываемости метана. На основании предлагаемого принципа параметризации аварийных моделей в качестве примера выполнена разработка модели развития пожара и взрыва в существующих протяженных тупиковых выработках (длиной более 1000 м), проходимых соосно друг другу на разных высотных отметках. Произведено численное моделирование различных аварийных ситуаций в выработках с учетом ведения горных работ в сложных горнотехнических условиях.

Ключевые слова

рудник, подземный пожар, взрыв, аварийная ситуация, ударная волна, моделирование, АэроСеть, параметризация, безопасность

Благодарности

Исследование выполнено при финансовой поддержке Российского научного фонда в рамках проекта № 20-35-90072.

Для цитирования

Perestoronin M.O., Parshakov O.S., Popov M.D. Parameterization of a ventilation network model for the analysis of mine working emergency ventilation modes. *Mining Science and Technology* (*Russia*). 2023;8(2):150–161. https://doi.org/10.17073/2500-0632-2022-10-13

Introduction

In accordance with Industrial Safety Law No. FZ-116, a mining enterprise is a hazardous production facility characterized by an increased risk of emergency. The issue of the safety of people is especially acute in dead-end underground workings under construction, which have only one emergency exit from a work area. For such dangerous working conditions, technical solutions and measures need to be developed, in order to ensure the safe evacuation of people and the effective conduct of mine rescue operations. At the same time, it is advisable to use the capabilities of numerical simulation for developing solutions and measures.

According to statistics [1, 2], mine fires and explosions are the most destructive and frequent accidents. Therefore, in order to develop optimal measures to improve the safety of miners, these particular emergency situations need to be predictable. However, adequate parameterization of such models is a highly complex task.

For instance, in terms of the spread of combustion products in mine workings, the issue of fire development simulation is covered in the studies [3–5]. A common drawback of the studies presented here and other existing studies in this field is that emergency heat and gas releases are considered without reference to a specific origin of combustion. As a rule, the abstract parameters that reflect the possible most unfavorable aerological and heat-and-gas-dynamic conditions are used as input data for simulation, such as 100 % gas release [6, 7] or 50 MW heat generation [8] in the case of a "severe" fire. This simplification is due to the significant complexity of calculating these parameters, since they can be determined only based on the results of full-scale experiments, such as in [9, 10], or in additional fire physical process simulation such as in [11].

Analytical calculation of heat and gas releases in the case of a fire, taking into account specific mining conditions is optimal. This approach allows for the adoption of adequate simulation parameters at relatively low labor costs. To date, since such analytical relationships are not available, and no methodology for calculating heat and gas releases from a mine fire has been developed, scientific research in this area is very relevant.

In turn, in the case of mine explosions, the studies of Abinov A.G., Vasenin I.M., Lukashov O.Yu., Paleev D.Yu., Plotnikov V.M. et al. should be mentioned. Their findings form the basis for the *Gas Dynamic Calculation Methodology*[1], currently used to

[1] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia "On implementing the "Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions" dated April 27, 2004, 16 p.

define the parameters of air shock waves generated by explosions in mines. This methodology introduces the concept of an "active combustion area". This is a mining area filled with an explosive mixture, and determines the initial excess pressure at the shock front in an explosion origin. However, the focus of the methodology on emergency calculations does the length of this area to be established without actually measured gaseousness (gas hazard) parameters of a mine working. In other words, this methodology does not answer the question of how to calculate the length of an active combustion area for a non-emergency working conditions. This requires evacuation, and for mine rescue measures to be developed in advance. In the event of an unauthorized explosion of explosives, the required length can be determined by the analytical relationships presented in [12]. However, in the event of an explosion of a methane-air mixture (firedamp), this question remains open and therefore requires investigation.

In connection with the above, and using the example of extensive dead-end workings at one of the Russian mines, this paper proposes a methodology for calculating the parameters of a mine fire and explosion development model in the AeroNetwork analytical software package. This is one of the main tools for solving problems in the field of mine ventilation and mine safety.

The findings of this study are expected to be useful not only for AeroNetwork users digitally simulating the development of accidents in mine workings, but also for other aerological safety specialists involved in calculating mine fires and explosions.

Subject of research

The research considers two extensive dead-end workings in a Russian mine. The workings were driven, in order to perform geological and geotechnical studies and to provide a ventilation connection between the mine shafts. A schematic diagram of the spatial location of the workings is shown in Fig. 1.

The workings involved can be characterized by the following routing features and driving conditions:

– the workings are being driven simultaneously towards Shaft No. 2;

– working No. 1 is located at a depth of 1750–1850 m (ascending slope 3° towards Shaft No. 2), while a depth of working No. 2 is 1950 m (with no gradient);

– the design length of the workings is 1840 m; No. 1 is curvilinear, while No. 2 is rectilinear with a minimum number of turns;

– the cross-sectional shape of the workings is arched, the cross-sectional area is 17.8 m^2 in drivage and 17.0 m 2 in clear;

– a drilling and blasting complex used to drive the workings consists of: an Epiroc Boomer 282 drilling rig, an Epiroc ST-1030 bucket LHD, and a Sandvik TH 320 dump truck;

– a ventilation system for ventilating the workings consists of: 3 fans on the surface, 5 flexible ducts in Shaft No. 1, 2 ventilation chambers, 4 underground booster fans, and 2 rigid ducts in the workings (Fig. 2);

– the intake air consumption in each working is 20 m^3/s; the booster fan (located in ventilation chamber) performance is 19.3 m^3/s; the booster fan (located in the niche) performance is 17.2 m^3/s; the air consumption at the face is 15.1 m^3/s;

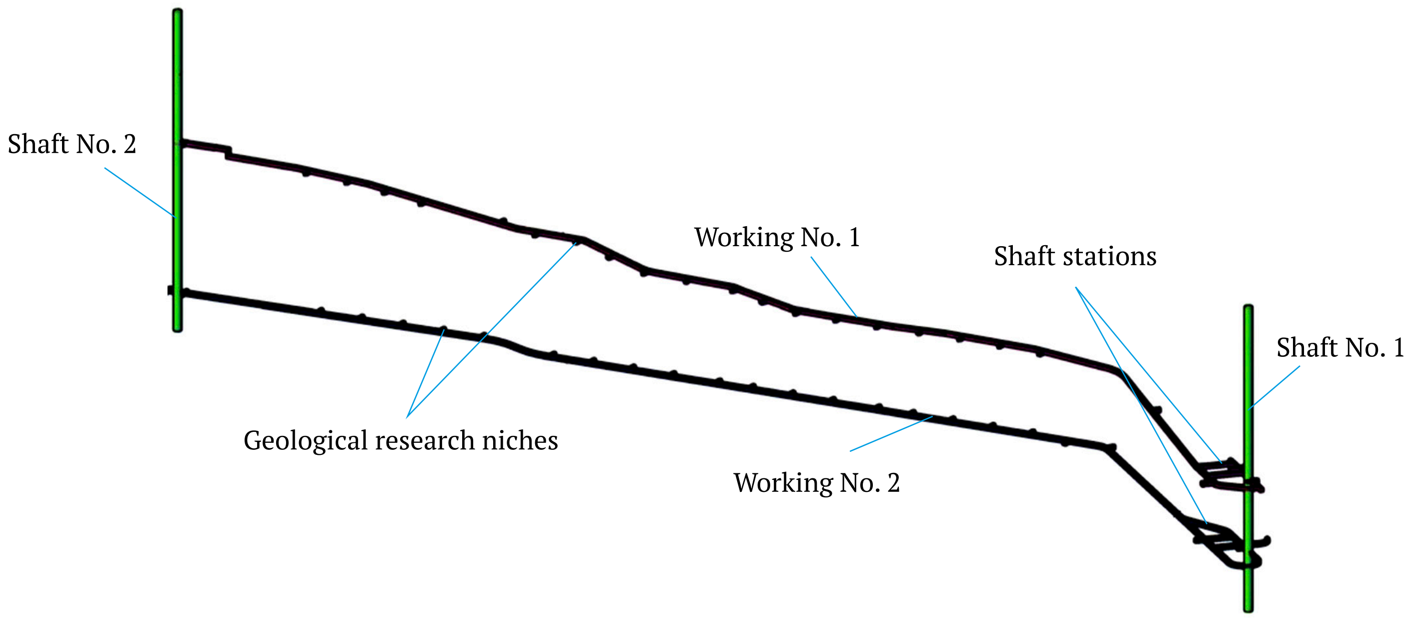


Fig. 1. Schematic diagram of the spatial location of the workings

– the average temperature of the intact rock mass surrounding working No. 1 is 44.5 °C, and that for working No. 2, 46.6 °C;

– at an outdoor temperature of 21.0° C, as a result of hydrostatic compression, friction, and heat exchange, the temperatures of the intake air in workings No. 1 and No. 2 are 33.3 and 34.4 °C, respectively.

Fire development model parameterization

The most dangerous endogenous fire is one caused by a fire in process vehicles. Such a fire is characterized by rapid development and accompanied by significant heat and gas releases. In this regard, in order to predict an emergency air-gas dynamic situation in workings, a fire of a vehicle containing the maximum fire load should be taken into account.

The main fire load of a mining vehicle can be ascribed to fuel, luboil, and rubber [13]. The content of other combustible components is negligible, so their impact on the development of fire can be neglected. An approximate fire load of a vehicle can be determined using its technical cer-tificate. For instance, the fuel tank volume reflects fuel content, the volume of the hydraulic system reflects the luboil content, and the tire size reflects the rubber content.

The key parameters of a mine working fire development model are specific heat and gas releases. These parameters are time-varying, since a fire proceeds in several stages with differing combustion intensity [14]. In order to simplify the simulation, equivalent values should be set throughout all stages of a fire (Fig. 3).

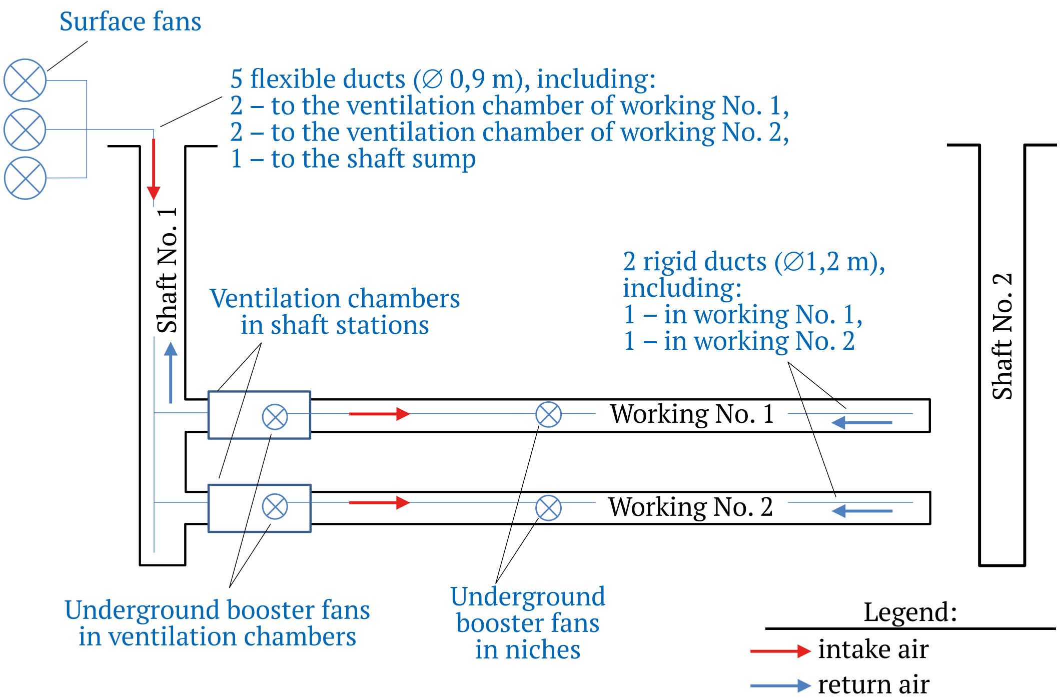


Fig. 2. Workings ventilation schematic diagram

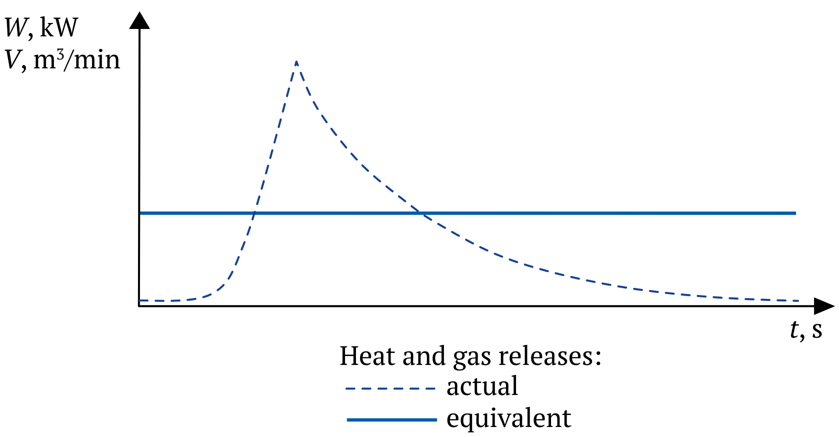


Fig. 3. Principal presentation of equivalent heat and gas releases during the combustion of vehicles

In order to calculate the maximum heat releases, kW, from the combustion of a certain fuel component at some instant, a well-known formula can be used [15]:

$$W_i = \psi_i Q_i \eta, \quad (1)$$

where ψ_i is mass rate of burnout of a material of the fire load at a time, kg/s ($\psi_i = \psi_{spec\,i}\, S_i$, where $\psi_{spec\,i}$ is specific burnout rate of a material, kg/(s·m^2), S_i is combustion area at a time, m^2); Q_i is lower calorific value of a material, kJ/kg; η is combustion rate factor (assumed to be 0.85 in accordance with [15]).

In this case, the burnout time (s) of the combustible load is determined by the formula:

$$t_{spec\,i} = \frac{m_i \eta}{\psi_{spec\,i} S_i}, \quad (2)$$

where m_i s mass of fuel component, kg.

For expression (2), it is proposed to take, the surface area of a sphere as a combustion area, into which the entire mass of the fire load for each component is inscribed. Then the equivalent of heat releases, kW, from a burning vehicle throughout all stages of a fire will be of a certain average value. This can be determined by summing up the average heat releases from each of the components:

$$W_{spec} = \sum_i W_{spec\,i}. \quad (3)$$

At the same time, the average value of heat generation, kW, from each of the components can be determined based on the maximum burning time of a vehicle t_{max}. This corresponds to the time of complete burnout of the last burning component:

$$W_{spec\,i} = \frac{m_i \eta Q_i}{t_{max}}. \quad (4)$$

In the conditions of these workings, the potential origins of significant fire are the following mining machines: Epiroc Boomer 282 drilling rig; Epiroc ST-1030 LHD; and the Sandvik TH 320 dump truck. A comparison of technical data shows that the Sandvik TH 320 dump truck is most hazardous when burning, since it has a maximum fire load. In this regard, the specific heat and gas releases should be calculated for this vehicle only.

The results of calculating the equivalent heat releases during combustion a Sandvik TH 320 dump truck are presented in Table 1.

According to the calculation results, the burning time of a Sandvik TH 320 dump truck will be 108.0 minutes. At the same time, the average heat generation will be 4.67 MW.

In order to calculate the specific gas releases, it is necessary to know the specific volume of a certain equipment component combustion products and the composition of the combustible mass.

According to the Fire Extinguishing Manager's Handbook [15], the specific volume of combustion products when burning diesel fuel, oil, rubber is: 11.95, 11.86, 10.79 m^3/kg, respectively. At the same time, the basic composition of the combustion products originating from the combustion of diesel fuel, oil, and rubber [16] is as follows:

– diesel fuel – 86.3 % C^G, 13.3 % H^G, 0.3 % S^G, 0.1 % ($O^G + N^G$);

– luboil – 86.5 % C^G, 12.6 % H^G, 0.4 % S^G, 0.5 % ($O^G + N^G$);

– rubber – 85.5 % C^G, 11.8 % H^G, 2.0 % S^G, 0.7 % ($O^G + N^G$).

Thus, carbon compounds are the key components of the combustion products of the involved materials. At the same time, a fire will largely release only carbon dioxide CO_2. Carbon monoxide CO, as a by-product of the combustion reaction, will be significantly released only in the conditions of oxygen shortage.

In order to simplify the solution of the emergency gas distribution problem, the oxygen content in the air arriving at a fire origin is assumed to be sufficient for the combustion reaction to occur normally. As a result the content of carbon monoxide CO in the combustion products is negligible. Then, as characteristic gas releases from a fire, we can take carbon

Table 1

Heat generation from dump truck burning

Dump Truck	Component	Weight, kg	Maximal heat generation, MW	Burnout time, min	Equivalent heat generation, MW
Sandvik TH 320	fuel	283.0	4.32	39.5	1.58
	luboil	340.2	4.54	44.3	1.87
	rubber	278.0	1.22	108.0	1.22
	a dump truck burning time and the fire heat release:			*108.0*	*4.67*

dioxide CO_2 releases, m³, determined by the following formula [16]:

$$V_{CO_2} = \left(0.0187 + \frac{C^G}{100}\right) V_G, \quad (5)$$

where C^G is carbon C content in a combustible material, %; V_G is total volume of combustion products, m³.

In this case, the specific gas releases, m³/min, of carbon dioxide CO_2 will be:

$$v_{CO_2} = \frac{V_{CO_2}}{t}, \quad (6)$$

where t is an equipment burning time, min.

According to the calculation results, the specific gas releases of carbon dioxide CO_2 during the combustion of a Sandvik TH 320 dump truck will be 72.2 m³/min.

Explosion development model parameterization

In mining conditions, the most probable explosions are those connected with:

– explosives (unauthorized firing);
– methane-air mixture (firedump);
– dust (coal or sulfide) [12].

The current study analyzes the unauthorized explosion of explosives and the explosion of a methane-air mixture. The study of explosions of coal and sulfide dust present in the mine workings of coal and pyrite mines, respectively, is outside the scope of our work. Thus, the paper focuses on the study of explosions in gas-hazardous mines with low dust hazard.

Assessing the consequences of an explosion and developing prevention measures and minimizing the damage area requires knowledge of the pressure distribution at the shock front at some distance from the origin of the explosion. At the same time, the calculation of shock wave parameters at a distance from the explosion origin begins by determining the pressure at the point of origin.

According to the *Gas-Dynamic Calculation Technique*[2] the pressure in the explosion zone, ΔP_f, MPa, depends on the dimensionless length of the active combustion area in accordance with the dependence shown in Fig. 4.

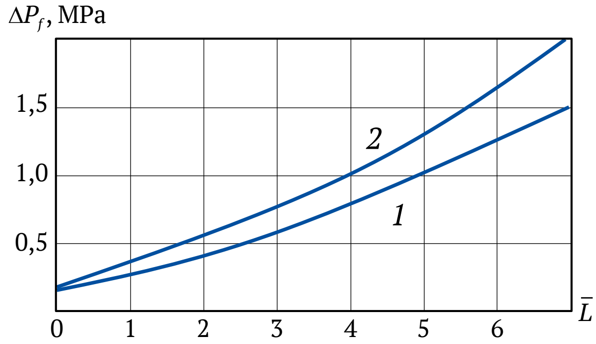


Fig. 4. Excess pressure in an explosion zone as a function of dimensionless length of a working:
1 – in the case of a methane explosion; *2* – in the case of a methane and coal dust explosion

The dimensionless length of an active combustion area is the length of a working length part from the nucleation site for ignition to the "combustible mixture-air" interface and can be deter-mined by the following formula[3]:

$$\bar{L} = \sum_{i=1}^{n} \frac{L_i P_i}{4 S_i}, \quad (7)$$

where L_i is the length of the i-th section of the explosion zone, m; $i = 1, 2, ..., n$ is the actual number of the sections; S_i is cross-sectional area of the i-th section of a working, m²; P_i is a working perimeter, m (in the case of an arched working $P = 3.84\sqrt{S}$).

When calculating an unauthorized explosion of explosives in a mine, the required parameter can be determined by the following formula [12]:

$$\bar{L} \approx \frac{M_{es} q_{es} P}{7 S^2}, \quad (8)$$

where M_{es} is mass of an explosive, kg; q_{es} is specific heat of an explosive, depending on its type, MJ/kg.

Thus, in order to determine the pressure in the origin of an unauthorized explosion of an explosive, it is sufficient to know its type and mass.

For example, under the conditions of these workings, AS-8 granulite weighing 180 kg is used to perform a drivage cycle in each mine working. Taking this into account, the dimensionless length of the active combustion area is 7.3 m.

It is more difficult to calculate the pressure in a methane-air mixture explosion origin. This is due to the fact that when calculating a predicted methane-air mixture explosion, the required dimensionless length of the active combustion area $\bar{L}$, actually determined by the volume of a working filled with an explosive mixture, can be determined only approximately.

[2] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia "On implementing the "Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions" dated April 27, 2004, 16 p.

[3] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia "On implementing the "Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions" dated April 27, 2004, 16 p.

One optimal approach to determining the maximum gas volume of a mine working, m³, is to calculate the gas content of rocks in terms of free combustible gases and their minimum concentration sufficient to cause an explosion:

$$V_g = \frac{gS_{sink}(L_{sink} + B)100}{C_{low}}, \qquad (9)$$

where g is gas content of rocks (free combustible gases), m³/m³; S_{sink} is drivage cross-sectional area of a working, m²; L_{sink} is a blast cut length, m; B is the length of the rock mass releasing gases in front of the working (a zone of greatest fracturing), m; C_{low} is lower explosive limit of methane, %.

The lower explosive limit of methane under normal conditions is 5 %. However, under conditions of pressure other than normal, it should be recalculated using the following formula [17]:

$$C_{low} = \frac{5}{k}, \qquad (10)$$

where k is the coefficient for converting bulk concentration of methane to molar one ($k = p/98070$, where p бis barometric pressure in a working, Pa).

In this case, the dimensionless length of the active combustion area is found by the following formula:

$$\bar{L} = \frac{V_g}{S_{expl}}, \qquad (11)$$

where S_{expl} is cross-sectional area of a working in the clear, m².

This approach assumes that methane is released into the near-face working space from the broken rock volume, as well as from the section of the abutment pressure zone in front of the face, which is most susceptible to fracturing (Fig. 5). The gas releases from the walls, roof, and bottom of a mine working exposed before blasting are not taken into account. This is due to their insignificance with regard to degassing these areas in previous driving cycles.

The blast cut length is 2.3 m in the conditions of these workings. At the same time, according to the findings of the study [18], the zone of greatest fracturing extends to a depth of 5.3 m from the face. With a gas content of rocks in terms of free combustible gases of 0.15 m³/m³ and lower explosive limit of methane of 4.11 % (working No. 1) and 4.02 % (working No. 2), the required dimensionless length of the active combustion area will be 29.1 m and 29.7 m for workings No. 1 and No. 2, respectively.

Fire development simulation findings

The creation of a fire development model is preceded by the development of ventilation and heat-and-gas-dynamic models of mine workings. In AeroNetwork software, the development of a ventilation model begins with the construction of the ventilation network topology. Then, for all mine workings, aerodynamic parameters (cross-sectional areas, perimeters, lengths, roughness coefficients) are set. On this basis, the aerodynamic drag of the network elements is calculated. Subsequently, information regarding ventilation facilities and draught sources, characterizing their operation modes, is entered into the model.

The heat-and-gas-dynamic model is parameterized by activating/deactivating the accounting of different physical processes that affect heat and gas distribution in mine workings. Considering a fire in a dead-end working, the heat-and-gas-dynamic calculation should take into account the following:

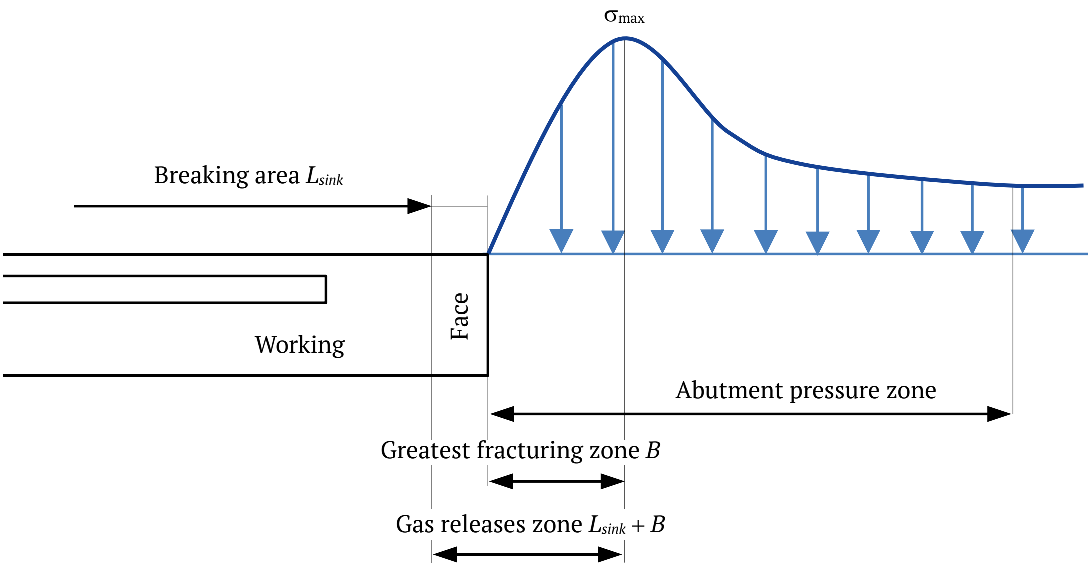


Fig. 5. Gas releases zone

air hydrostatic compression; pressure work; heat exchange in the "combustion origin – rock mass – air in a working – air in the duct" system; as well as the effect of thermal drop of ventilation pressure. A detailed description of the mathematical model of thermal and aerodynamic processes in AeroNetwork is presented in [19]. The assignment of a heat and gas release origin with the calculated parameters (4.67 MW, 72.2 m³/min) in the heat-and-gas-dynamic model allows the development of a fire to be calculated, in terms of determining gas and temperature distributions in the mine workings over time. At the same time, the simulation results directly depend on the location of a combustion origin.

In the case of these dead-end workings, the total break is hauled by LHDs running between the faces and the mine shaft. Therefore, a fire is possible in any part of the dead-end workings. However, given a concentration of mining works in the face space, a fire at the face should be considered

Given this particular problem, in the case of fire, the integrity of a duct is assumed not to have been violated due to its rigid metal construction and the location of the fire origin at the face. However, when a fire is located along the length of a dead-end working and a flexible non-fire-resistant duct is used, a possible violation of its tightness or breakage as a result of thermal exposure should be assumed.

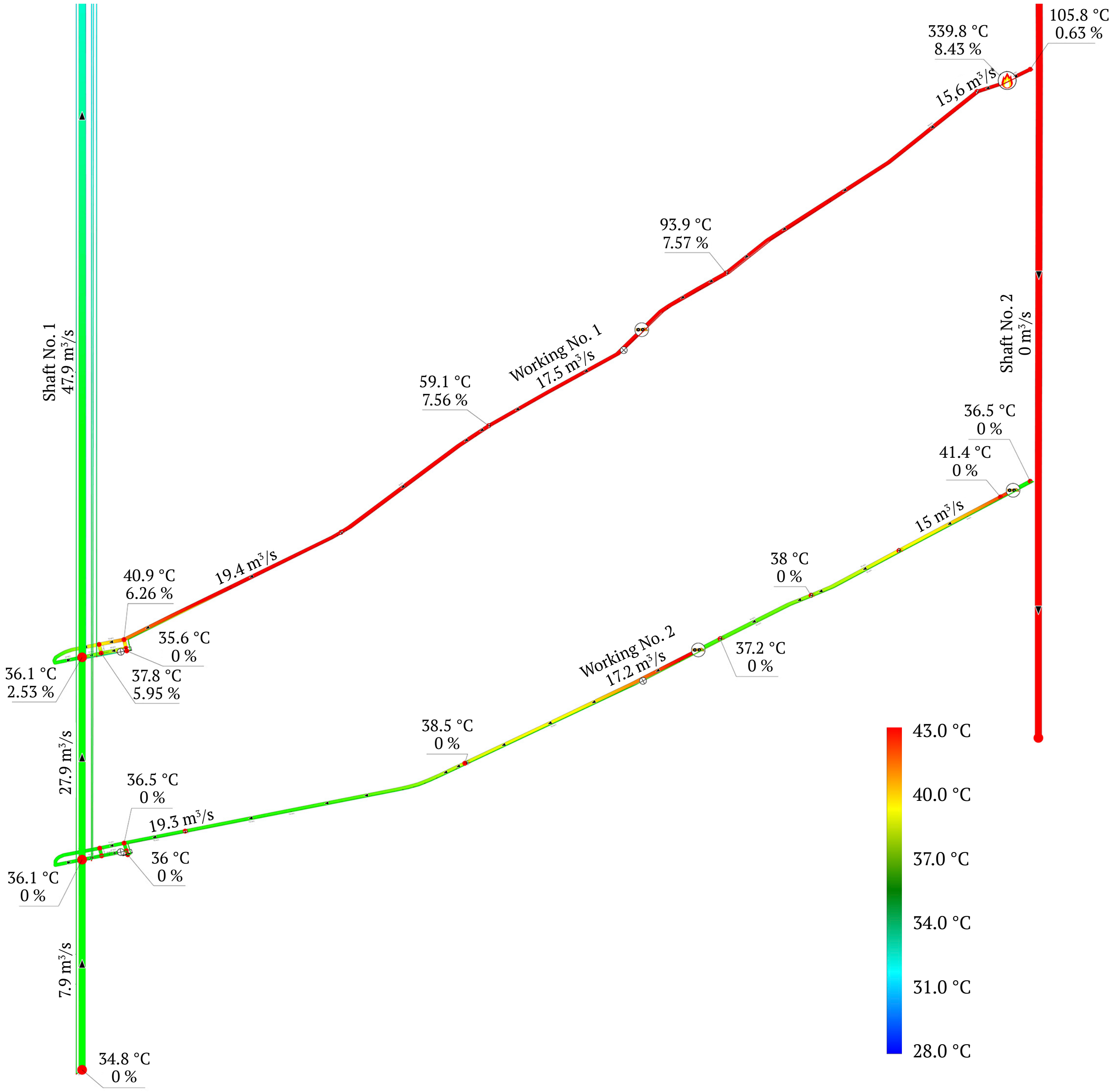


Fig. 6. Air temperature distribution in the mine workings in the event of a fire at the face of working No. 1

eISSN 2500-0632
https://mst.misis.ru/

The results of the air temperature distribution simulation, 108 minutes after a fire break-out in working No. 1 are presented in Fig. 6. Additionally, the Figure shows the values of carbon dioxide CO_2 concentrations at key points in the working.

The simulation showed that a fire at the mouth of mine working No. 1 will not lead to a significant change in air flow-rate in working No. 2. At the same time, in the fire origin, the air temperature will reach 339.8° C, and the concentration of carbon dioxide CO_2 will achieve 8.43 %. It should be noted that a fire at the mouth of working No. 1 will not lead to hazardous air condi-tions in terms of pollution and heating in working No. 2. This is due to the fact that the heated combustion products, with a lower density compared to the air in the shaft, will be removed to-

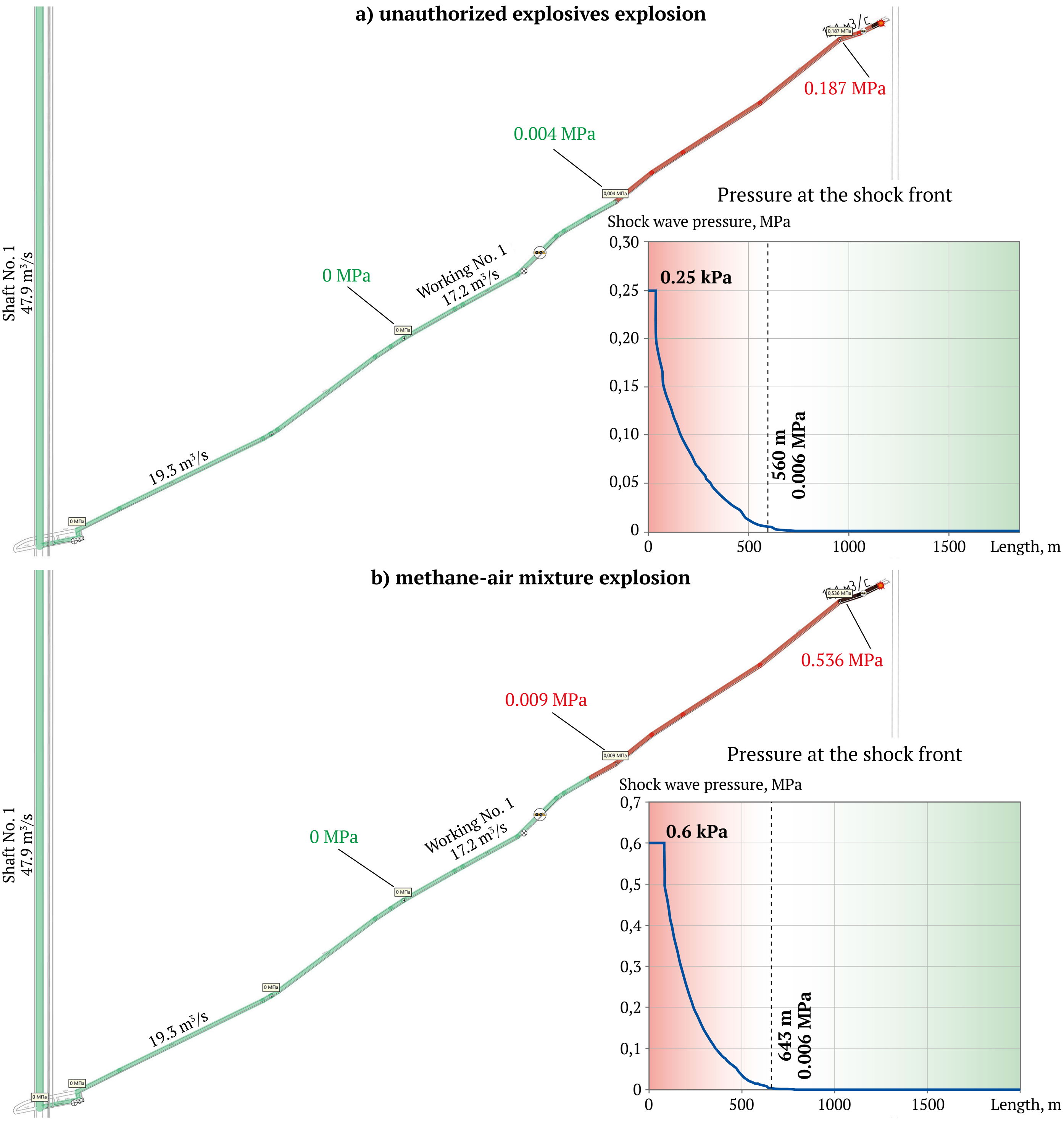


Fig. 7. Pressure distribution at the shock front at an explosion at the face of working No. 1:
a – explosive explosion; *b* – methane-air mixture explosion

wards daylight surface. In addition, the operation of surface fans supplying air and displacing smoke from working No. 1 to the outside will prevent origination of gas hazard conditions in mine working No. 2.

Similar results were obtained when simulating the development of a fire at the mouth of working No. 2. This was due to the identical ventilation parameters of these workings. However, in the event of a fire at the mouth of working No. 2, the combustion products will enter the shaft station at working No. 1, as a result of diffusion processes and thermal drop of ventilation pres-sure.

Results of shock wave propagation simulation

A model of shock wave propagation, equivalent to a fire development model, is based on the model of mine workings ventilation. Setting an explosion origin in the model with initial parameters (the type and mass of an explosive or the dimensionless length of the active methane-air mix-ture combustion area) allows the distribution of excess pressures in the workings at the time of the explosion to be calculated. However, the simulation results will depend on the location of the explosion origin.

An unauthorized explosion of explosives is possible in any part of a dead-end mine working, since the explosives are delivered from the mine shaft to the face. In turn, an explosion of a methane-air mixture is most likely at the face of a working. This is because the face is prone to bleed-ing and sudden gas release. We considered the consequences of explosive and methane-air mix-ture explosions at the face of a dead-end working and performed a comparative analysis.

The pressure distribution at the shock front at an explosion of explosives / methane-air mixture at the face of working No. 1 is shown in Fig. 7. In accordance with the *Gas-Dynamic Calcu-lation Methodology*[4], an excess pressure at the shock front equal to 0.006 MPa was taken as a shock wave hazard criterion for people in a mine.

The simulation showed that an explosion of explosives at the face of mine working No. 1 will cause excess pressure in the explosion origin of 0.25 MPa. At the same time, the zone of haz-ardous impact of the shock wave will spread over a distance of 560 m, corresponding to 30 % of the total length of the dead-end working (1840 m). When a methane-air mixture explodes at the face of mine working No. 1, the excess pressure in the explosion origin will be 0.6 MPa. The zone of hazardous shock wave will spread over a distance of 643 m, corresponding to 35 % of the total length of the dead-end working. Similar simulation results were obtained when considering the explosion at the mouth of working No. 2, the only difference being that in this case the zone of hazardous shock wave will have a larger propagation radius due to the rectilinearity of working No. 2. Thus, the explosion of methane-air mixture is of the greatest hazard in the conditions of the involved workings.

Conclusion

This study formulates a general principle for determining the parameters of mine fire and explosion models. The aim was to assess their development using the AeroNetwork analytical package. According to this principle, a fire development model parameterization consists in determining heat and gas releases from a combustion origin, taking into account the following fea-tures:

– to predict the potential most unfavorable conditions of a mine air in the event of an exogenous mine fire, a fire of equipment (a vehicle) only with a maximum fire load is advisable to be considered;

– the main fire load of a vehicle is fuel, oil, and rubber. In this way the fire load can be approximately determined based on the technical characteristics of a vehicle, such as the volume of the fuel tank, the volume of the hydraulic system, and the tire size;

– as heat and gas releases from a burning vehicle, the equivalent values determined by the recalculation for individual combustible components is advisable to be taken;

– taking into account the chemical composition of the fire load, it is sufficient to consider the propagation of carbon dioxide CO_2, in order to assess the toxicity of a mine air if a fire breaks out.

Parameterization of the explosion development model consists in determining the excess pressure at the shock front in an explosion origin. This takes the following features into account:

– excess pressure at the shock front in an explosion origin, determined depending on the dimensionless length of the active combustion area $\bar{L}$;

– in the event of an unauthorized explosive explosion, the parameter $\bar{L}$ is determined by the weight and specific heat of an explosive, as well as the geometric parameters of a mine working;

– in the event of a methane-air mixture explosion, the parameter $\bar{L}$ takes the following into account: the gas content of rocks in terms of free combustible gases; the length of a blast cut; the size of the area of increased fracturing; and the lower explosive limit of methane, calculated on the basis of the actual pressure in a working.

[4] Order No. R-7 of Federal Mining and Industrial Inspectorate of Russia "On implementing the "Methodology for gas-dynamic calculation of the parameters of air shock waves from gas and dust explosions" dated April 27, 2004, 16 p.

References

1. Pakhomov V.P., Rudakova L.V. Catastrophes formed by a technical reaction of the character of mining industries. *Economy of Regions*. 2006;(2):23–36. (In Russ.)

2. Remizov A.V., Hobta A.A. The causes of emergency situations in coal mines and the possibilities of their prevention. *Bulletin of the Siberian State Industrial University*. 2016;(1):14–16 (In Russ.) URL: https://www.sibsiu.ru/downloads/public/vestniksibgiu/vestnik15.pdf

3. Brake D.J. Fire modelling in underground mines using Ventsim Visual VentFIRE Software. In: Chalmers D. (ed.) *The Australian Mine Ventilation Conference*. Adelaide, South Australia, 1–3 July 2013. The AusIMM; 2013. Pp. 265–276. URL: https://ventsim.com/wp-content/uploads/2019/04/Fire_Modelling_in_Underground_Mines_using_Ventsim_VentFIRE.pdf

4. De Rosa M.I. *Analysis of mine fires for all US metal/non-metal mining categories, 1990–2001*. National Institute for Occupational Safety and Health (NIOSH); 2004. URL: https://www.cdc.gov/NIOSH/Mining/UserFiles/works/pdfs/2005-105.pdf

5. Paleyev D., Lukashov O. Software complex "Mining Aerology (Ventilation)". *Russian Mining Industry*. 2007;(6):20–23. (In Russ.) URL: https://mining-media.ru/ru/article/newtech/866-programma-rascheta-ventilyatsionnykh-rezhimov-v-shakhtakh-i-rudnikakh

6. Lönnermark A., Blomqvist P. *Emissions from tyre fires*. Borås, Sweden: SP Swedish National Testing and Research Institute; 2005.

7. Liskova M.Yu., Naumov I.S. Design of emergency situations in mines. *Nauchnyye Issledovaniya i Innovatsii*. 2013;7(1–4):78–81. (In Russ.)

8. Shalimov A.V. Numerical modeling of air flows in mines under emergency state ventilation. *Journal of Mining Science*. 2011;47(6):807–813. https://doi.org/10.1134/S106273914706013X (Orig. ver.: Shalimov A.V. Numerical modeling of air flows in mines under emergency state ventilation. *Fiziko-Texhnicheskiye Problemy Razrabbotki Poleznykh Iskopaemykh*. 2011;(6):84–92. (In Russ.))

9. Hansen R., Ingason H. *Full-scale fire experiments with mining vehicles in an underground mine*. Research report. Västerås, Sweden: Mälardalen University; 2013.

10. Hansen R. Analysis of methodologies for calculating the heat release rates of mining vehicle fires in underground mines. *Fire Safety Journal*. 2015;71:194–216. https://doi.org/10.1016/j.firesaf.2014.11.008

11. Danilov A.I., Maslak V.A., Vagin A.V., Sivakov I.A. Numerical simulation of a subway car fire. *Fire and Explosion Safety*. 2017;26(10):27-35. (In Russ.) https://doi.org/10.18322/pvb.2017.26.10.27-35

12. Paleev D.Yu., Lukashov O.Yu., Kosterenko V.N. et al. Shock waves during explosions in coal mines. In: *Mining Engineer's Library. Volume 6 "Industrial Safety". Part 3.* Moscow: Gornoe Delo Publ, Cimmerian Center LLC; 2011. 312 p. (In Russ.)

13. Smolin I.M., Poletayev N.L., Gordienko D.M. et al. *Manual for the application of SP 12.13130.2009 "Determining the categories of premises, buildings, and outdoor installations in terms of explosion and fire hazard"*. Moscow: VNIIPO Publ.; 2014. 147 p. (In Russ.) URL: https://ohranatruda.ru/upload/iblock/c84/4293768102.pdf

14. Karsakov O.G. On the problem of justifying the critical time of a fire at the initial stage. *Problemy obespecheniya bezopasnosti pri likvidatsii posledstviy chrezvychaynykh situatsiy*. 2015;4(1–1):330–332. (In Russ.)

15. Ivannikov V.P., Klyus P.P. *Fire extinguishing manager's handbook*. Moscow: Stroyizdat Publ.; 1987. 288 p. (In Russ.)

16. Bystritsky G.F., Gasangadzhiev G.G., Kozhichenkov V.S. *General power engineering. Core equipment*. Textbook. 2nd update. Moscow: Yurait Publ. House; 2018. 416 p. (In Russ.) URL: https://mx3.urait.ru/uploads/pdf_review/90FAE97C-FD7D-41FC-ACD5-6E038A39261C.pdf

17. Kolesnitchenko I.E., Kolesnitchenko E.A., Artemiev V.B., Icheretchukin V.G. Dependence of volumetrically concentration limit of methane blasting on physical parameters of the atmosphere. *Mining Informational and Analytical Bulletin*. 2015;(S7):174–181. (In Russ.)

18. Cherdancev N.V., Zykov V.S. The solution to a problem of in-seam working areas abutment pressure parameters determination based on the simulation experiment. *Bulletin of Scientific Centre VostNII for Industrial and Environmental Safety*. 2017;(3):16–30. (In Russ.) URL: http://vestnik.nc-vostnii.ru/arhiv/vypusk-3-2017/reshenie-zadachi-opredeleniya-parametrov-opornogo-davleniya-v-okrestnosti-plastovoy-vyrabotki-na-osnove-vychislitelnogo-eksperimenta/

19. Levin L. Y., Semin M. A., Zaitsev A. V. Mathematical methods of forecasting microclimate conditions in an arbitrary layout network of underground excavations. *Journal of Mining Science*. 2014;50(2):371–378. https://doi.org/10.1134/S1062739114020203 (Orig. ver.: Levin L. Y., Semin M. A., Zaitsev A. V. Mathematical methods of forecasting microclimate conditions in an arbitrary layout network of underground excavations. *Fiziko-Texhnicheskiye Problemy Razrabbotki Poleznykh Iskopaemykh*. 2014;(2):154–161. (In Russ.))

Information about the authors

Maxim O. Perestoronin – Postgraduate Student, Mining Thermal Physics Sector, Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0009-0003-0203-9304, Scopus ID 57701516700; e-mail per.maks1m.97@gmail.com

Oleg S. Parshakov – Cand. Sci. (Eng.), Mining Thermal Physics Sector, Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0000-0001-5545-442X; Scopus ID 57202379375; e-mail olegparshakov@gmail.com

Maxim D. Popov – Postgraduate Student, Mining Thermal Physics Sector, Department of Aerology and Thermophysics, Mining Institute of the Ural Branch of the Russian Academy of Sciences, Perm, Russian Federation; ORCID 0009-0007-6388-608X, Scopus ID 57208722129; e-mail maxpan09@gmail.com

Поступила в редакцию	06.10.2022	**Received**	06.10.2022
Поступила после рецензирования	19.01.2023	**Revised**	19.01.2023
Принята к публикации	27.01.2023	**Accepted**	27.01.2023

eISSN 2500-0632
https://mst.misis.ru/

MINING MACHINERY, TRANSPORT, AND MECHANICAL ENGINEERING

Research paper

https://doi.org/10.17073/2500-0632-2022-11-21
УДК. 621.671.22

Development and substantiation of an improved version of a main drainage facility classical scheme at a kimberlite mine developed by block caving method

N. P. Ovchinnikov
North-Eastern Federal University named after M.K. Ammosov, Yakutsk, Russian Federation
ovchinnlar1986@mail.ru

Abstract
Evidence demonstrates that as the production capacity of a kimberlite mine increases, there is a corresponding increase in the volumetric concentration of suspended solids in the mine water extracted from its water-collecting workings. The Udachny mine, known for its high productivity in comparison to other domestic kimberlite mines, experiences a higher concentration of suspended solids in the mine waters, leading to significant sludge settling within the primary drainage facility's water-collecting workings. This determinal effect adversely affects the operational efficiency of pumping equipment and the reliability of LHDs. To address these issues, an enhanced version of the conventional main drainage facility scheme, specifically designed for kimberlite mine utilizing the block caving method, is proposed. This modified scheme aims to provide improved clarification of the mine water in the water-collecting workings and facilitate more efficient dewatering of the settled slurry sludges. Furthermore, a methodology has been developed to determine the optimal operating parameters for the water-collecting workings. This methodology takes into account factors such as the time required for slurry sludge removal, the sedimentation characteristics of the solid phase, and the rheological properties of the liquid phase of the mine water.

Keywords
kimberlite mine, main drainage facility, efficiency, suspended solids, water collector, water clarification, dewatering, technique

For citation
Ovchinnikov N. P. Development and substantiation of an improved version of a main drainage facility classical scheme at a kimberlite mine developed by block caving method. *Mining Science and Technology* (*Russia*). 2023;8(2):162–172. https://doi.org/10.17073/2500-0632-2022-11-21

ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Разработка и обоснование усовершенствованного варианта классической схемы главного водоотлива кимберлитового рудника с этажным обрушением руды

Н.П. Овчинников
Северо-Восточный федеральный университет им. М.К. Аммосова, г. Якутск, Российская Федерация
ovchinnlar1986@mail.ru

Аннотация
Практика показывает, что с ростом производственной мощности кимберлитового рудника отмечается увеличение объемного содержания твердых частиц в шахтных водах, откачиваемых из его водосборных горных выработок. На руднике «Удачный» в связи с высокой производительностью по сравнению с другими отечественными кимберлитовыми рудниками отмечаются более высокая концентрация взвешенных твердых частиц в шахтных водах, а также интенсивное заиление водосборных горных выработок системы главного водоотлива. Данные обстоятельства крайне негативно влияют на эффективность эксплуатации насосного оборудования и надежности погрузочно-доставочных машин. Для обеспечения более качественного осветления шахтных вод в водосборных горных выработках и дальнейшего в них обезвоживания осевшей ило-шламовой пульпы предложен усовершенствованный вариант классической схемы главного водоотлива кимберлитового рудника, где применяется технология этажного обрушения руды. Кроме того, разработана методика по обоснованию рабочих параметров во-

досборных горных выработок, учитывающая их продолжительность нахождения в процессе очистки от ило-шламовых отложений, седиментационные характеристики твердой фазы, а также реологические характеристики жидкой фазы шахтных вод.

Ключевые слова
кимберлитовый рудник, главный водоотлив, эффективность, механические примеси, водосборник, осветление воды, обезвоживание, методика

Для цитирования
Ovchinnikov N. P. Development and substantiation of an improved version of a main drainage facility classical scheme at a kimberlite mine developed by block caving method. *Mining Science and Technology* (*Russia*). 2023;8(2):162–172. https://doi.org/10.17073/2500-0632-2022-11-21

Introduction

The Udachny mine, named after F.B. Andreeva, is currently the most productive underground mining operation of ALROSA and the only one utilizing the block caving method [1–3].

The decision to replace the conventionsl goaf solid stowing with the block caving method at the mine was primarily driven by a significant reduction in cement consumption.

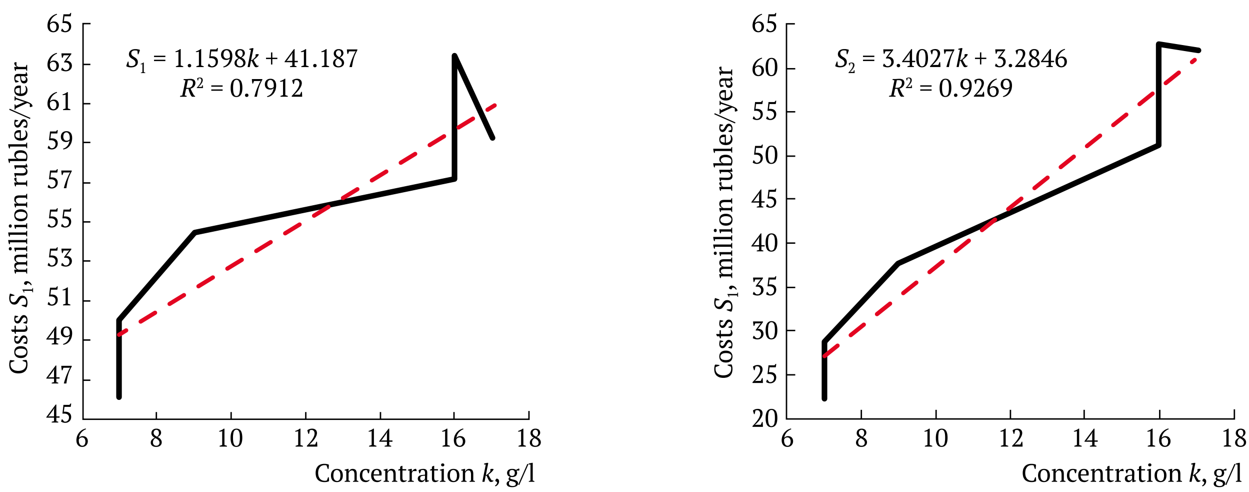
This successful implementation of the block caving method method has led to its planned utilization in the underground mining of the Yubileinaya kimberlite pipe, the largest diamond-bearing deposit in Russia, until 2035, following open pit minin.

Research has demonstrated that as the production capacity of a kimberlite mine increases, the volume of solids in the mine water extracted from its water-collecting workings (water collectors) also increases.

At the Udachny mine, due to its high productivity compared to other domestic kimberlite mines operated by ALROSA, there is a higher concentration of suspended solids in the mine waters. Additionally, the main drainage facility experiences intensive sludge settling (siltation) in its clarification reservoirs and water collectors [4]. These factors have a severe detrimental impact on the reliability, energy efficiency of pumping equipment, and the reliability of LHDs. For example, an 1 g/l increase in the average concentration k of mechanical impurities in the mine waters at the outlet of water collectors leads to an expected rise in the total power consumption costs of vertical split casing pumps S1 by 1.16 million rubles/year and the overhaul costs of these pumps S2 by 3.4 million rubles/year (Fig. 1, *a*, *b*).

Given these circumstances, the development and validation of various designs and process solutions to mitigate the adverse effect of the solid phase in mine waters have become highly relevant. These efforts are crucial future planning and design considerations for the Yubileyny underground mine.

Thorough analysis of various publicly available sources indicates a substantial body of literature focused on enhancing the efficiency of mine drainage by mitigating the content and the detrimental effects of suspended solid phase in mine water. Despite the range of studies on this subject, the proposed designs in these works would prove ineffective in the specific conditions of a kimberlite mine developed using the block caving method.



a *b*

Fig. 1. Total electricity consumption costs S_1 (*a*) and overhaul costs S_2 (*b*) of vertical split casing pumps as functions of average concentration of mechanical impurities k in mine waters

One disadvantage of a drainage facility [5, 6], incorporating a hydraulic elevator within its structure, is the inadequate performance of the sealing elements of centrifugal pumps on the suction side when operating above the critical pressure threshold.

The practical application of a drainage facility featuring self-cleaning water collectors [7] and a mobile sludge collection unit utilizing a LHD [8] proves advantageous in underground mining scenarios involving hydraulic stowing of excavated space.

However, in the case of implementing a design [9] within a mine developed using the block caving method, a disadvantage arises due to premature failure of the cofferdam's steel plates caused by the high corrosiveness of the mine water.

During the implementation a drainage facility, there is an increased risk of flexible piping within the submersible pump (a component of the facility) becoming clogged with slurry sludges, potentially resulting in piping failure.

The drawback of utilizing a clarification reactor [10] lies in the application of chemical reagents, which are injected into the subsurface together with mine water. This practice can incur additional financial costs and contribute to environmental degradation in the vicinity of the kimberlite pipe. These drawbacks are also applicable to the design described in [11]. Successful implementation of the design [12] necessitates pre-treatment of the water.

According to the data presented in Fig. 2, the average concentration of suspended solid particles present in the mine waters pumped out by the primary drainage facility of the Udachny mine diminishes from 25 to 16 g/l as they travers through the water-collecting workings (water collectors) [13].

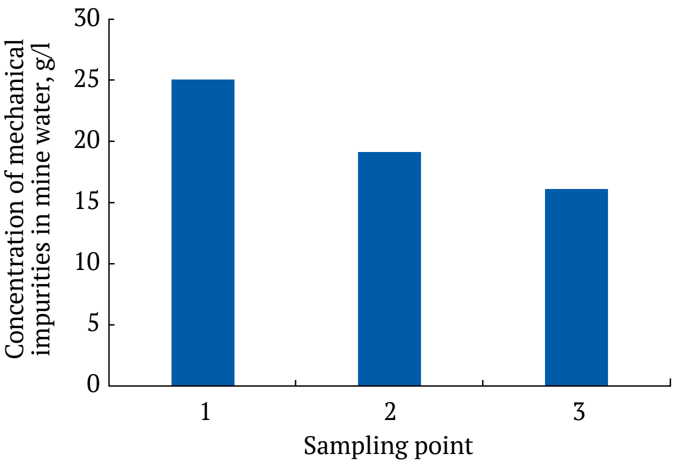


Fig. 2. Concentration of suspended solids in water collectors:
1 – before clarification reservoir; *2* – at the inlet of water collector; *3* – at the outlet of water collector

Therefore, it is evident that as the capacity of clarification reservoirs increases, there should be a significant improvement in the quality of mine water clarification. However, the construction of water collecting workings involves significant financial costs. In order to ensure the utmost efficiency of the main drainage facility, it is crucial to develop of a methodology for justifying the operating parameters of clarification reservoirs. It is important to note that improved clarification of mine water will result in an increased volume of deposited slurry sludges, which necessitates timely removal. Hence, there is a need to develop an efficient and prompt method for dewatering the slurry sludges (sediments).

The objective of this study is to propose an enhanced version of the traditional scheme for the main drainage facility in a kimberlite mine developed using the block caving method. Additionally, a methodology will be developed to justify the operating parameters of clarification reservoirs to achieve proper clarification of mine water and facilitate the subsequent dewatering of settled slurry sludges within them.

Description of an improved classic scheme for the main drainage facility in a mine, developed by the block caving method

Fig. 3 illustrates the improved version of the classic scheme for the main drainage facility in a kimberlite mine developed by the block caving method. Let us delve deeper into the operational principles and key advantages of this scheme.

Mine water entering the underground mine is directed towards the operational clarification reservoir (see Fig. 3, pos. 1). In the design of clarification reservoirs, the far wall is constructed as a concrete cofferdam (see Fig. 3, pos. 2) with metal pipes embedded within it (see Fig. 3, pos. 3). At the ends of these pipes, ball valves are installed to facilitate the discharge of clarified water.

During the process of filling the clarification reservoir with mine water, a significant portion of the suspended solids it contains undergoes deposition. The resulting clarified water flows over the concrete cofferdam via gravity and enters one of the two water collectors (see Fig. 3, pos. 4), as well as the clarification reservoirs, follows an alternating pattern, with one in operation while the other undergoes cleaning to remove settled slurry sludges. The clarified water is then pumped out using the pumping equipment of the main drainage facilities (see Fig. 3, pos. 5), ultimately reaching the surface.

When the settling of sludge becomes excessively severe, the clarification reservoir is taken out of service.

In practice, decommissioned sludge clarification reservoirs are typically divided into distinct layers: the outer layer (upper), comprising the initial mine water; the intermediate layer, considered neutral; and the lower layer, consisting of thickened solid sludge.

After a certain period of time, the outer layer undergoes clarification and is subsequently discharged through the pipes located in the upper part of the concrete cofferdam, flowing into the operational water collector.

Subsequently, the remaining slurry within the clarification reservoir, represented by the intermediate and lower layers, undergoes a longer settling process.

The mine water, which undergoes sedimentation in the clarification reservoir, is then discharged. In case where the pipes in the lower section of the concrete cofferdam are obstructed by thickened slurry sludge, the water is pumped into the operating water collector using a submersible slurry pump (see Fig. 3, pos. 6). The pump is mobilized by a crane beam (see Fig. 3, pos. 7).

In order to ensure effective operation, the pump should not have an agitator (mixer) as this would prevent the disturbance of settled slurry sludge during its operation.

If required, quick access to the clarification reservoir can be facilitated by a ladder (see Fig. 3, pos. 8) installed on the concrete cofferdam.

The remaining dewatered slurry sludges are extracted from the clarification reservoir using an LHD bucket and subsequently transported to the surface through a shaft.

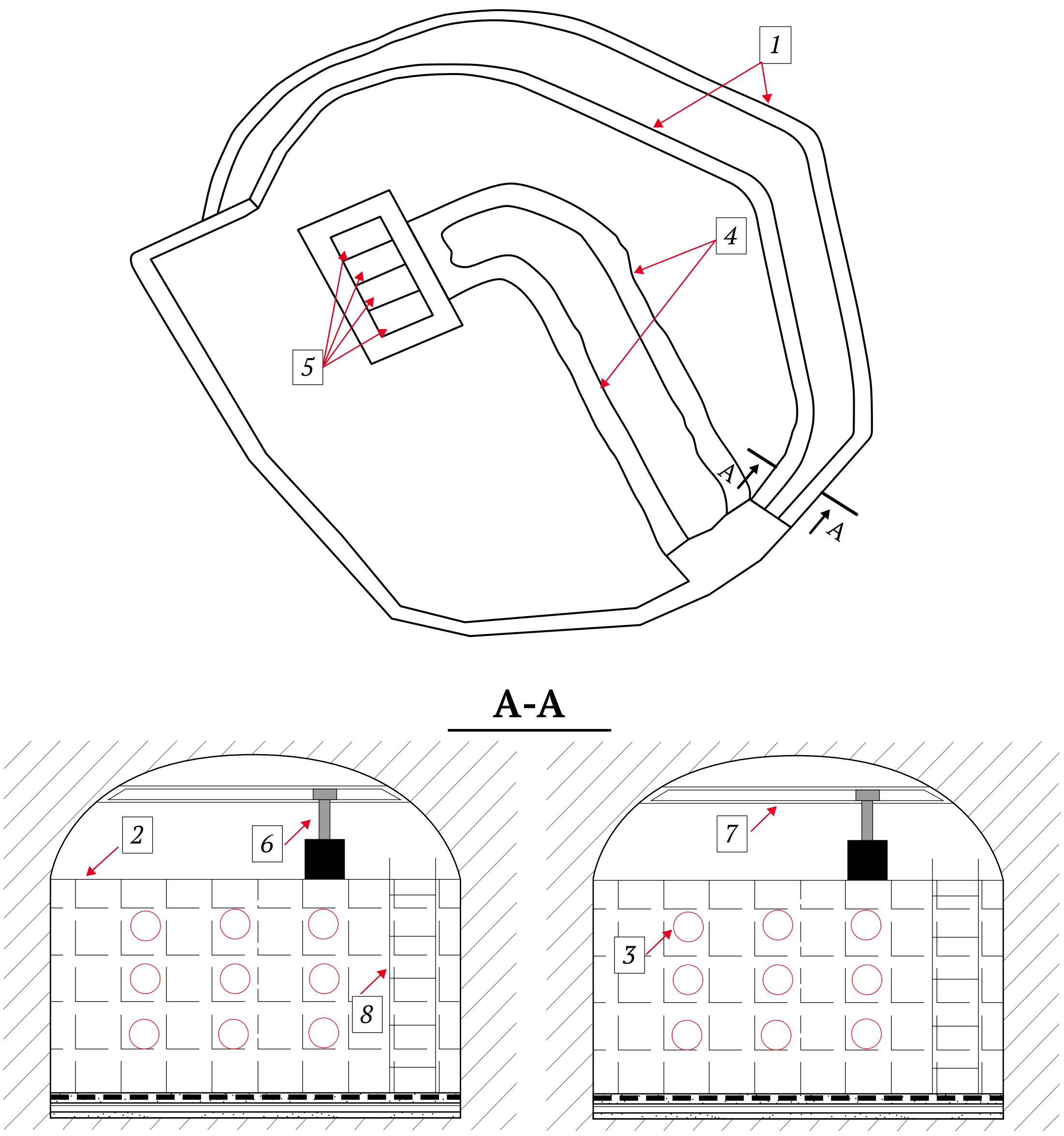


Fig. 3. Proposed process flow diagram of the main drainage facility of a kimberlite mine:
1 – clarification reservoir; *2* – concrete cofferdam; *3* – pipes; *4* – water collectors; *5* – pumps of the drainage facility; *6* – submersible pump; *7* – crane beam; *8* – ladder

Method for determining the operating parameters of clarification reservoirs

In order to achieve effective clarification of mine water in a clarification reservoir, it is essential to satisfy the following condition:

$$t_{settl} \geq t_{sed}, \quad (1)$$

where t_{settl} represents the settling time of water in the clarification reservoir, h; t_{sed} corresponds to the time required for the sedimentation of the majority of suspended solids present in the mine water, h.

In this case

$$t_{settl} = \frac{V}{q}, \quad (2)$$

where V denotes the capacity of the clarification reservoir, m^3; q signifies the average water inflow to the mine, m^3/h.

Calculating the optimal value of the parameter V necessitates knowledge of the time t_{sed}.

However, determining its precise value under actual production conditions proves to be challenging. Consequently, simulating the sedimentation of suspended solids in a clarification reservoir under laboratory conditions offers the most viable solution.

The time t_{sed} is dependent on the Reynolds number Re and the operating water level h in the clarification reservoir [14–16].

The Reynolds number Re is defined as:

$$\mathrm{Re} = \frac{\rho \upsilon D}{\mu}, \quad (3)$$

where ρ represents the density of the mine water, kg/m^3; υ corresponds to the velocity of the mine water in the clarification reservoir, m/s; D signifies the hydraulic diameter of the clarification reservoir, m; and μ denotes the dynamic viscosity of the mine water, Pa·s.

Here,

$$\upsilon = \frac{q}{3600bh}, \quad (4)$$

where b represents the width of the working area for the clarification reservoir, m.

The diameter (for a conventional rectangular cross-section of the clarification reservoir) is given by:

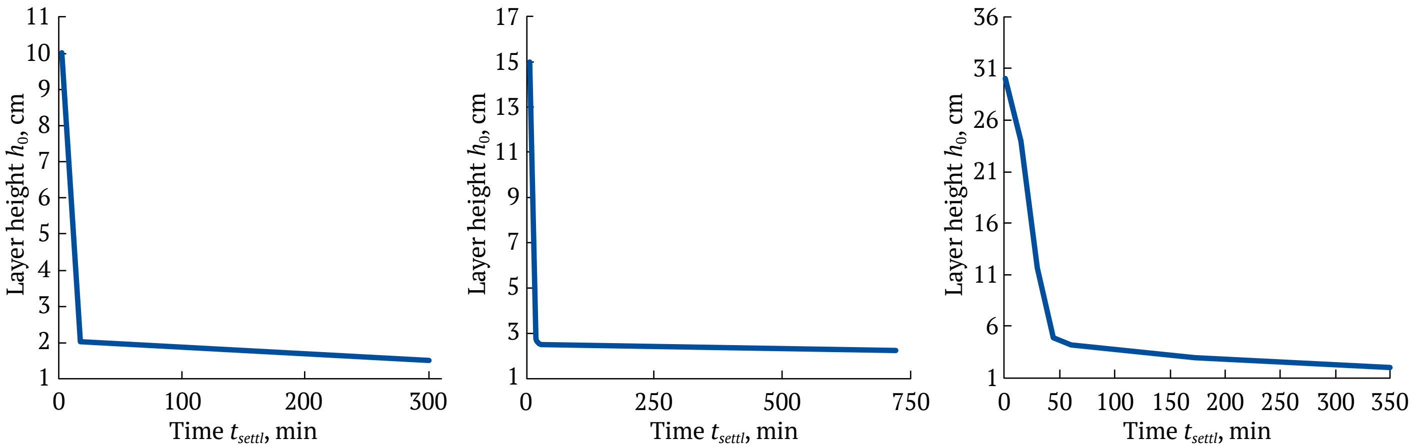
$$D = \frac{4hb}{2(h+b)}. \quad (5)$$

To determing the reqired time t_{sed} for effective clarification of mine water, sedimentation analysis of its solid phase must be conducted. The research focused on mine water samples collected from the operational clarification reservoirs of the main drainage facility at the Udachny mine.

The variation in the sludge height h_0 as a function of the time t_{settl} and the operating water level h in the measuring reservoirs is depicted in Fig. 4, *a–c* [13].

It has been observed that a significant proportion (approximately 75-80 %) of suspended solids present in mine waters entering the clarification reservoirs of the main drainage facility at the Udachny underground mine rapidly transition into a sludge state. Specifically, at a water level of h = 10 cm, this transition occurs within 17 min; at h = 15 cm, it takes in 30 min; and at h = 30 cm, it required 45 min. However, subsequent research reveals a substantial decrease in the sedimentation rate and sludge thickening.

Through mathematical analysis of the obtained sedimentation analysis data, an empirical formula was derived to calculate the minimum settling time of mine water, $t_{settl\ min}$, at which the majority of suspended solids settles. This calculation is specific to the clarification reservoirs of the main drainage fa-



a *b* *c*

Fig. 4. Height of sludge layer h_0 as a function of mine water settling time t_{settl} at their different operating levels h in measuring reservoirs: *a* – 10 cm; *b* – 15 cm; *c* – 30 cm

cility at the Udachny mine and takes into account the operating water level h, in the reservoir (assuming laminar liquid flow) (Fig. 5) [13].

In the case of laminar liquid flow, the minimum settling time $t_{settl\ min}$, in addition to the water operating level h, is strongly influenced by the physical properties of the solid and liquid phases of the mine water:

$$t_{settl\ min} = \frac{18\mu h}{d^2 \Delta g}, \tag{6}$$

where d represents the average diameter of a suspended solid particle; and Δ represents the density difference between the solid and liquid phases of the mine water.

To calculated the minimum settling time $t_{settl\,min}$ for other domestic kimberlite mines, the following formula can be used:

$$t_{settl\ min} = \frac{\mu^* \rho^*}{\mu_0 \rho_0}(1.3077h + 6.6923), \tag{7}$$

where μ_0 and ρ_0 are the dynamic viscosity and density of mine water sampled from the clarification reservoirs of the main drainage facility at the Udachny mine, respectively; μ^* and ρ^* are the dynamic viscosity and density of mine water sampled at other kimberlite mines, respectively.

It should be noted that laminar flow is not typical for mine water entering clarification reservoirs in underground conditions, as it is not feasible to use workings with large cross-sections.

However, according to studies [14], formula (7) may also be applicable in cases of transient liquid flow regimes (where 10,000 > Re number > 2,300).

In underground mine conditions, proper clarification of mine waters, including transient flow regimes, can be achieved by increasing the time $t_{settl\,min}$ with a correction factor k_{corr}. This factor is determined by the ratio of the Reynolds number during actual turbulent movement of mine waters in a clarification reservoir (Re_{turb}) to the Reynold number during the transient regime, where Re_{trans} = 2,301 ... 9,999:

$$k_{corr} = \frac{Re_{turb}}{Re_{trans}}. \tag{8}$$

Based on the findings of the studies [17], the volume of the sludge V_{sludge} within a clarification reservoir can be calculated using the following formula:

$$V_{sludge} = k_h \frac{1000GT24q}{\rho_{solid}}, \tag{9}$$

where k_h represents the ratio between the height of the neutral layer h_1 and the height of the thickened solid sediment layer h_2 of the settled slurry sludge; G denotes the difference in concentration of suspended solid phase (mechanical impurities) between the inlet of the clarification reservoir and the inlet of the water collector, kg/l; T signifies the operating time of the clarification reservoir, days; ρ_{solid} refers to the average density of the suspended solids (solid phase), kg/m³.

The coefficient k_h can be determined as follows:

$$k_h = 1 + \frac{h_1}{h_2}. \tag{10}$$

To establish the coefficient k_h, a regression statistics method was employed to develop a mathematical model based on the results of earlier sedimentation analysis of the solid phase in the sampled mine water. This model accurately describes the relationship between k_h and n (n is the ratio between t_{settl} and $t_{settl\,min}$ with a high degree of confidence (Fig. 6).

According to the suspended solids sedimentation analysis performed for the sampled mine waters, G can be calculated as follows:

$$G = 0{,}75\ldots0{,}8 \cdot K, \tag{11}$$

here, K denotes the concentration of suspended solids in mine waters at the inlet of a clarification reservoir, kg/l.

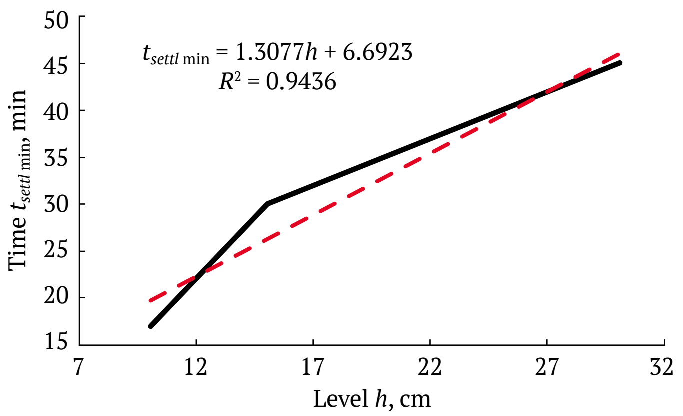


Fig. 5. Minimum time of mine water suspended solids settling $t_{settl\ min}$ as a function of the water operating level h in a measuring reservoir

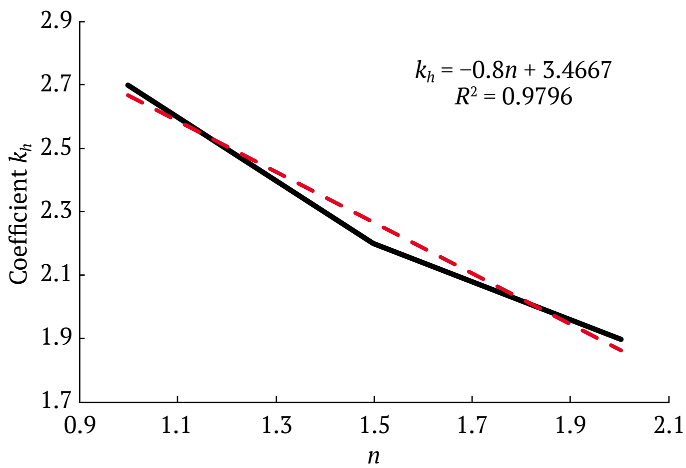


Fig. 6. k_h as a function of parameter n

Based on the experience gained from utilizing water collecting workings as parts of main drainage facilities in kimberlite mines, it is observed that the settling degree of sludge in clarification reservoirs often reaches up to 90 %.

Therefore, when determining the capacity of a clarification reservoir, accounting of sludge settling V^*, the following equation can be used:

$$V^* = \frac{100\,\%}{90\,\%} V_{sludge} = 1.11 V_{sludge}. \quad (12)$$

During decommissioning, it is essential for a sludge clarification reservoir to continue effectively clarifying the mine water flowing into it.

The capacity V can be considered optimally selected only if the following requirements are met:

$$V > V^* = k_{corr} nqt_{settl\,\min} > 1.11\, k_h \frac{1000GT24q}{\rho_{solid}}; \quad (13)$$

$$V - V_{sludge} > k_h qt_{settl\,\min}. \quad (14)$$

The time T (as mentioned in formula (9)) must be equal to or greater than the time required for cleaning process of a non-functioning (filled with sludge) clarification reservoir, denotes as T_0 (removing settled slurry sludges):

$$T_0 = t_1 + t_2 + t_3 + t_4 + t_5, \quad (15)$$

where t_1 represents the time for mine water to settle after ceasing the operation of a sludge-filled clarification reservoir, days; t_2 signifies the time for discharging clarified mine water from the clarification reservoir, days; t_3 denotes the time for slurry sludge settling in the clarification reservoir, days; t_4 represents the time for discharging released clarified mine water contained in slurry (or the time for water pumping out by submersible slurry pump, days); t_5 represents the time for hauling of dewatered sludges, days.

The time t_1 can be determined using formula (7), and the resulting value should be divided by 1,440 to convert it into days.

The time t_2 can be calculated as:

$$t_2 = \frac{0.1V}{1440\, NSh_h} \sqrt{\frac{2h_{out}}{g}}, \quad (16)$$

where N represents the number of concrete cofferdam pipes involved; S is the cross-sectional area of a pipe, m^2; and h_{out} is the height of the outer layer (raw mine water layer) in the clarification reservoir at the time of its withdrawal from operation, m.

The area S can be calculated using the following equation:

$$S = \frac{\pi d_0^2}{4}, \quad (17)$$

here, d_0 represents the inner diameter of a pipe in the concrete cofferdam, m.

To calculate the time t_3, which depends on the parameter h_{sum} (total height of layers h_1 and h_2 determined based on the results of field tests), an empirical formula was derived (Fig. 7). It should be noted that the calculated value of time t_3 should be further divided by 24 to convert it to days.

When considering the discharge of released clarified mine water, the time t_4 can be calculated using formula (16) with the following modifications: Parameter $0.1V$ is replaced by the volume of clarified released mine water V_{clar}, and parameter h_h is replaced with the height of the clarified water layer h_{clar}.

The volume V_{clar} is defined as follows:

$$V_{clar} = V - 0.1V - V_{dewat}, \quad (18)$$

where V_{dewat} represents the amount of dewatered slurry sludges removed by an LHD bucket, m^3.

The height of the clarified water layer h_{clar} is determined as follows:

$$h_{clar} = \frac{hV_{clar}}{V}. \quad (19)$$

The volume V_{dewat} is calculated as:

$$V_{dewat} = k_{dewat} \frac{1000GT24q}{\rho_{solid}}, \quad (20)$$

where k_{dewat} is a coefficient that takes into account the efficiency of dewatering settled slurry sludges (k_{dewat} = 1.1...1.2).

In the case of water pumping by a submersible slurry pump, the time t_4 is calculated as follows:

$$t_4 = \frac{V - 0.1V - V_{dewat}}{24Q}, \quad (21)$$

where Q represents the flow rate of the pump, m^3/h.

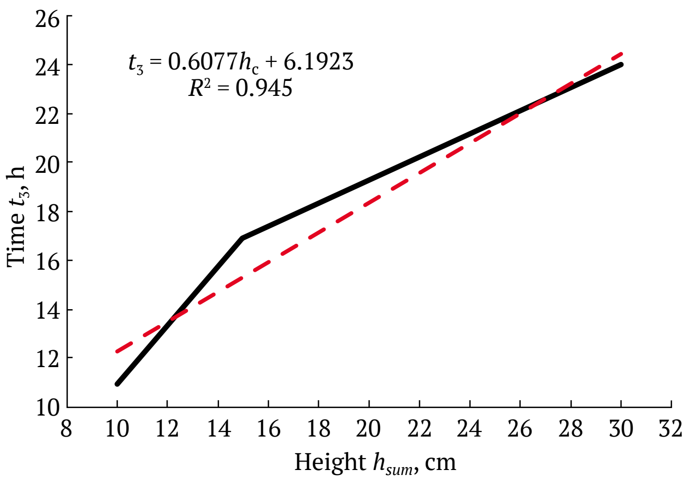


Fig. 7. Slurry settling time t_3 as a function of total height of neutral layer h_{sum}

The time t_5 should satisfy the following inequality:

$$t_5 > \frac{Q_{\max}}{V_{dewat}}, \quad (22)$$

where $Q_{\max}$ represents the maximum performance of the PDM in hauling dewatered slurry sludges from a clarification reservoir, m³/day.

The performance $Q_{\max}$ is determined as:

$$Q_{\max} = k_{fil} V_{vol} n_0, \quad (23)$$

where k_{fil} represents the LHD bucket filling factor; V_{vol} is the LHD bucket volume, m³; n_0 is the maximum number of LHD trips per day.

The parameter n_0 can be calculated as follows:

$$n_0 > \frac{60 t_{LHD}}{t_0}, \quad (24)$$

where t_0 represents the time of one LHD trip in the process of cleaning a clarification reservoir from slurry sludges, min; t_{LHD} is the maximum LHD operation time in the process of cleaning a clarification reservoir from slurry sludges per day, h.

The time t_{LHD} in the improved version of the classical scheme of the main drainage facility is determined as follows:

$$t_{LHD} = 24 - t_{check}, \quad (26)$$

where t_{check} represents the total daily LHD technical checkup time, hours.

Based on the results of LHD work measurement in the conditions of the Udachny mine's main drainage facility operation, processed using regression statistics, an empirical formula was derived to establish the value of the parameter t_0 as a function of the average distance of slurry sludge hauling S_0 (Fig. 8).

Regarding the non-sludge section of a clarification reservoir (refer to formula (14)), when calculating the parameter $t_{settl\,\min}$ (refer to formula (7)), the value of the parameter h needs to be divided by 10.

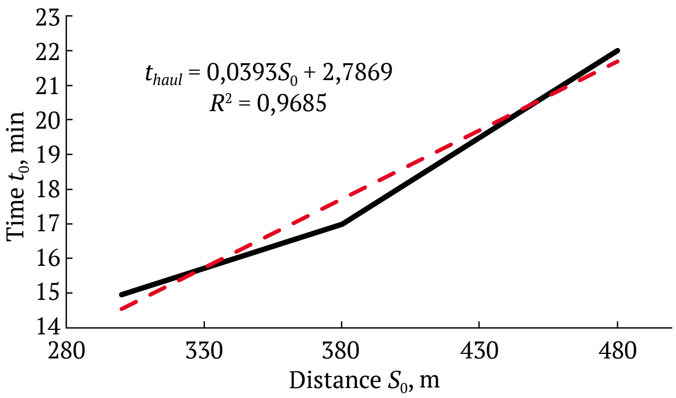


Fig. 8. Average time of a LHD trip for hauling slurry sludges from a clarification reservoir t_0 as a function of an average distance of the slurry sludges hauling S_0

Validation of a methodology for justification of operating parameters of clarification reservoirs

The methodology discussed in this study was applied to justify the operational parameters of clarification reservoirs in the context of an economic contract work titled "Justification of technique and process equipment for effective clarification of mine water and dewatering of slurry sludges contained in mine water as applied to the main drainage facility of the Udachny underground mine".

Based on the calculations presented in Tables 1 and 2, it can be observed for design clarification reservoir No. 5 equality (13) is satisfied when the parameter V assumes values of 3,328.4 and 3,426.25 m³. For clarification reservoir No. 6, equality is satisfied at V values of 3,915.7 and 4,013.6 m³. In both considered cases, the second option is deemed preferable, as it results in the highest value of ΔV (the difference between V and V^*), which, in turn, positively impacts the time T.

Taking into consideration the requirement for both design clarification reservoirs to have a small slope, the final volume values V are determined as 3,430 and 4,030 m³ for reservoirs No. 5 and No. 6, respectively.

Calculation of the expected technical and economic effect

The total costs S_{sum}, measured in million rubles, associated with pumping mine water and cleaning drainage workings from settled slurry sludges in the context of the main drainage facility at the Udachny mine can be define as [18]:

$$S_{sum} = (0.0024\Delta + 67.636) + (0.0011 V_{sum} + 21.765), \quad (27)$$

where Δ represents the quantity of suspended solids pumped together with mine water by the pumping equipment of the main drainage facility, tpy; and V_{sum} represents the total volume of settled slurry sludges removed, m³.

For the calculation of indicator Δ, the following formula is proposed:

$$\Delta = \frac{K q_g}{1000}, \quad (28)$$

where q_g represents the total water inflow to the mine, m³ per year.

It should be noted that in the case of the proposed modernization of the main drainage facility, the volume V_{sum} will increase by V_0, which can be calculated as:

$$V_0 = k_{LHD} N V_{dewat}, \quad (29)$$

where k_{LHD} is a coefficient that takes into account the severity of LHD operation conditions when cleaning water-collecting workings from settled slurry sludges; and N is the number of cleanings of the design clarification reservoirs.

Assuming an expected total water inflow to the mine of q_g = 3,200,000 m^3/year, the cost S_{sum} will amount to:

– with the mine's main drainage facility in place:

$$S_{sum} = \left(0.0024\frac{17\cdot 3,200,000}{1,000} + 67.636\right) +$$
$$+\ (0.0011\cdot 1,730 + 21.765) = 239 \text{ mln rubles};$$

– with the improved version of the mine's main drainage facility in place:

$$S_{sum} = \left(0.0024\frac{4\cdot 3,200,000}{1,000} + 67.636\right) +$$
$$+(0.0011\cdot(1,730 + 0.7\cdot 29,433.56) + 21.765) =$$
$$= 161.8 \text{ mln rubles}.$$

As observed, the difference between these two cost values, ΔZ, is equal to 77.2 mln rubles.

The expected payback period for the proposed design, T_{pay}, will be approximately 4.4 years:

$$T_{pay} = \frac{Z_1 + Z_2}{\Delta Z} = \frac{340.87}{77.2} = 4.4 \text{ years}, \qquad (30)$$

where Z_1 represents the costs of implementing the proposed design, million rubles; and Z_2 represents the additional costs when implementing the proposed design, million rubles.

Once the payback period expires, the expected annual technical and economic effect, Z_0, from the practical implementation of the proposed design will be approximately 73 million rubles:

Table 1

Results of the calculations for establishing optimum volume of design clarification reservoir No. 5

n	*V*	k_h	V^*	ΔV_d
1	1957.9	2.667	4189.2	−2231
1.05	2055.8	2.627	4126.3	−2071
1.1	2153.6	2.587	4063.5	−1910
1.15	2251.5	2.547	4000.7	−1749
1.2	2349.4	2.507	3937.8	−1588
1.25	2447.3	2.467	3875	−1428
1.3	2545.2	2.427	3812.2	−1267
1.35	2643.1	2.387	3749.3	−1106
1.4	2741	2.347	3686.5	−945.5
1.45	2838.9	2.307	3623.7	−784.8
1.5	2936.8	2.267	3560.9	−624.1
1.55	3034.7	2.227	3498	−463.3
1.6	3132.6	2.187	3435.2	−302.6
1.65	3230.5	2.147	3372.4	−141.9
1.7	3328.4	2.107	3309.5	18.823
1.75	3426.3	2.067	3246.7	179.54
1.8	3524.1	2.027	3183.9	340.27
1.85	3622	1.987	3121.1	500.99
1.9	3719.9	1.947	3058.2	661.71
1.95	3817.8	1.907	2995.4	822.43
2	3915.7	1.867	2932.6	983.16
2.05	4013.6	1.827	2869.7	1143.9
2.1	4111.5	1.787	2806.9	1304.6
1	1957.9	2.667	4189.2	−2231
1.05	2055.8	2.627	4126.3	−2071

Table 2

Results of the calculations for establishing optimum volume of design clarification reservoir No. 6

n	*V*	k_h	V^*	ΔV_d
1	1957.86	2.667	5585.54	−3627.7
1.05	2055.75	2.627	5501.76	−3446
1.1	2153.65	2.587	5417.99	−3264.3
1.15	2251.54	2.547	5334.22	−3082.7
1.2	2349.43	2.507	5250.44	−2901
1.25	2447.33	2.467	5166.67	−2719.3
1.3	2545.22	2.427	5082.9	−2537.7
1.35	2643.11	2.387	4999.13	−2356
1.4	2741	2.347	4915.35	−2174.4
1.45	2838.9	2.307	4831.58	−1992.7
1.5	2936.79	2.267	4747.81	−1811
1.55	3034.68	2.227	4664.04	−1629.4
1.6	3132.58	2.187	4580.26	−1447.7
1.65	3230.47	2.147	4496.49	−1266
1.7	3328.36	2.107	4412.72	−1084.4
1.75	3426.26	2.067	4328.95	−902.69
1.8	3524.15	2.027	4245.17	−721.03
1.85	3622.04	1.987	4161.4	−539.36
1.9	3719.93	1.947	4077.63	−357.7
1.95	3817.83	1.907	3993.86	−176.03
2	3915.72	1.867	3910.1	5.6
2.05	4013.61	1.827	3826.31	187.3
2.1	4111.51	1.787	3742.54	368.97
2.15	4209.4	1.747	3658.8	550.6
2.2	4307.29	1.707	3575	732.3

eISSN 2500-0632
https://mst.misis.ru/

$$Z_0 = \Delta Z - Z_2 = 77.2 - 4.5 = 72.7 \text{ mln rubles.} \quad (31)$$

Thus, it is evident that the proposed modernization of the main drainage facility at the Udachny mine is a financially viable solution.

Conclusion

The research conducted has yielded several significant finding:

1. An improved version of the classical scheme of the main drainage facility for a kimberlite mine developed by block caving method is proposed to ensure effective clarification of mine water in water-collecting workings and subsequent dewatering of settled slurry sludges.

2. A methodology has been developed to justify the operating parameters of clarification reservoirs in the main drainage facility of a kimberlite mine developed by block caving method. This methodology takes into account the sedimentation characteristics of the solid phase of mine water, the rheological characteristics of the liquid phase of mine water, and the duration required to clean a sludge-filled clarification reservoir from slurry sludges.

3. The proposed methodology has been successfully tested during the implementation of the economic contract work titled "Justification of technique and process equipment for effective clarification of mine water and dewatering of slurry sludges contained in mine water as applied to the main drainage facility of the Udachny underground mine".

4. The expected technical and economic benefits resulting from the proposed modernization of the main drainage facility at the Udachny mine will amount to approximately 73 million rubles after the investment has been recouped.

References

1. Anisimov K.A. Geomechanical problems in the development of under-pit reserves of diamondiferous deposits in the conditions of the Udachny Mine. 2020;(5):29–36. *Advances in Current Natural Sciences*. (In Russ.) https://doi.org/10.17513/use.37388

2. Kovalenko A.A., Tishkov M.V. The evaluation of the Udachnaya pipe deposit underground mining using caving system. *Mining Informational and Analytical Bulletin*. 2016;(12):134–145. (In Russ.) URL: https://giab-online.ru/files/Data/2016/12/134_145_12_2016.pdf

3. Zelberg A.S., Zyrianov I.V., Bondarenko I.F. Current and emerging technologies in development of diamond deposits. *Russian Mining Industry*. 2019;(3):26–31. (In Russ.) https://doi.org/10.30686/1609-9192-2019-3-145-26-31

4. Ovchinnikov N.P. Assessment of mine water solid phase impact on section pumps performance in the development of kimberlite ores. *Mining Science and Technology* (*Russia*). 2022;7(2):150–160. https://doi.org/10.17073/2500-0632-2022-2-150-160

5. Timukhin S.A., Ugol'nikov A.V., Petrovykh L.V. et al. *Shaft pumping plant*. Patent of the Russian Federation No. 2472971 dated 20.01.2013.

6. Timuchin S.A., Dolganov A.V., Petrovyh L.V. To a question of a background hidroelevators installations the ore's drainages stations. *Mining Informational and Analytical Bulletin*. 2011;(2):118–120. (In Russ.) URL: https://giab-online.ru/files/Data/2011/2/Timuhin_2_2011.pdf

7. Kim Ch.Kh. *Development of a process flow diagram for a drainage facility with self-cleaning water collectors: (DPRK)*. [Ph.D. thesis in Eng. Sci.]. Donetsk; 1990. 20 p. (In Russ.)

8. Korpachev V.V., Kharkov A.V., Berezin S.E. Slurry settler cleaning technique using submersible pumps. *Russian Mining Industry*. 2013;(1):58–59. (In Russ.)

9. Mingazhev M.M. *Improvement of drainage technique in the underground development of sulfide copper deposits with the use of solid stowing*. [Ph.D. thesis in Eng. Sci.]. Magnitogorsk; 2012. 17 p. (In Russ.)

10. Plekhanova V. The new technology of mine water purification. *European Research*. 2016;(4):57–60. (In Russ.)

11. Touahria S., Hazourli S., Touahria K. et al. Clarification of industrial mining wastewater using electrocoagulation. *International Journal of Electrochemical Science*. 2016;(11):5710–5723. https://doi.org/10.20964/2016.07.51

12. Sunka P., Babický V., Clupek M. et al. Generation of chemically active species by electrical discharges in water. *Plasma Sources Science and Technology*. 1999;8(2):258–260. https://doi.org/10.1088/0963-0252/8/2/006

13. Ovchinnikov N.P. Removal of mechanical admixture from the mine waters of the underground kimberlite mine "Udachy" by their deposition. In: *IOP Conference Series: Earth and Environmental Science*. *V International Workshop on Innovations in Agro and Food Technologies (WIAFT-V-2021)*. 17–18 June 2021, Volgograd, Russian Federation. 2021;848(1):012122. https://doi.org/10.1088/1755-1315/848/1/012122

14. Mazo A. B. *Simulation of turbulent incompressible fluid flows*. Kazan: KGU Publ.; 2007. 106 p. (In Russ.)

15. Sencus V. V., Stefanyuk B. M. Investigation of slurry sedimentation in settling reservoirs. *News of the Higher Institutions. Mining Journal.* 2006;(5):54–62. (In Russ.)

16. Sencus V. V., Stefanyuk B. M., Butorin V. K. Simulation of slurry sedimentation processes in coal mine's settling reservoirs. *Mining Informational and Analytical Bulletin*. 2007;(7):102–109. (In Russ.)

17. Olizarenko V. V., Mingazhev M. M. Determination of sludge settling time and cleaning frequency for underground mine main water collectors. *Mining Informational and Analytical Bulletin.* 2010;(7):27–30. (In Russ.)

18. Ovchinnikov N. P., Zyryanov I. V. Integrated assessment of mine water pollution influence on water removal efficiency in Udachny Mine. *Gornyi Zhurnal.* 2022;(7):95–99. (In Russ.) https://doi.org/10.17580/gzh.2022.07.16

Information about the author

Nickolay P. Ovchinnikov – Cand. Sci. (Eng.), Associate Professor, Director of the Mining Institute, North-Eastern Federal University named after M. K. Ammosov, Yakutsk, Russian Federation; ORCID 0000-0002-4355-5028, Scopus ID 57191629443; ovchinnlar1986@mail.ru

Received 09.11.2022
Revised 03.04.2023
Accepted 11.04.2023

eISSN 2500-0632
https://mst.misis.ru/

EXPERIENCE OF MINING PROJECT IMPLEMENTATION

Research paper

https://doi.org/10.17073/2500-0632-2022-12-68
УДК 622:502.7

Detection of violations of open-pit mining lease boundaries using Sentinel-2 MSI data in the case of Lao Cai and Yen Bai provinces of North Vietnam

X.B. Tran[1] ✉, L.H. Trinh[2], Q.L. Nguyen[3], Yu.M. Levkin[4], I.V. Zenkov[5], T.H. Tong[2]

[1] *Hanoi University of Natural Resources and Environment, Hanoi, Vietnam*
[2] *Le Quy Don Technical University, Hanoi, Vietnam*
[3] *Hanoi University of Mining and Geology, Hanoi, Vietnam*
[4] *Russian Union of Surveyors, Moscow, Russian Federation*
[5] *Siberian Federal University, Krasnoyarsk, Russian Federation*
✉ *txbien.ph@hunre.edu.vn*

Abstract
Illegal mining, including the violation of lease boundaries during the extraction of mineral deposits in Vietnam, has witnessed a significant surge in recent years, leading to substantial environmental degradation. Due to the remote locations of mining areas in relation to settlements, the detection of illegal mining activities using conventional methods poses considerable challenges. This study presents a methodology for identifying lease boundary violations in open-pit mining of mineral deposits by utilizing high-resolution satellite images from the Sentinel-2 MSI system. The proposed methodology involves overlaying Sentinel-2 MSI radar-acquired satellite images to identify disparities between approved lease boundaries and actual boundaries of mining areas. The research focuses on the mineral-rich provinces of Lao Cai and Yen Bai in North Vietnam. The findings of this research rhold great potential for effectively monitoring and promptly detecting violations of mining lease boundaries.

Keywords
illegal mining, remote sensing, Sentinel-2B MSI data, Vietnam, Lao Cai and Yen Bai provinces

Acknowledgments
The researchers express their gratitude to the research sponsor for providing all the necessary materials, enabling the timely completion of the project. These materials played a crucial role in addressing the objectives outlined in the project titled "Monitoring of the boundaries of mining areas in some northern provinces of Vietnam using remote sensing and UAV imaging", with code: SXTN.2020.08.01.

For citation
Tran X.B., Trinh L.H., Nguyen Q.L., Levkin Yu.M., Zenkov I.V., Tong T.H. Detection of violations of open-pit mining lease boundaries using Sentinel-2 MSI data in the case of Lao Cai and Yen Bai provinces of North Vietnam. *Mining Science and Technology* (*Russia*). 2023;8(2):173–182. https://doi.org/10.17073/2500-0632-2022-12-68

ОПЫТ РЕАЛИЗАЦИИ ПРОЕКТОВ В ГОРНОПРОМЫШЛЕННОМ СЕКТОРЕ ЭКОНОМИКИ

Научная статья

Выявление нарушений границ разработки месторождений полезных ископаемых открытым способом с использованием данных Sentinel-2 MSI на примере провинций Северного Вьетнама Лао Кай и Йень Бай

С.Б. Чан[1] ✉, Л.Х. Чинь[2], К.Л. Нгуен[3], Ю.М. Левкин[4], И.В. Зеньков[5], Т.Х. Тонг[2]

[1] *Ханойский университет природных ресурсов и окружающей среды, г. Ханой, Вьетнам*
[2] *Вьетнамский государственный технический университет им. Ле Куй Дона, г. Ханой, Вьетнам*
[3] *Ханойский университет горного дела и геологии, г. Ханой, Вьетнам*
[4] *Союз маркшейдеров России, г. Москва, Российская Федерация*
[5] *Сибирский федеральный университет, г. Красноярск, Российская Федерация*
✉ *txbien.ph@hunre.edu.vn*

Аннотация
Незаконная добыча полезных ископаемых, в том числе нарушение лицензионных границ при отработке месторождений полезных ископаемых во Вьетнаме за последние годы резко возросли. Это приводит к значительному ухудшению состояния окружающей среды. Поскольку районы добычи

полезных ископаемых часто расположены далеко от населенных пунктов, традиционными методами трудно обнаружить районы незаконной добычи. В данной работе представлена методика обнаружения нарушения лицензионной границы открытой разработки месторождений минерального сырья по спутниковым снимкам высокого разрешения Sentinel-2 MSI. В разработанной методике при наложении полученных радаром Sentinel-2 MSI снимков со спутника определяется несоответствие лицензионных границ месторождений полезных ископаемых фактическим. Район исследования расположен в богатых минеральными ресурсами Северного Вьетнама провинциях Лао Кай и Йень Бай. Полученные в ходе исследования результаты могут быть эффективно использованы для мониторинга и раннего выявления нарушений лицензированных границ горнодобывающего предприятия.

Ключевые слова
незаконная добыча полезных ископаемых, дистанционное зондирование, данные Sentinel-2B MSI, Вьетнам, провинции Лао Кай и Йень Бай

Благодарности
Научные сотрудники, проводившие исследования, благодарят заказчика проведения исследований за предоставление в полном объеме необходимых материалов, что позволило в установленные сроки выполнить поставленную задачу. Эти материалы помогли решить задачи, поставленные проектом «Мониторинг границ добычи полезных ископаемых в некоторых северных провинциях Вьетнама с использованием дистанционного зондирования и получения изображений с БПЛА». Код: SXTN.2020.08.01.

Для цитирования
Tran X.B., Trinh L.H., Nguyen Q.L., Levkin Yu.M., Zenkov I.V., Tong T.H. Detection of violations of open-pit mining lease boundaries using Sentinel-2 MSI data in the case of Lao Cai and Yen Bai provinces of North Vietnam. *Mining Science and Technology* (*Russia*). 2023;8(2):173–182. https://doi.org/10.17073/2500-0632-2022-12-68

Introduction

Monitoring mining lease boundaries in states involved in open-pit mining is carried out through various methods, such as radiation interferometry, image synthesis, and spectral analog techniques. Implementing these procedures can significantly increase the payments made by subsoil users to the state budget [1]. It also enables the control of mining parameters, land allotments, and the efficient utilization of mineral resources.

In Northern provinces of Vietnam, mining servses as a significant source of revenue for the state budget. However, the approved boundaries of land allotments for open-pit mining in Lao Cai and Yen Bai provinces are frequently violated. These violations have detrimental effect on the environment and the health of local population. The rugged terrain of mining areas allows lease owners who infringe upon boundaries to evade legal consequences. Advanced remote sensing techniques, such as using Sentinel-2 MSI radar aboard space satellites, provide high-resolution images of extensive areas of the Earth's surface. The frequent updating of these images facilitates the monitoring of lease boundaries to identify violators.

Remote sensing and other monitoring approaches of Earth's surface are employed in numerous countries worldwide to arrdess illegal mining, whish often occurs in remote regions [2, 3]. For example the Government of Ghana, detected illegal mining zones with areas measuring 102, 60, and 33 km^2 from 2015 to 201 by processing Sentinel-1 radar remote sensing satellite images using a threshold assessment method. This discovery significantly contributed to increased budget revenues through additional payments, such as MET [4, 5].

Similarly, Landsat satellite images were employed to curb illegal gold mining in India, occurring between 1986 and 2002 and from 2007 to 2013. These satellite images were used to compare the mining lease area with the actual mining area, facilitating the estimation of the extent of illegal mining [6]. The development of the DinSAR radar satellite interferometry technique has provided solutions for creating digital terrain models, aiding the detection of illegal open-pit mining areas, even in mountainous regions with dense vegetation [7–10].

This paper presents the research findings derived from analyzing satellite images captured by the Sentinel-2 MSI radar. The study resulted in the development of a methodology for detecting violations of open-pit mining lease boundaries by mining companies.

By overlapping satellite images, it was possible to identify and evaluate the degree of infringement of mining rights by mining enterprises in North Vietnam, including those with official lease boundaries.

The Sentinel-2 MSI radar information, with its frequent updates, is available free of charge to all interested organizations, thus enhancing the effectiveness of mining activity monitoring [11–13].

eISSN 2500-0632
https://mst.misis.ru/

Materials and methodology

Study area

The study area encompasses the provinces of Lao Cai and Yen Bai in North Vietnam. These provinces are characterized by mountainous terrain, challenging topography, and undeveloped infrastructure. Extensive reserves of 35 minerals types, including iron, copper, zinc, and kaolin clays, have been explored in this region. The exploration efforts have resulted in the identification of substantional reserves, such as over 2.5 billion tons of apatite and copper ore, as well as 200 million tons of iron ore, including reserves of over 120 million tons in the Quy Sa mine. Additionally, rare earth ores, crucial for the advancement global high-tech industry, have also been discovered. The exploration of these mineral resources involves more than 500 small-scale mining enterprises, of which 240 possess valid licenss and leases. The lack of stringent plans for increasing mineral production and developing these regions creates opportunities for the illegal extraction of valuable minerals.

Materials

The study utilized multispectral data from the Sentinel-2 MSI radar, which were acquired in November 29, 2022, in Lao Cai Province, and in November 4, 2022, in Yen Bai Province, for the purpose of identifying illegal mining activities. The implementation of the Sentinel-2 MSI imaging technique enabled the capture of data across 13 spectral ranges, ranging from visible and near infrared (VNIR) to shortwave infrared (SWIR), at wavelengths within an orbital height of 290 km. The spatial resolution of the Sentinel-2 MSI images varied between 10 and 60 m, with the visible (2, 3, 4) and near-infrared (8) ranges having a spatial resolution of 10 m (Table 1).

Prior to analysis, the Sentinel-2 MSI radar images underwent pre-processing steps. These included the removal of clouds and the extraction of information within the boundaries of the research areas (Fig. 2). The images utilized in the study were L2A level products, obtained from the Copernicus Open Access Hub website (https://scihub.copernicus.eu). These products represent lower atmosphere reflectivity images (BOA) derived from the corresponding Level 1C products.

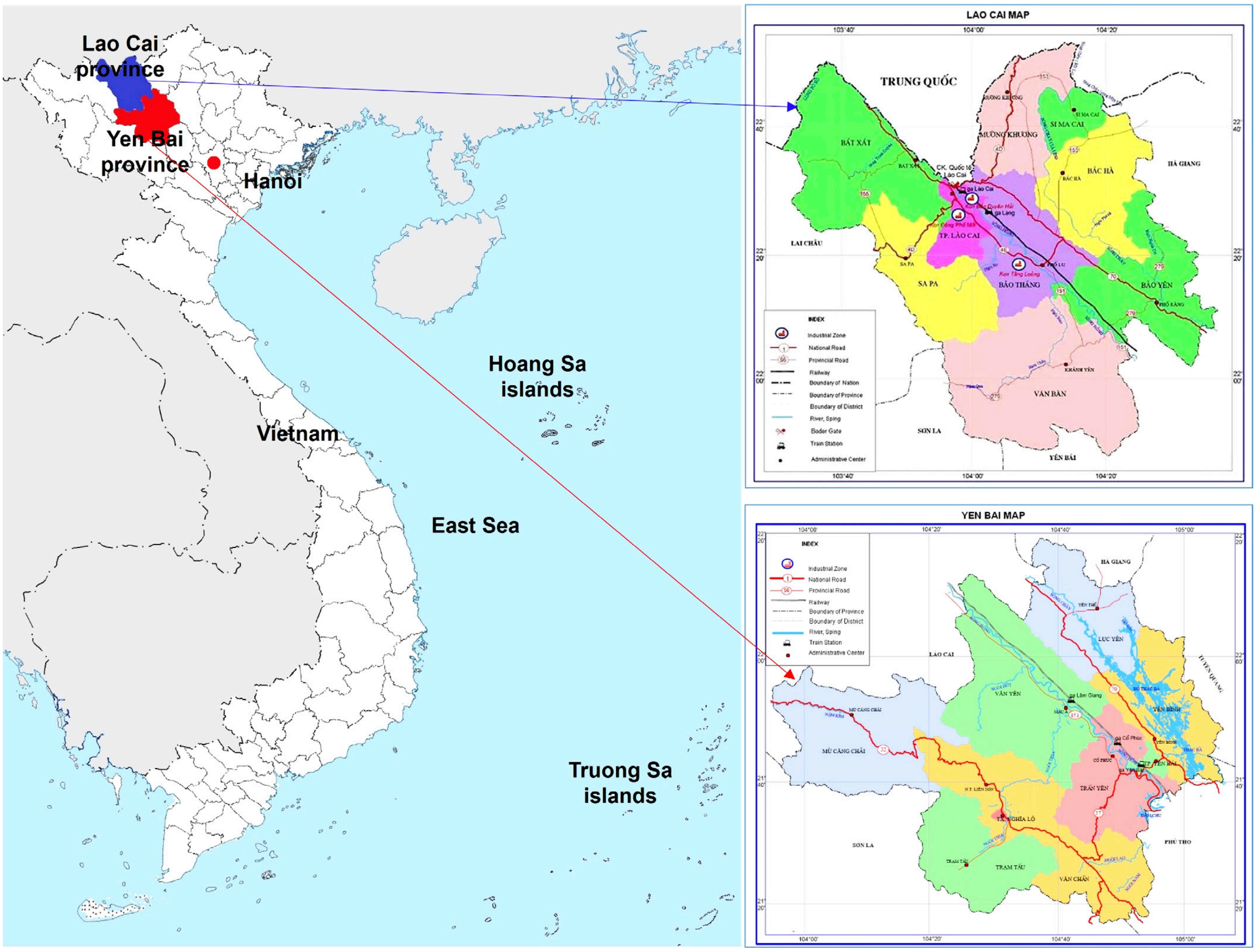


Fig. 1. Research areas in Lao Cai and Yen Bai provinces, Vietnam

Methodology

The multispectral processing of the Sentinel-2 MSI radar sensing images involved applying atmospheric and geometric corrections. The geometric correction process aimed to rectify geometric errors and transform the image coordinates captured by the Sentinel-2 MSI radar into local coordinates (VN-2000) consistent with the coordinate system of the lease boundary.

To identify illegal mining areas, spectral ranges with a spatial resolution of 10 m were utilized. These specific ranges were selected due to their highest spatial resolution among the available MSI Sentinel-2 ranges, enabling the detection of illegal mining areas with greater precision.

Subsequently, images depicting mining lease boundaries were superimposed onto Sentinel-2 MSI satellite images, allowing for a comparison between the designated lese boundaries and the actual boundaries. In this assessment, a digitization technique was employed to evaluate the extent of mining operation beyond the lease boundary, following the methodology for detecting illegal expansion of mining leases (Fig. 3).

Table 1

Sentinel-2 MSI images

Channels	Spectral range, μm	Spatial resolution, m
Coastal aerosol	0.421–0.457	60
Blue	0.439–0.535	10
Green	0.537–0.582	10
Red	0.646–0.685	10
Red edge of vegetation	0.694–0.714	20
Red edge of vegetation	0.731–0.749	20
Red edge of vegetation	0.768–0.796	20
Near IR	0.767–0.908	10
Red edge of vegetation	0.848–0.881	20
Water vapor	0.931–0.958	60
Shortwave infrared— cirrus cloud	1.338–1.414	60
Shortwave infrared	1.539–1.681	20
Shortwave infrared	2.072–2.312	20

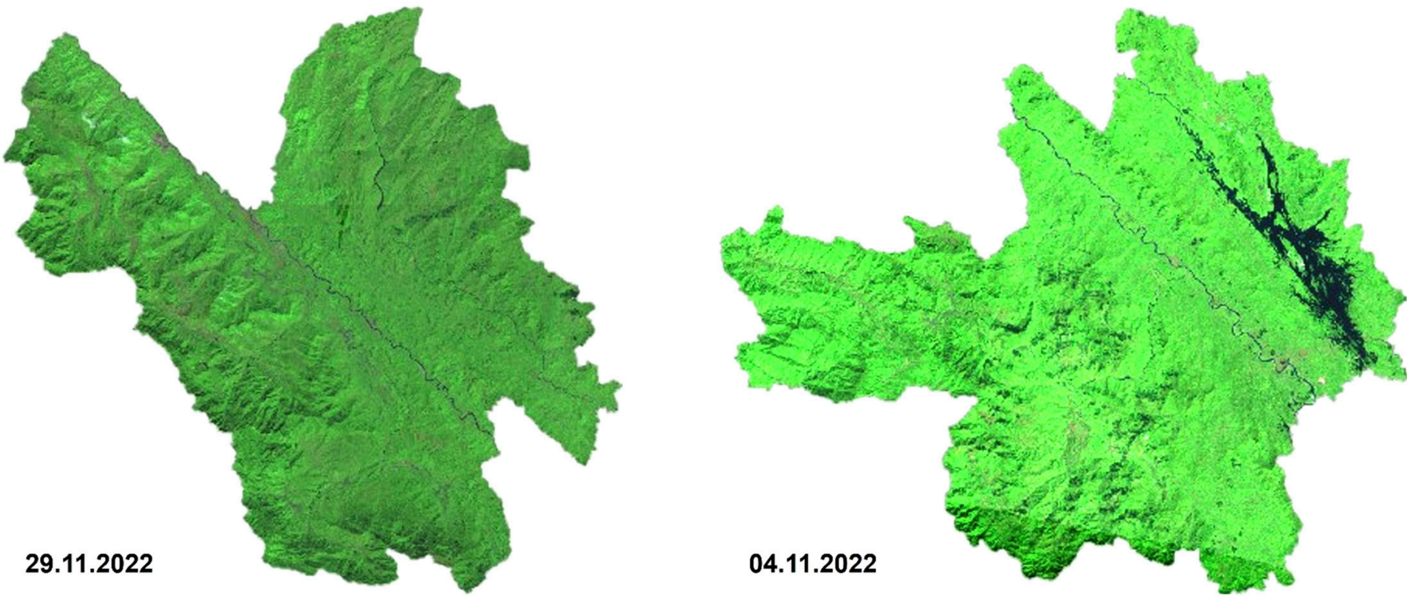


Fig. 2. Sentinel-2 MSI images within Lao Cai and Yen Bai provinces after pre-processing and cutting along the boundaries of the study areas

Scientific and methodological justification of solutions

a) *General methodology for processing Sentinel-2 MSI multispectral images*

The first step was to access the Sentinel-2 MSI image data from the Copernicus Open Access Hub database. This required selecting the coordinates of the study area and other conditions such as image type, processing level, cloudiness, and imaging time. Figure 4 provides a visual guide on how to select and download Sentinel-2 MSI images from https://scihub.copernicus.eu.

Spectral channels with a spatial resolution of 10 m (2, 3, 4, and 8) were used to detect illegal mining areas.

b) *Models for converting image coordinates into local coordinates*

The Sentinel-2 MSI images, obtained from the Copernicus database in the WGS 84 coordinate system, were converted to the local coordinate system (VN2000) (*Department of Geodesy, Map, and Geographic Information, Ministry of Natural Resources and Environment of Vietnam*) based on the following transformation equations:

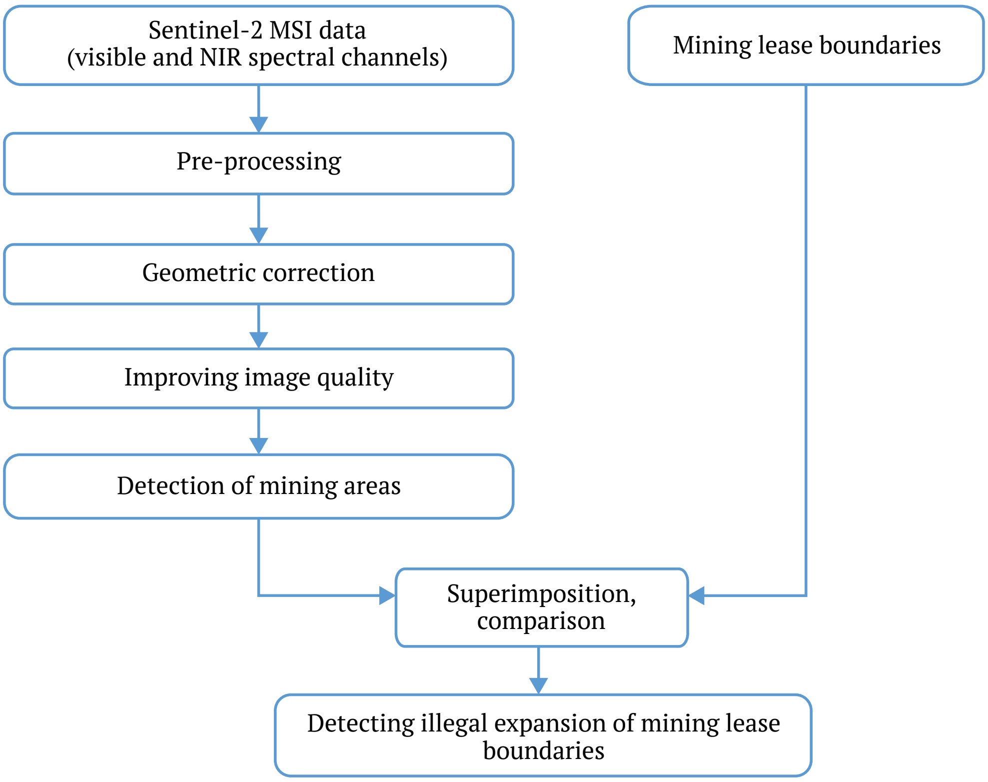


Fig. 3. The stages of the methodology for detecting illegal mining lease expansion based on Sentinel-2 MSI data

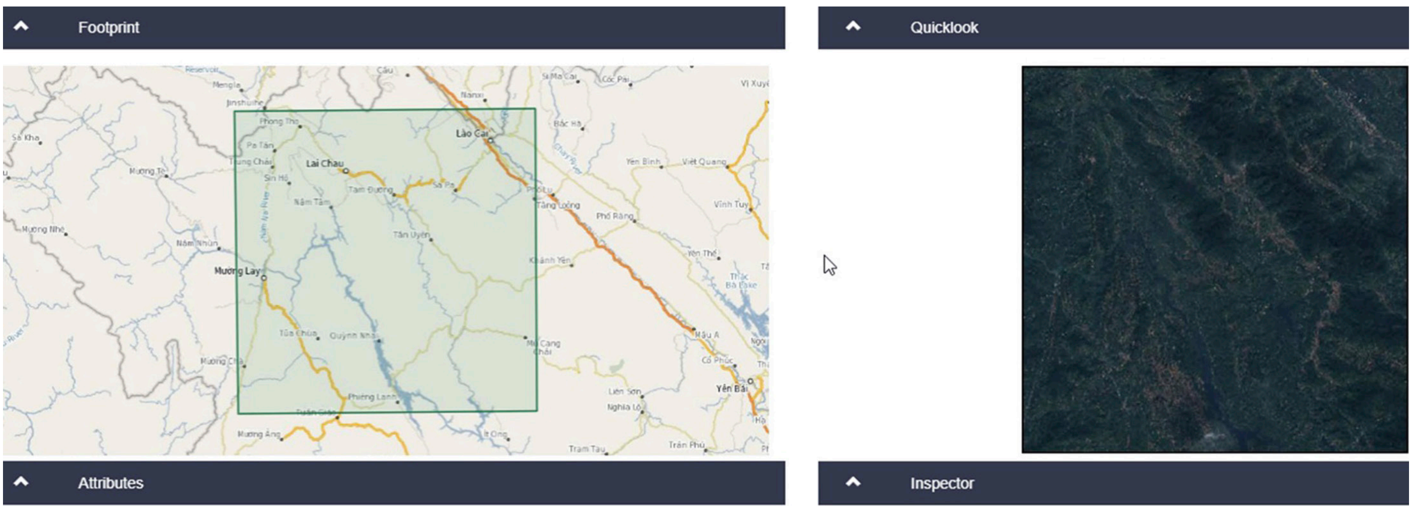


Fig. 4. Collection of Sentinel-2 image data in the Copernicus database

$$X = \Delta x_0 + k(X' + \varepsilon_0 Y' - \psi_0 Z');$$
$$Y = \Delta y_0 + k(-\varepsilon_0 X' + Y' + \omega_0 Z');$$
$$Z = \Delta z_0 + k(\psi_0 X' - \omega_0 Y' + Z'),$$

where X, Y, Z represent the coordinates in the Cartesian coordinate system that require convertion into meters; X', Y', Z' кrepresent the displacement coordinates in the Cartesian coordinate system, m; Δx_0, Δy_0, Δz_0 are parameters indicating the displacement of the coordinate origin, m; ω_0, ψ_0, ε_0 are the three rotation angles (Elege rotation), corresponding to the X, Y, Z axes, rad. The scale factor is denoted by k.

c) *Proposals for improving the image processing method (or algorithm) for enhanced accuracy (resolution), accounting for atmospheric and geometric corrections*

The Sentinel-2 MSI image underwent preprocessing procedures. This includes the application of geometric correction techniques and the conversion of the image to the local coordinate system (VN2000). Subsequently, clouds cover wes eliminated from the image, and specific information pertaining to the boundaries of the study areas was extracted and isolated.

The cloud filtering process for Sentinel-2 image is conducted using the Google Earth Engine (GEE) platform. GEE is a cloud-based geospatial analysis platform that provides users with the capability to visualize and analyze satellite images of the Earth. The offers a vast dataset containing remote sensing data collected from satellite systems spanning the past 40 years. Furthermore, GEE provides computational tools necessary for analyzing and utilizing this extensive data without the need to download to a local computer. Additionally, the data from GEE can be optimized to use in other software application such as QGIS, GIS, and Foris.

In order to filter and select the necessary images, the study utilized a reference image set from Sentinel-2, where the selected images had a cloud coverage of less then 80 %. The cloud filtering process was performed on the GEE platform using the CloudScore algorithm, which helps identify and filter out cloud pixels. Additionally, the Temporal Dark Outlier Mask (TDOM) algorithm was employed to detect and identify claud shadow pixels. used to. The outcomes of the cloud filtering and cropping of the Sentinel-2 MSI image along the boundaries of the study area are depicted in Fig. 2.

d) *New technique and algorithm*

This study introduces a novel approach by utilizing the GEE cloud computing platform for processing Sentinel-2 MSI satellite image data. The GEE platform offers an online JavaScript application interface (API) known as Code Editor, which is well-suited for handling large volumes of remote sensing data. Given the substantial amount of data generated by satellite remote sensing systems, the use of GEE enables efficient processing and analysis. Moreover, the platform enhances the capacity for monitoring and detecting changes on the Earth's surface by leveraging the temporal heterogeneous of remote sensing data.

This study pioneers the use of spectral imaging ranges with the highest spatial resolution among the MSI Sentinel-2 ranges, specifically the 10 m visible and near-infrared (NIR) bands. This selection allows for the detection of illegal mining areas concealed within dense jungle thickets. By utilizing the Sentinel-2 MSI multispectral images, which provide a short time resolution of 5 days, the monitoring of mining areas becomes more effective and timely.

Table 2

Comparison of lease and actual mining areas at several mines in Lao Cai Province

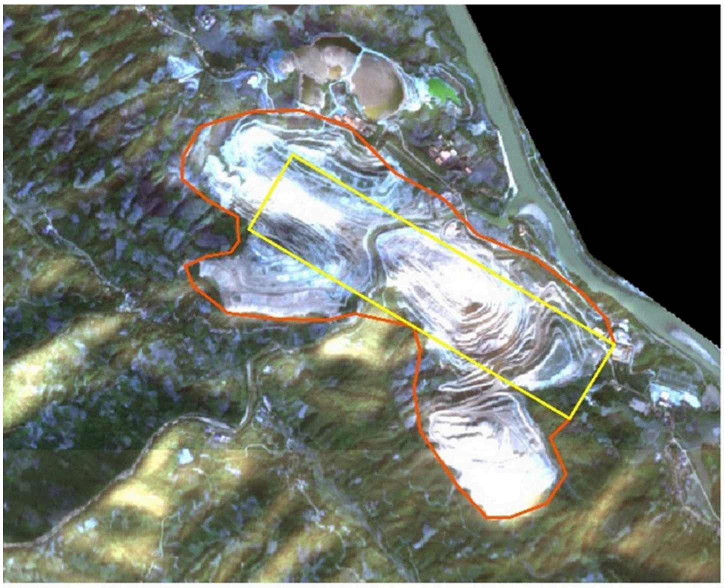
Mining enterprise	Address	Lease (licensed mining area), ha	Actual mining area, ha	Difference in mining area, ha
Apatite	Chieng Ken Municipality, Van Ban District	4.02	9.80	5.78
Kaolin	Lang Giang Municipality, Van Ban District	4.33	6.4	2.07
Apatite	Bao Ha Municipality, Bao Yen District	12.55	20.41	7.86
Kaolin	Van Hoa Municipality, Lao Cai City	28.32	43.57	15.25
Apatite	Cam Duong Municipality, Lao Cai City	49.85	63.91	14.06
Iron	Vo Lao Municipality, Van Ban District	51.03	96.96	45.93
Apatite	Dong Tuyen Municipality, Lao Cai City	76.19	150.32	74.13
Apatite	Ta Phoi Municipality, Lao Cai City	77.92	97.48	19.56
Iron	Quy Xa Municipality, Van Ban District	81.53	151.65	70.12
Apatite	Son Thuy Municipality, Van Ban District	91.96	107.59	15.63
Copper	Coc My Municipality, Bat Sat District	207.78	525.76	317.98

eISSN 2500-0632
https://mst.misis.ru/

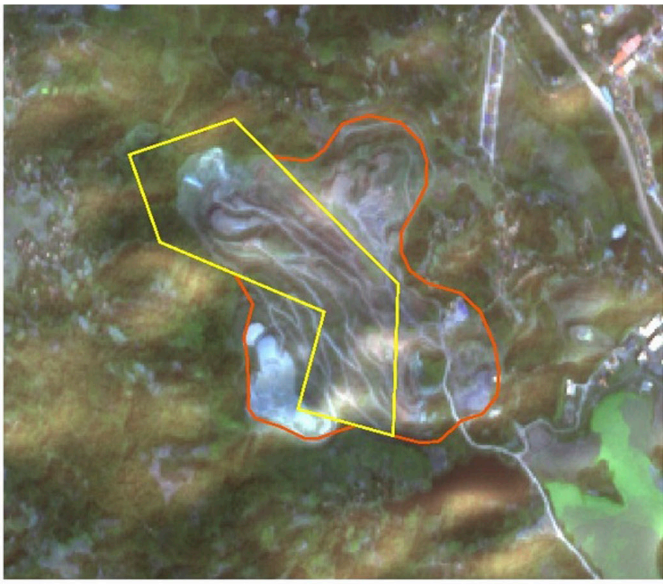
Findings and Discussion

The analysis of Sentinel-2 MSI satellite images of open-pit mining areas reveals that the actual production areas often exceed the corresponding official lease areas (Table 2). Notably, at 11 mines, the actual mining areas significantly surpass their lease areas. For example, there are cases where the actual mining area is twice as large as the lease area, such as in a copper mine in Koc Mi Municipality, Bat Sat District; and an apatite mine in Dong Tuen Municipality, Lao Cai City (Fig. 5).

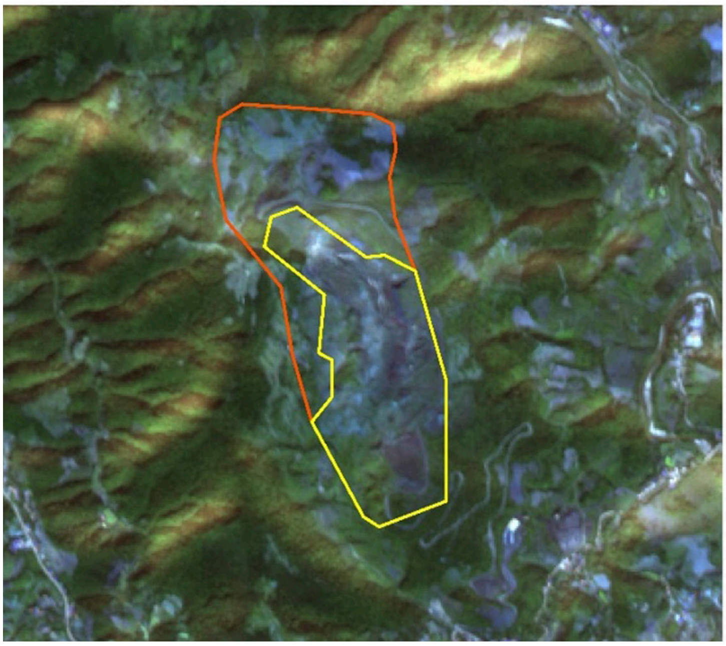
In the evaluation of open-pit mining areas in Yen Bai Province, a total of 12 mining zone were examined to determine the extent of illegal expansion (as indicated in Table 2). By analysing satellite images depicting the boundaries of the actual mining area (as shown in Fig. 6), it was confirmed the five leases had indeed experienced illegal expansion (as documented in Table 2). As an illustration, a limestone quarry located in Yen Thang Municipality, Luc Yen District, originally designated with a lease area of 2.18 hectares, was found to have expanded its production area to cover approximately 26.62 hectares (refer to Table 3).



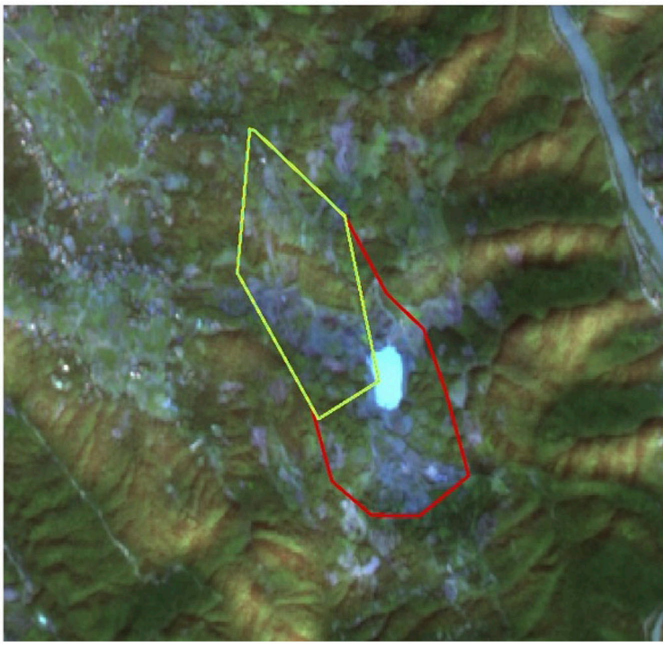
Sinh Quyen copper mine



Bao Ha apatite mine



Iron mine
(Vietnam mineral and metallurgical company)



Lang Vinh iron mine

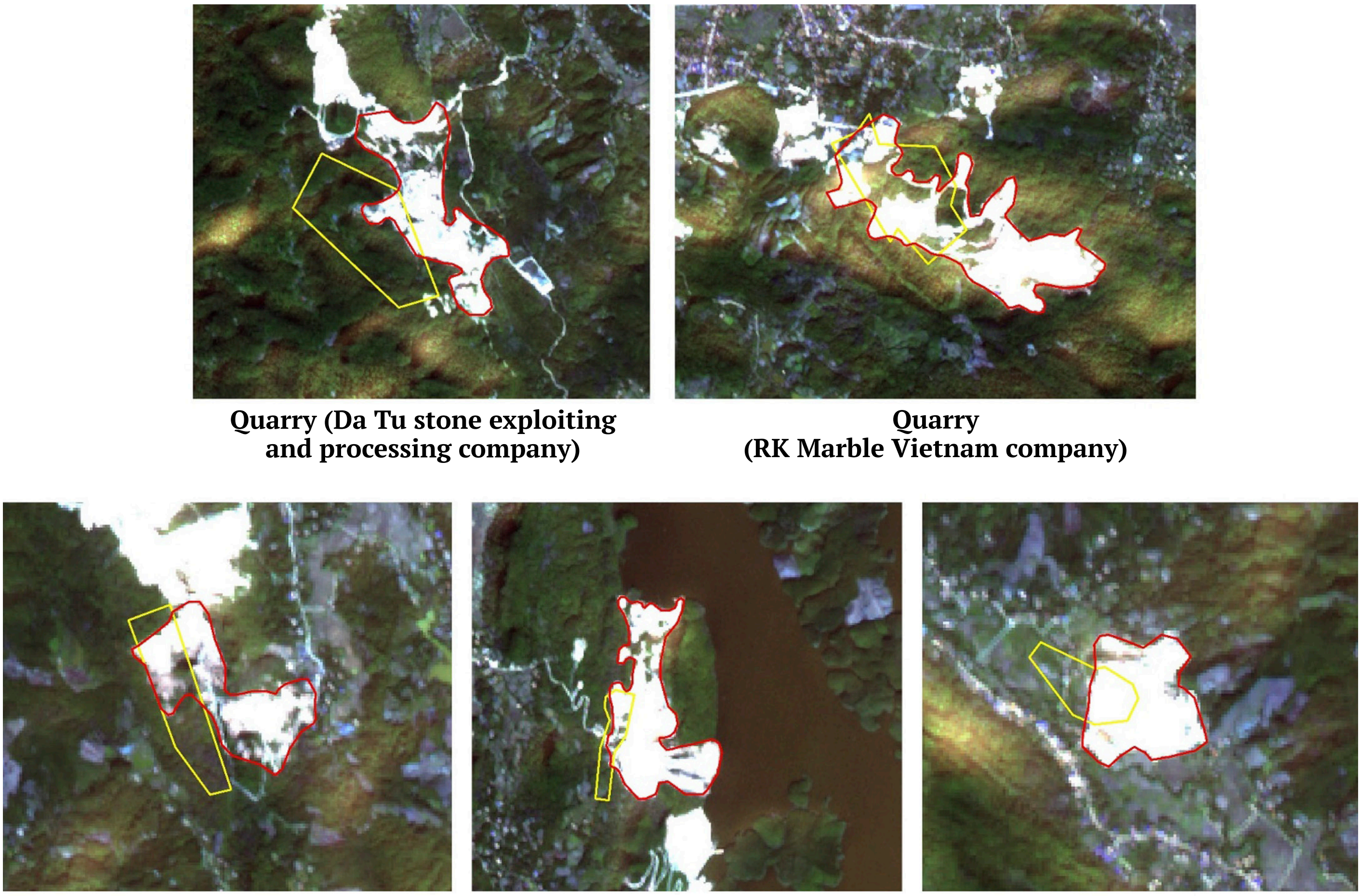
Fig. 5. Satellite images of actual mining areas (red) and lease (yellow) boundaries in Lao Cai Province, captured by the Sentinel-2 MSI radar

eISSN 2500-0632
https://mst.misis.ru/

Table 3

Comparison of lease and actual mining areas at several mines in Yen Bai Province

Mining enterprise	Address	Lease (licensed mining area), ha	Actual mining area, ha	Difference in mining area, ha
White marble quarry	Yen Thang Municipality, Luc Yen District	26.80	51.87	25.07
K-feldspar	Tan Lap Municipality, Luc Yen District	5.01	16.25	11.24
Marble quarry	Yen The Municipality, Luc Yen District	43.32	98.18	54.86
Marble quarry	Mong Son Municipality, Yen Binh district	10.01	45.85	35.84
Graphite	Yen Thai Municipality, Van Yen district	11.65	24.70	13.05
Marble quarry	Lieu Do Municipality, Luc Yen District	49.80	65.88	16.08
White marble quarry	Tan Linh Municipality, Luc Yen District	5.21	16.48	11.27
Marble quarry	An Phu Municipality, Luc Yen District	5.91	36.84	30.93
Iron	Hung Khanh Municipality, Tran Yen District	113.00	146.63	33.63
Limestone quarry	Yen Thang Municipality, Luc Yen District	2.18	28.80	26.62
Quarry	Yen Thang Municipality, Luc Yen District	2.18	9.96	7.78
Marble quarry	An Phu Municipality, Luc Yen District	16.10	43.58	27.48



Quarry (Da Tu stone exploiting and processing company)

Quarry (RK Marble Vietnam company)

Quarry (Phanxipang company)

Quarry (Thai Duong company)

Quarry (Hung Dai company)

Fig. 6. Satellite images of actual mining areas (red) and lease (yellow) boundaries in Yen Bai Province, obtained by the Sentinel-2 MSI radar

Conclusions

In November 2022, the Sentinel-2 MSI radar captured satellite images of the mine areas in Lao Cai and Yen Bai provinces in Northern Vietna. These images were processed with the aim of detecting and assessing areas of illegal mining. The results of the analysis revealed that the actual mining areas in many of the surveyed districts significantly exceeded the designated lease areas. The use of Sentinel-2 MSI radar imaging provided high spatial resolution, with details down to 10 m. Additionally, the five-day time resolution of image capture enabled effective monitoring and early detection of violations in mining lease boundaries. The research findings offer valuable insights that will assist managers in monitoring and inspecting mining activities to ensure compliance with official lease boundaries set by mine operators.

References

1. Kozinska P., Gorniak-Zimroz J. A review of methods in the field of detecting illegal open-pit mining activities. In: *IOP Conference Series: Earth and Environmental Science. XXI Conference of PhD Students and Young Scientists (CPSYS 2021)*. 23–25 June 2021 (virtual), Wroclaw, Poland. 2021;942:012027. https://doi.org/10.1088/1755-1315/942/1/012027

2. Levkin Yu.M. The usage of modern surveying instruments in mining. In: Nguyen Q.L., Pham T.L., Nguyen V.N. et al. (Eds.) *The Proceeding of Geo-spatial Technologies and Earth Resources Conference* (GTER 2017). 5–6 October 2017, Hanoi, Vietnam. Hanoi: Publ. House for Science and Technology; 2017. Pp. 307–311.

3. Liu Y., Zhong C., Bai B., Zhou Y. Assessment of government supervision on the loss of sea sand resource in China. *Economic Research*. 2022;35(1):2732–2746. https://doi.org/10.1080/1331677X.2021.1977672

4. Forkuor G., Ullmann T., Griesbeck M. Mapping and monitoring small-scale mining activities in Ghana using Sentinel-1 time series (2015–2019). *Remote Sensing*. 2020;12(6):911. https://doi.org/10.3390/rs12060911

5. Owusu-Nimo F., Mantey J., Nyarko K.B., et al. Spatial distribution patterns of illegal artisanal small scale gold mining (Galamsey) operations in Ghana: A focus on the Western Region. *Heliyon*. 2018;4(2):e00534. https://doi.org/10.1016/j.heliyon.2018.e00534

6. Merugu S., Jain K. Change detection and estimation of illegal mining using satellite images. In: *Proceedings of 2nd International Conference on Innovations in Electronics and Communication Engineering (ICIECE-2013)*. 9–10 August 2013, Hyderabad, India. Pp. 246–251.

7. Hu Z., Ge L., Li X., Rizos C. Designing an illegal mining detection system based on DinSAR. In: *2010 IEEE International Geoscience and Remote Sensing Symposium*. 25–30 July 2010, Honolulu, HI, USA. Pp. 3952–3955. https://doi.org/10.1109/IGARSS.2010.5652978

8. Xia Y., Wan Y. InSAR- and PIM-based inclined goaf determination for illegal mining detection. *Remote Sensing*. 2020;12(23):3884. https://doi.org/10.3390/rs12233884

9. Wang L., Yang L., Wang W. et al. Monitoring mining activities using Sentinel-1A InSAR coherence in open-pit coal mines. *Remote Sensing*. 2021;13(21):4485. https://doi.org/10.3390/rs13214485

10. Zhang B., Wu S., Ding X. et al. Use of multiplatform SAR imagery in mining deformation monitoring with dense vegetation coverage: A case study in the Fengfeng Mining Area, China. *Remote Sensing*. 2021;13(16):3091. https://doi.org/10.3390/rs13163091

11. Le M.H., Do T.P.T., Vu T.T.H. et al. Using optical satellite images to detect the signs of illegal mining in Thai Nguyen province. *Science of* Natural Resources and Environment. 2018;20:30–42. (In Vietnamese)

12. Trinh L.H., Zablotskii V.R. The application of Landsat multi-temporal thermal infrared data to identify coal fire in the Khanh Hoa coal mine, Thai Nguyen province, Vietnam. *Izvestiya. Atmospheric and Oceanic Physics*. 2017;53(9):1181–1188. https://doi.org/10.1134/S0001433817090183

13. Trinh L.H. Hydrothermal minerals mapping using based on remotely sensed data from Sentinel 2 sattelite: a case study in Vinh Phuc Province, Northern Vietnam. *Mining Science and Technology* (*Russia*). 2019;4(4):309–317. https://doi.org/10.17073/2500-0632-2019-4-309-317

Information about the authors

Xuan Bien Tran – Lecturer, Hanoi University of Natural Resources and Environment, Hanoi, Vietnam; ORCID 0009-0005-1113-1545, Scopus ID 57951801800; e-mail txbien.ph@hunre.edu.vn

Le Hung Trinh– Cand. Sci. (Eng.), Associate Professor, Le Quy Don Technical University, Hanoi, Vietnam; ORCID 0000-0002-2403-063X, Scopus ID 57035066200; e-mail trinhlehung@lqdtu.edu.vn

Quoc Long Nguyen – Cand. Sci. (Mine Surveying), Head of Mine Surveying Department, Hanoi University of Mining and Geology, Hanoi, Vietnam; ORCID 0000-0002-4792-3684, Scopus ID 57204138384; e-mail nguyenquoclong@humg.edu.vn

Yuri M. Levkin – Dr. Sci. (Eng.), Professor, Russian Union of Surveyors, Moscow, Russian Federation; ORCID 0009-0004-4364-0785, Scopus ID 57297910200; e-mail lev5353@bk.ru

Igor V. Zenkov – Dr. Sci. (Eng.), Professor, Department of Ecology and Nature Management, Siberian Federal University, Krasnoyarsk, Russian Federation; ORCID 0000-0003-4427-4196, Scopus ID 57188958340; e-mail zenkoviv@mail.ru

Thi Hanh Tong – Lecturer, Le Quy Don Technical University, Hanoi, Vietnam; ORCID 0000-0002-6639-0318, Scopus ID 57314239400; e-mail hanhkhuenam@gmail.com

Received	22.12.2022
Revised	14.04.2023
Accepted	15.04.2023

eISSN 2500-0632
https://mst.misis.ru/

PROFESSIONAL PERSONNEL TRAINING

Research paper

https://doi.org/10.17073/2500-0632-2023-01-71
УДК 622:378

Applied geology – basic training program for mining and geological industry personnel

A. A. Vercheba[1] ✉, **V. A. Makarov**[2]

[1] *Sergo Ordzhonikidze Russian State University for Geological Prospecting, Moscow, Russian Federation*
[2] *Siberian Federal University, Krasnoyarsk, Russian Federation*
✉ *aa_ver@mail.ru*

Abstract
The development of the human resources potential of the mining and geological industry in Russia is largely a task of the state and its institutions. The shortage of qualified personnel in the field of geological study of the subsurface, as well as the gap in the "education – science – production" system are indicated among other things in the list of challenges and threats to the development of the mineral resource base of the Russian Federation in the new Strategy of Development of the Mineral Resource Base of the Russian Federation until 2035. This strategy was developed and adopted by Order of the Government of the Russian Federation No. 2914 of 22.12.2018 (hereinafter – Strategy). Obviously, the solution of the tasks aimed at developing the geological industry of Russia and reproduction of the mineral resource base, formulated in the Strategy, will be provided mainly by the geological knowledge and skills formed in the scientific and practical activities of the new generation of geologists. The current modernization of geological education in the absence of professional standards is aimed at combining the competences of university graduates and qualifications of representatives of the profession of geologists, geophysicists, geochemists, hydrogeologists and geological prospectors. Interaction of universities with mining and geological companies in terms of improving educational standards and training programs is especially important in the conditions of the development and large-scale implementation of new technologies for mineral resources study at all stages of the geological exploration process. Reproduction of the personnel potential of the exploration industry should certainly be under the close attention of the state and under its direct management, as it will largely determine the mineral resources sovereignty of the country.

Key words
applied geology, personnel training, geological study of the subsurface, system approach, integration, research, production, education, strategy

For citation
Vercheba A.A., Makarov V.A. Applied geology – basic training program for mining and geological industry personnel. *Mining Science and Technology* (*Russia*). 2023;8(2):183–190. https://doi.org/10.17073/2500-0632-2023-01-71

ПОДГОТОВКА ПРОФЕССИОНАЛЬНЫХ КАДРОВ. ОРГАНИЗАЦИЯ ИССЛЕДОВАНИЙ

Научная статья

Прикладная геология – базовое направление подготовки кадров горно-геологической отрасли

А.А. Верчеба[1] ✉, **В.А. Макаров**[2]

[1] *Российский государственный геологоразведочный университет имени Серго Орджоникидзе (МГРИ), г. Москва, Российская Федерация*
[2] *Сибирский федеральный университет, г. Красноярск, Российская Федерация*
✉ *aa_ver@mail.ru*

Аннотация
Развитие кадрового потенциала горно-геологической отрасли России – во многом задача государства и его институтов. В списке вызовов и угроз развитию минерально-сырьевой базы Российской Федерации в новой Стратегии развития минерально-сырьевой базы Российской Федерации до 2035 года, которая была разработана и принята Распоряжением Правительства Российской Федерации № 2914 от 22.12.2018 г. (далее – Стратегия), среди прочих указан дефицит квалифицированных кадров в области геологического изучения недр, а также разрыв связей в системе «образование – наука – производство». Очевидно, что решение задач, направленных на развитие геологической отрасли России и воспроиз-

водство минерально-сырьевой базы, сформулированных в Стратегии, будет обеспечиваться главным образом геологическими знаниями и навыками, формируемыми в научно-практической деятельности нового поколения геологов. Современная модернизация геологического образования при отсутствии профессиональных стандартов направлена на сопряжение компетенций выпускников вузов и квалификации представителей профессии геологов, геофизиков, геохимиков, гидрогеологов и геологоразведчиков. Взаимодействие вузов с горными и геологическими компаниями в части совершенствования образовательных стандартов и программ обучения особенно важно в условиях развития и масштабного внедрения новых технологий изучения минерального сырья на всех стадиях геологоразведочного процесса. Воспроизводство кадрового потенциала геологоразведочной отрасли безусловно должно быть под пристальным вниманием государства и при его непосредственном управлении, так как во многом будет определять минерально-сырьевой суверенитет страны.

Ключевые слова
прикладная геология, подготовка кадров, геологическое изучение недр, системный подход, интеграция, исследования, производство, образование, стратегия

Для цитирования
Vercheba A.A., Makarov V.A. Applied geology – basic training program for mining and geological industry personnel. *Mining Science and Technology* (*Russia*). 2023;8(2):183–190. https://doi.org/10.17073/2500-0632-2023-01-71

Introduction

Development of the personnel training system for the mineral resources complex of the country is one of the priorities of all state institutions [1–3]. It is important to constantly analyze not only the quantitative characteristics of the training system [4–6], and features of scientific and pedagogical schools, but also many other important aspects which affect the quality and efficiency of specialist training [7–9].

As a field of science and education, geology in the Russian Federation is manifested in two interrelated and complementary spheres. The first of them is fundamental geology, which is the science of the history, structure, material composition of the Earth and its cosmic relations, the origin and evolution of life. This sphere forms the core of geology – classical general geology in its broadest sense.

The second sphere is applied geology, based on the foundation of the first one and is represented by a complex of disciplines on metallogeny, forecast, prospecting and exploration of mineral resources. Specialists of this sphere were and are focused on the reproduction of the mineral resource base (MRB) and geological support of the economic activity of the country.

Higher geological education in Russia from the first days of its foundation has been based on the methodological triad of the conjugation of geological science, geological training and geological practice[1] [6, 8]. Implementation of this principle in the Soviet Union allowed strong geological schools to be formed in Russia and the Union republics which formed part of the USSR.

[1] The concept of geological education in Russia: Proceedings of the joint meeting of the boards of the Ministry of Education of Russia and the Ministry of Natural Resources of Russia. Moscow: NIA-Priroda; 2000. 24 pp.

Historical background

Before large-scale reforms in the system of the Russian higher education, the special feature of professional education of specialists-geologists was the relevance (closeness to production) of educational programs and the high uniformity of university curricula. The dynamic development of geological education and the geological industry as a whole (in the so-called "golden age of geology") was also facilitated by a well-functioning system of developing scientific and pedagogical staff, coordinated policy in conducting field training and production practices, and state allocation of mining and geological graduates to the industry enterprises after graduation [10].

The USSR Ministry of Geology played an important coordinating role in this process, participating in the planning of enrollment in geological disciplines and determining their nomenclature. The Ministry assisted universities in organizing educational and industrial geological practices, building a system of advanced training and retraining of geological personnel. The support of scientific researches in higher educational institutions and financing of scientific researches in industry-related research institutes and production departments were of great importance. The result of this policy was the high level of qualification of engineering geological staff. For example, during this period up to 20–30 % of lead specialists-geologists in thematic and geological survey expeditions of the Krasnoyarsk Geological Administration had scientific degrees. The implementation of a well-coordinated personnel policy allowed the Soviet Union to establish one of the world's best systems of professional higher geological education, ensuring the dynamic development of the native mineral resource complex and a stock of reserves of most mineral resources for many years ahead.

It is no secret that the mineral resource base of solid minerals in Russia was largely formed in Soviet times. From the USSR, Russia inherited the position of a country most prosperous in mineral resources. The country's share in the world oil reserves is 13 %, gas 32 %, coal 11 %, lead, zinc, cobalt, nickel, and iron – from 10 to 36 %, etc. The gross value of explored reserves and preliminary estimated resources in the subsurface is about $ 30 T [10, 11].

After the collapse of the Soviet Union, Russia also faced the problem of self-sufficiency in certain types of minerals. There was a deficit of more than 15 types of solid minerals (manganese, chromium, strontium, mercury, etc.). Almost all commercial reserves of chromium remained beyond the borders of the Russian Federation, in Kazakhstan. 80 % of uranium reserves are located in Kazakhstan, Uzbekistan and Ukraine. Manganese deposits remained in Ukraine and Georgia, about 40 % of gold resources are in Uzbekistan and Kazakhstan, etc. The iron ore reserves were reduced by 30 % of what they were in the Soviet Union.

This circumstance, as well as the trends formed in the recent decades in the mining and geological industry of the country, namely a decrease in the rate of growth and depletion of reserves of many major types of solid minerals, a decrease in their production volumes, slowing development of new deposits, identified the need to update the development strategy of the mineral resource base of Russia as a whole.

Actualness

The new Strategy for the Development of the Mineral Resource Base of the Russian Federation until 2035 was developed and adopted by Order of the Government of the Russian Federation No. 2914 of 22.12.2018 (hereinafter – the Strategy)[2]. The Strategy reflects the current negative situation with scarce mineral resources, including uranium, manganese, chromium, titanium, bauxite, zirconium, beryllium, lithium, rhenium, rare earths of the yttrium group, and fluorspar. It is demonstrated that the reproduction of resources of these types of minerals should be provided by the discovery of deposits with high-quality ores. These in turn should be based on the introduction of improved forecast and prospecting complexes, as well as the development of new cost-effective technologies for the enrichment and processing of low-quality minerals and their involvement in the development.

The list of challenges and threats to the development of the mineral resource base in the Russian Federation in the new Strategy includes, inter alia, the lack of qualified personnel in the field of geological exploration of mineral resources, as well as the gap in the "education – science – production" system. Obviously, the resolution of tasks aimed at developing the geological industry of Russia and reproduction of the mineral resource base, formulated in the Strategy, will be provided mainly by geological knowledge and skills formed in the scientific and practical activities of the new generation of geologists.

In order to ensure sustainable development of the scientific and personnel potential of the geological industry, capable of providing works on expanded reproduction of the MRB of the Russian Federation, the Strategy proposes a number of measures, the key ones being:

1) development and implementation of monitoring and forecasting (medium- and long-term) with respect to the need for personnel;

2) development and improvement of the system of industry-related professional standards;

3) creation of a continuous professional development system aimed at formation of new competences of specialists, necessary for the innovative development of the industry;

4) creation and development of a network of industry-related regional centers of competence for the coordination of interaction between educational organizations of different levels and enterprises of the industry in the regions in order to ensure a high quality of professional training.

Activities and tasks defined by the Strategy in the field of personnel policy of the geological industry, including training of geological engineers in the field of applied geology, are still far from being implemented.

Monitoring of the state and forecast of the need for geological personnel

In the recent years, there has been a large shortage of applied geologists both in specialized geological organizations and in mining companies working in support of mining operations. At the same time, there has been no increase in target figures for enrollment in the field of applied geology training. In some leading universities (Irkutsk, Krasnoyarsk, Moscow, and Tomsk) in the recent 5–8 years there has been a decrease in the number of applicants to this type of training. There is a lack of coordination between the departments of the Ministry of Education and Science of Russia and the Ministry of Natural Resources of Russia in determining target figures for enrollment, and the needs of the geological industry for specialists.

Unfortunately, there are serious problems with enrollment for geological disciplines. For a number of reasons, they are especially acute in the case

---

[2] Strategy of Development of the Mineral Resource Base of the Russian Federation until 2035. Decree of the Government of the Russian Federation of 22.12.2018, No. 2914-r.

of regional universities. As a rule, this is due to a low number of school graduates, the outflow of applicants with high USE scores to universities in Moscow, difficulties in attracting foreign students, the low prestige of mining, geological and metallurgical professions among young people. There is no state policy in terms of monitoring and forecasting the need for geologists. The work on occupational guidance of young people and popularization of geological professions leaves much to be desired.

Development and improvement of the system of industry-related professional standards

Industry-related professional standards should define the content of educational standards for educational institutions which provide training in the relevant field. As of today, professional standards containing generalized labor functions and qualification requirements for mining engineers have not been developed.

In this case, universities and faculties are given the right to independently establish professional competencies implemented in the basic educational program for specializations of their educational program.

It is due to these circumstances that during the recent five years mining and geological universities and faculties have carried out work on modernizing federal state educational standards of higher education (hereinafter, FSES HE) – specialist program.

The federal state educational standard of higher education – specialist program "Applied geology" was approved by Order of the Ministry of Education and Science No. 953 dated August 12, 2020 and introduced into the system of the Russian higher education since September 2021[3].

Coordination of the activities of the mining and geological universities in the development of educational standards was carried out by the Federal Educational and Methodological Union in the Higher Education System. This system was created in 2016 for enlarged groups of specialties and fields of training "Applied geology, mining, oil and gas engineering and geodesy".

The federal state educational standard for "Applied geology" provides for the formation of universal, general professional and professional competencies for graduates in the field of "Applied geology". The FSES HE takes into account the provisions of the Resolution of the Russian Ministry of Labor No. 37 of 21.08.98, which stipulate that professionals in the "Applied geology" field should be trained to meet qualification requirements for the positions of mining engineers – geologist, mineralogist, geochemist, etc. depending on the area of specialization obtained.

Independent public and professional expertise has established the correspondence of the content of FSES HE in terms of implementation of universal and general professional competences of graduates with the priority areas of scientific and technological development of the Russian Federation, namely:

– transition to advanced digital, intellectual, production technologies, robotized systems, new materials and methods of designing, creation of systems for processing large volumes of data, machine learning and artificial intelligence;

– transition to environmentally friendly and resource-saving energy, increasing the efficiency of hydrocarbon production and deep processing, formation of new sources, methods of transportation and storage of energy;

– potential for effective response on the part of Russian society to meet great challenges, taking into account the interaction between man and nature, man and technology, social institutions at the current stage of global development.

Due to the absence of industry-related professional standards, and taking into account the experience of harmonizing the requirements for qualification levels of specialists and researchers in different sectors of the economy available in the world geological science and practice, a "Basic Qualifications Register" (BQR) in the sphere of mining and geological research and development of the subsurface needs to be developed. This should also apply to the training of scientific and technical personnel. For this purpose, the most demanded spheres of professional activities need to be included in the BQR, such as scientific-research; design-survey; industrial-technological; pedagogical; and organizational-managerial, which are established in the FSES HE.

The BQR will serve as the basis for the development of improved educational HE programs in the relevant types of professional activities and at the same time as a criterion for the development of the features (job description) of specific positions of scientific and technical workers. This will provide an opportunity to create a higher education trajectory, taking into account new fields of geological science, the regional features and labor market in the organizations of the geological service of Russia and companies of the mineral resources complex. It will also support the training of elite specialists in the field of applied geology, inter alia.

In addition to the choice of areas of professional activity, the higher educational organization in accor-

[3] Federal state educational standard of higher education – specialist program 21.05.02 Applied geology. Moscow: Ministry of Education and Science of the Russian Federation; 2020. 18 pp.

dance with the standard will be able to choose a specialization of the educational program on "Applied geology" of solid mineral deposits from the following[4]:

– geological survey, prospecting and exploration of mineral deposits;

– geology of oil and gas fields;

– prospecting and exploration of groundwater and engineering-geological surveys;

– applied geochemistry, mineralogy and gemology;

– field geology;

– exploration and evaluation of strategic minerals.

When choosing a specialization, an educational organization should base is choice on the changing demand for personnel and the regional specifics of enterprises of the mineral resource sector. The list of specializations should not be static. For example, the specialization "Exploration and evaluation of strategic minerals" was initially focused on training specialists in the field of research of rare and radioactive metals deposits. Today the list of strategic types of mineral resources has been significantly expanded. By Order of the Government of the Russian Federation No. 2473-r dated August 30, 2022, this list was increased from 29 to 61 items. It includes all major types of mineral resources – oil, natural gas, non-ferrous, ferrous, noble, rare and disseminated metals, and other types of raw materials important for ensuring the country's economic and defense sovereignty. This document was adopted against the backdrop of political turbulence and unprecedented, worsening sanctions. It emphasizes the importance of ensuring the country's raw material independence in terms of the uninterrupted functioning of the production of "critical types" of mineral resources important for the economy and defense.

At present, certain leading universities (National Research Tomsk Polytechnic University and Russian State University for Geological Prospecting) are already implementing the "Geology of deposits of strategic types of mineral resources" field of training since 2019, even before Government Order No. 2473-r was issued, according to the master's degree program.

Experts from Rosgeologiya JSC came to the conclusion that a high-tech economy requires full confidence in sufficient reserves of rare-earth metals, tin, titanium, manganese, chromium, tungsten, gold and a number of other minerals (including non-metallic minerals). At the same time, forecasts show a moderate increase in the consumption of fossil fuels in the midterm, despite the development of "green energy". This means that resources and the human capital asset need to be reallocated toward the accelerated reproduction of solid mineral resources and appropriate human resource transformations.

The principle of inter-industry balance in the mineral resource sector of solid minerals should be reoriented towards a significant increase in the volume of thematic, experimental and methodological, and research exploration work. Primary attention should be paid to the development of new methods and technologies of prospecting and appraisal works focused on the identification of weak mineralization and potential deposits of scarce types of mineral resources. This will require the transformation of the educational programs of universities which train specialists in the "Applied geology" of deposits of solid minerals. They need to take into account the current features:

– a fundamental knowledge of the geology of rare and radioactive metals, physical and chemical geotechnology and related disciplines at the world level;

– an understanding of the rules of creating design documents for the exploration and development of deposits, taking into account modern international standards and regulations;

– an ability to analyze the scientific-technical and industrial-technological work and make non-standard creative decisions;

– the use of modern computer technologies and software systems in mining and geological practice;

– mobility and the ability to work in a team.

The formation of these qualities among young specialists in the period of training, assumes the formation of general professional and professional competences as a combination of knowledge and skills of theoretical training and practical activity:

– an ability to apply the basic provisions of fundamental natural sciences and scientific theories in carrying out research work on the study and reproduction of the mineral resource base;

– an ability to apply the legal basics of geological study of the subsurface and subsurface use, ensuring environmental and industrial safety, and ability to take them into account when prospecting, exploring and exploiting deposits;

– an ability to study and analyze the material composition of rocks and ores and geological-industrial and genetic types of mineral deposits when resolving problems on the sound and integrated development of the mineral resource base;

– an ability to work with software of general, special purpose, including modeling of mining and geological objects;

– an ability to perform engineering design for projects, technical-economic and functional-cost analysis of project efficiency;

[4] Federal state educational standard of higher education – specialist program 21.05.02 Applied geology. Moscow: Ministry of Education and Science of the Russian Federation; 2020. 18 p.

– an ability to plan and perform analytical, simulation and experimental studies, to critically evaluate research results and draw conclusions;

– an ability to estimate forecast resources and calculate reserves of solid mineral deposits.

According to the expert community, the training of such specialists should be based on the formation of not only universal and professional competencies, as established in the FSES HE "Applied geology", but also specialized professional competencies. These competences are developed by a given university, taking into account the opinion of employers and lead specialists of research institutes (Institute of Mineralogy, Geochemistry and Crystal Chemistry of Rare Elements, All-Russian Scientific-Research Institute of Mineral Resources named after N.M. Fedorovsky and Central Geological Research Institute for Nonferrous and Precious Metals), the institutes of the Russian Academy of Sciences (Institute of Geology and Earth Mechanics, Institute of Physics) and structural subdivisions of Rosgeologiya JSC.

The future successful scientific and production activity of graduates lies in the fact that during the process of training in "Applied geology", they will be able to enhance scientific forecasting, prospecting and appraisal of deposits of solid minerals and the basics of mineralogical, analytical, technological methods of study and evaluation of in-demand types of raw materials.

The motivation for training of highly qualified specialists in exploration and appraisal of solid minerals should be to provide students with financial support in the form of scholarships and grants, at the expense of leading mining and geological companies. This should be aimed at the practical mastering of modern methods to study the ores of mineral resources and geotechnology of their integrated processing [12].

The educational and methodological support of the system for training mining engineers and geologists should not be forgotten. The publication of popular science and educational literature on the geology of deposits of strategic mineral resources and creation of electronic textbooks, as well as scientific and reference literature, are of great importance today, taking into account the current state of the mineral resource base and peculiarities of marketing of scarce metals.

The science intensive nature of Russian industry, and the concentration of advanced competitive developments therein, stipulate the necessity for advanced investments in personnel training, scientific and technical improvement of this cluster of the mineral resource complex in order to maintain its high technological potential.

Continuous education and innovative development of the geological industry

The rapid development of technologies in the mineral resource sector of the economy determines the need for continuous training and retraining of personnel. Production often requires specialists who do not fit into the framework of educational programs for particular specializations. Advanced training in the field of geoinformatics is particularly relevant in the field of applied geology, where digital technologies (introduction of computer modeling of deposits, remote sensing technologies, use of neural network analysis and artificial intelligence in working with large data arrays in forecasting, etc.) are actively emerging. In mining (mine) geology in the world and in Russia a new field is being formed – geometallurgy. This field combines the competences of the mine geologist, miner, processor and metallurgist. In the conditions of global warming, for construction, mining and metallurgical companies operating in the permafrost zone, competences in geocryology become relevant for geologists-applicants of the "Prospecting and exploration of groundwater and engineering-geological surveys" specialization.

In the Russian Federation as a whole, the system of continuous professional development and retraining, as well as obtaining additional education is constructed at different levels. These are advanced training courses, master's degree, and post-graduate courses. The implementation of additional education and retraining of geological personnel is carried out both in corporate centers and educational institutions, and in state universities, including the use of remote and network technologies. An example of the successful implementation and active development of remote technologies in Russia is the Geowebinars educational platform. The platform has been created with the participation of specialists from reputable mining companies, scientific and educational institutions. This platform hosts online conferences and lectures on a regular basis, as well as enrollment in refresher courses in industry-related disciplines[5].

In the Russian Federation, certain negative trends can be noted in the field of training geological personnel at the highest level of qualification – candidates and doctors of sciences. According to the RF State Commission for Academic Degrees and Titles, there are 363 thousand candidates and 79 thousand doctors of science in Russia. More than 50 % of the doctors of science are over 60 years old. In the field of natural sciences, including "Earth Sciences", 21 % of the

[5] Geowebinars. Geology and mining knowledge platform. URL: https://geowebinar.com

total number of scientists have been awarded academic degrees, of which only 1 % in geological and mineralogical sciences.

The number of awarded degrees in geological and mineralogical sciences has decreased 5 times compared to 2010. This is due to the closure of a large number of industry-related geological research institutes, the reduction of the number of dissertation councils, a fall in the interest of young people in scientific research and, as a consequence, the loss of scientific schools in a number of training centers.

A comprehensive governmental approach is required, in order to resolve this problem. This would include: incentives by employers for employees who improve their qualifications through university degrees, postgraduate and doctoral studies; as well as increased targeted funding for geological research through the Ministry of Education and Science and the Ministry of Natural Resources, including support for young researchers with grants.

The creation and development of a network of industry-related regional centers of competence for the coordination of interaction between educational organizations of different levels and enterprises of the industry in the regions, aimed at ensuring high quality of professional training is relevant in the conditions of reduction of the number of industry-related geological scientific research institutes and thematic teams at large regional geological offices. Such centers have been established in separate regions as entities with different legal organizational forms. For example, the Siberian School of Geosciences was established on the basis of the Irkutsk Research Institute as part of the Irkutsk Polytechnic University and, at the same time, as a major geological corporation in the ore exploration industry. The research program of this center is aimed at optimizing the methodology and technology of developing the mineral resource base for ore minerals in complex conditions. The Siberian School of Geosciences conducts scientific research and implements original educational programs aimed at creating a set of new exploration technologies with ultra-low cost and high productivity, and, based on these technologies, shifting of the University into the position of an active subject of the mining and geological industry[6].

Another example of the formation of a regional center of competencies as a result of interaction between a university and a large company is the NorNickel R&D Center at the Institute of Mining, Geology and Geotechnologies of the Siberian Federal University[7]. The Center was established in 2017 with the assistance of MMC Norilsk Nickel, as a "Scientific and Technological Center for Developing a System for Mineral Production and Processing Control and Quality Based on Deposit Modeling and Ore Flow Management". The Center develops competences in the field of computer modeling of deposits and mining scheduling, as well as the improvement of methods of process mapping and quality control of ores and their processing. The long-term objective of the center is to implement scientific projects and educational programs in the fields of "Geometallurgy" and "Mining geology".

Successful competence centers include basic departments of industry-related research institutes: All-Russian Scientific-Research Institute of Mineral Resources Named after N.M.Fedorovsky, Central Geological Research Institute for Nonferrous and Precious Metals, Institute of Mineralogy, Geochemistry and Crystal Chemistry of Rare Elements. In recent years they have been training highly qualified experts in solid minerals and forming the range of highly qualified personnel of the exploration industry.

An example of the network center of competence which is in the process of formation is the Engineering and Technical Center for Lithium Raw Materials Research. This center is based on the PJSC "Chemical and Metallurgical Plant" in Krasnoyarsk. The tasks of this Center will include geology, exploration, enrichment and processing of lithium raw materials, all of which are in high demand in the world market. It is assumed that the competence center will form the basis of the scientific and production cluster of "Lithium" rare-earth metals. This will bring together companies with licenses for deposits of lithium ores, the production capacities of JSC "Chemical and Metallurgical Plant", and laboratory and expert capacities of the industry-related geological institute All-Russian Scientific-Research Institute of Mineral Resources Named after N. M. Fedorovsky. They will also attract the educational and experimental capabilities of universities, such as the Moscow Institute of Steel and Alloys and the Siberian Federal University. The cluster approach will ensure not only the development of new technologies, but also training of specialists in the field of prospecting, mining and processing of strategically important minerals relevant for the national economy.

[6] Siberian School of Geosciences. URL: https://www.istu.edu/deyatelnost/obrazovanie/

[7] R&D Center of NN – Institute of Mining, Geology and Geotechnology, Siberian Federal University. URL: https://rdcnnsfu.ru/

Conclusion

It is impossible to resolve personnel issues in the geological industry, both current and in the long-term perspective, without addressing the issue of improving the image of the mineral resource industry and popularizing mining and geological professions. Here it is necessary to combine the efforts of the relevant ministry, universities and businesses in the implementation of long-term integrated measures including the development of joint career guidance programs by universities and mining and metallurgical companies in the region of presence. This involves the creation of positive newsbreaks in terms of science and innovation, and positive environmental solutions. The efforts of universities and companies in the promotion of mining and geological knowledge need to be combined in the creation of popular science (feature) films, articles, television programs, Internet resources (First Geological Channel), in order to promote the essence of geological professions, new mining projects, and their social and economic importance.

References

1. Kazanin O.I., Drebenshtedt K. Mining education in the XXI century: global challenges and prospects. *Journal of Mining Institute*. 2017;225:369–375. https://doi.org/10.18454/pmi.2017.3.369

2. Puchkov L.A., Petrov V.L. The system of higher mining education in Russia. *Eurasian Mining*. 2017;(2):57–60. https://doi.org/10.17580/em.2017.02.14

3. Martynov V.G., Koshelev V.N., Mayer V.V., Tumanov A.A. Oil and gas education in Russia: yesterday, today, tomorrow. *Vysshee Obrazovanie v Rossii*. 2021;30(8–9):144–157. (In Russ.) https://doi.org/10.31992/0869-3617-2021-30-8-9-144-157

4. Petrov V.L. Analytical review of the training system for mining engineers in Russia. *Mining Science and Technology* (*Russia*). 2022;7(3):240–259. https://doi.org/10.17073/2500-0632-2022-3-240-259

5. Kazanin O.I., Sergeev I.B. Training a modern mining engineer: Objectives of universities and professional communities. *Gornyi Zhurnal*. 2017;(10):75–80. https://doi.org/10.17580/gzh.2017.10.16

6. Vercheba A.A. Personnel training for the mining and geological sector of Russia. *Mining Science and Technology* (*Russia*). 2021;6(2):144–153. (In Russ.) https://doi.org/10.17073/2500-0632-2021-2-144-153

7. Chernikova A.A., Petrov V.L. Training of mining engineers at the Russian research universities. *Gornyi Zhurnal*. 2015;(8):103–106. (In Russ.) https://doi.org/10.17580/gzh.2015.08.22

8. Vercheba A.A., Oganesyan L.V. Ways of improving the higher geological education. *Razvedka i Okhrana Nedr*. 2016;(12):3–8. (In Russ.)

9. Klimov I.Yu. Analysis of soft skills-based approach effectiveness in advanced training program for mining company. *Mining Science and Technology* (*Russia*). 2020;5(1):56–68. (In Russ.) https://doi.org/10.17073/2500-0632-2020-1-56-68

10. Oganesyan L.V. *Main routes and narrow paths of the Russian Geological Survey*. Moscow: VNIIgeosistem; 2012. 264 p. (In Russ.)

11. Kozlovsky E.A. Problems of reorganization of geological research system in the light of mineral resources security of the country. *Problems of Economics and Management of Oil and Gas Complex*. 2016;(6):4–12. (In Russ.)

12. Boytsov V.Ye., Bercheba A.A. Personnel training for creating mineral and raw material base of nuclear power engineering. *Proceedings of Higher Educational Establishments. Geology and Exploration*. 2008;(2):12–17. (In Russ.)

Information about the authors

Alexander A. Vercheba – Dr. Sci. (Geol. and Mineral.), Professor, Assistant Vice Rector, Professor of the Department of Geology of Mineral Deposits, Sergo Ordzhonikidze Russian State University for Geological Prospecting "MGRI", Moscow, Russian Federation; ORCID 0009-0002-1785-4216, Scopus ID 57205211946; e-mail aa_ver@mail.ru

Vladimir A. Makarov – Dr. Sci. (Geol. and Mineral.), Professor, Head of Geology and exploration techniques, Siberian Federal University, Krasnoyarsk, Russian Federation; ORCID 0009-0005-5971-8070, Scopus ID 57188966055

Received 13.01.2023
Revised 03.05.2023
Accepted 05.05.2023