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Experimental Study on Dry Magnetic Separation of Kharganat Iron Ore

[1] Khussan B., [1*] Yesendosova A.N., [1] Kenetaeva A.A., [1] Rabatuly M., [2] Matayev Zh.Sh., [3] Duissyen J., [4] Toshov J.B.

[1]Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan
[2]Limited Liability Partnership Training Center Timerlan-2011, Karaganda, Kazakhstan
[3] National University of Mongolia, Ulaanbaatar, Mongolia
[4] Islam Karim Tashkent State Technical University, Tashkent, Uzbekistan

**Corresponding author email: a.yesendosova@ktu.edu.kz*

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ABSTRACT
A sample of iron ore from the Kharganat deposit was crushed to under 3 mm and subjected to dry magnetic separation, yielding a concentrate with 60.28% iron content and 98.92% metal recovery. When the sample was further crushed to under 1 mm and reprocessed, a concentrate with 66.7% iron content and 95.88% metal recovery was obtained. Through wet magnetic separation, a concentrate with 67.71% iron content and 96.9% metal recovery was produced. The tests confirmed that the most effective method was wet separation after crushing to under 1 mm and grinding for 40 minutes. In terms of beneficiation technology for the deposit, two process schemes—dry and wet magnetic separation—were developed. It was recommended that dry beneficiation be used in production instead of the water-intensive wet method. The sulfur and phosphorus content in the technological samples met standard requirements. Both previous studies and new exploration results were used in the resource estimation. It was confirmed that using a 10% cutoff grade for resource calculation is economically efficient. The minimum thickness of ore bodies was set at 2.0 meters, and the maximum thickness of waste rock at 4.0 meters. Resources were classified into Measured (B), Indicated (C), and Inferred (P1) categories. The geological structure of the deposit is simple, with a stable ore body distribution. The ore body thickness ranges from 5 to 40 meters, with an average of 23 meters. The deposit is suitable for open-pit mining, and no water drainage issues are expected in the initial years. It is planned to build an open-pit mine with an annual capacity of 500,000 tons of ore, with the cost of mining one ton of ore estimated at 4,312.8 MNT.

Keywords: Iron ore, Ore deposit, Mining hydrogeological conditions, Geological exploration.

Information about authors:

Khussan Bolatkhan	*Ph.D., Acting Associate Professor, Department of Development of Mineral Deposits of Abylkas Saginov Karaganda Technical University, 100027, The Republic of Kazakhstan, Karaganda, Ave. Nursultan Nazarbayev, 56. E-mail: h.bolathan@ktu.edu.kz; ORCID ID: https://orcid.org/ 0000-0003-0996-348X*
Yesendosova Ainel Nurtasovna	*Ph.D., Senior Lecturer, Department of Development of Mineral Deposits of Abylkas Saginov Karaganda Technical University, 100027, The Republic of Kazakhstan, Karaganda, Ave. Nursultan Nazarbayev, 56. E-mail: a.yesendosova@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0001-7415-3630*
Kenetaeva Aigul Akanovna	*lecturer of Karaganda Technical University, Master of Engineering and Technology specialty Mining, Karaganda, Kazakhstan. E-mail: aigul_tate@bk.ru; ORCID ID: https:// orcid.org/0000-0001-7943-3279*
Rabatuly Mukhammedrakhym	*Ph.D., Acting Associate Professor, Department of Development of Mineral Deposits of Abylkas Saginov Karaganda Technical University, 100027, The Republic of Kazakhstan, Karaganda, Ave. Nursultan Nazarbayev, 56. E-mail: mukhammedrakhym@mail.ru; ORCID ID: https://orcid.org/0000-0002-7558-128X*
Mataev Zhanmurat Shagizatovich	*Director, Limited Liability Partnership Training Center Timerlan-2011, 100000, The Republic of Kazakhstan, Karaganda, 102/1 Ermekova Street. E-mail: too-timerlan-2011@bk.ru; ORCID ID: https://orcid.org/0009-0000-9839-7170*
Duissyen Janat	*PhD student, Department of Geology and Geophysics, School of Science, National University of Mongolia, 14201, Mongolia, Ulaanbaatar, University Street-1. E-mail: d_jagii@yahoo.com; ORCID ID: https://orcid.org/0000-0001-8757-5525*
Toshov Javokhir Buriewicz	*Doctor of Technical Sciences, Professor of Islam Karim Tashkent State Technical University, 100095 Republic of Uzbekistan, Tashkent, Almazar district, Universitetskaya street 2. E-mail: j.toshov@tdtu.uz; ORCID ID: https://orcid.org/0000-0003-4278-1557*

Introduction

In Mongolia, the mining and mineral resources sector has become one of the main driving forces of economic development, with iron ore extraction and beneficiation gaining particular importance. The Kharganat iron ore deposit is located in Naranbulag soum of Uvs province, and the quality and reserves of its ore occupy a key position in the region's development strategy [[1],[2]]. Efficient and economically optimized beneficiation and utilization of the deposit's ore is a primary goal, as it ensures effective use of the reserves and supplies the industrial sector with essential raw materials. Within this framework, testing the beneficiation technology using a dry magnetic separator is a critical step toward developing an efficient solution tailored to the characteristics of the ore. The dry beneficiation method offers distinct advantages in water-scarce regions and is also significant for minimizing environmental impact. Therefore, adapting the Kharganat iron ore to dry magnetic beneficiation technology constitutes a study of not only industrial but also environmental relevance. Research Objective [[2], [3]].

The main objective of this study is to experimentally determine the feasibility of beneficiating ore from the Kharganat iron deposit using dry magnetic separator technology at the laboratory level; to evaluate the ore's beneficiation potential; to optimize the beneficiation process parameters; and to develop the necessary technological foundation for future industrial implementation [4].

The experimental part

Iron ore is most commonly beneficiated using dry magnetic separation in industrial applications. The Kharganat iron ore sample was screened into fractions ranging from 3 mm to 0.125 mm, and each fraction was beneficiated using a dry magnetic separator set at a magnetic field strength of 2.5A. According to the test results, when the sample was crushed to under 3 mm and the 3–2 mm fraction was processed using a dry magnetic separator, a concentrate with 60.28% iron content and 98.92% metal recovery was obtained. To increase the concentrate grade, the sample was further crushed to under 1 mm and processed again using a dry magnetic separator, yielding a concentrate with 66.7% iron content and 95.88% metal recovery. From the test results, it was observed that when the ore was ground for 40 minutes and processed through wet magnetic separation, the concentrate yield was 92.05%, with an iron content of 67.71% and metal recovery of 96.9% [[5],[6]].

Therefore, under the conditions of wet magnetic separation, crushing the primary ore to under 1 mm and grinding for 40 minutes was selected as the most optimal parameter. To confirm the results, this test was repeated with a 10 kg sample, yielding a concentrate with 81.55% yield, 65.71% iron content, and 95.42% metal recovery.

Based on the results of the tests and research, two process flows for beneficiating the Kharganat iron ore using dry and wet magnetic separators were developed.

Both technological flows can be used in industrial applications. However, due to the high water consumption associated with wet magnetic separation, the use of the dry magnetic separation process is recommended.

In the technological sample, the contents of harmful impurities were low: sulfur was below 0.1%, and phosphorus was below 0.2%, which are not considered to affect the quality of the concentrate [[7], [8], [9]].

For the resource estimation at the Kharganat deposit, chemical analysis results from 374 core samples obtained from 49 boreholes, drilled by both the current and previous researchers within a 100 x 40-50-meter exploration grid, were used, along with the results from 253 trench samples collected from 27 surface channels.

To determine the key conditional parameters used in the resource calculation—such as cutoff grade, minimum industrial grade within a block, minimum thickness of ore intervals, and maximum thickness of barren intervals and waste rock—calculations were performed by comparing ore sections delineated at a 10% cutoff grade with those at 15% and 20% cutoff grades. As a result, the economically optimal cutoff grade, the minimum industrial grade within a block, and the corresponding thickness were determined.

After running calculations using all three scenarios, it was confirmed that each is economically viable, thereby justifying the use of a 10% cutoff grade. We concluded that this approach enables the full and efficient utilization of the ore from the deposit.

Therefore, based on the selected cut-off grade, the minimum ore grade required for production within the block was calculated using the cost of geological exploration incurred per ton of extracted, processed, and newly added ore reserve, using the following formula:

$$C_{\min prom} = \frac{(Z_{olb}Z_{bolov} + Z_{gha}) \cdot C_k}{C_m \cdot K_m \cdot K_r} \frac{(4312{,}2 + 10388{,}98 + 25{,}15) \cdot 67}{105400 \cdot 0{,}975 \cdot 0{,}9588} = 10\%$$

Where:

- Z_{olb} – Cost of extracting 1 ton of ore, 4,312.8₮
- Z_{bolov} – Cost of processing 1 ton of ore, 10,388.98₮
- Z_{gha} – Cost of geological exploration for increasing 1 ton of ore reserves, 25.55₮
- C_m – Metal price (price of 1 ton of concentrate based on the Ministry of Finance reference), 85 USD or 105,400₮

Based on the calculated result of the minimum grade within a block, it is fully feasible to adopt a cutoff grade of 10%.

Relying on the results of the above study, we determined that a minimum ore body thickness of 1.0 m is appropriate and used this value in the calculations. However, for the marginal boreholes, the minimum ore body thickness was taken as 2.0 m when outlining the boundaries. (This was based on the anticipated bucket size of the excavator to be used in the future.)

In cases where high-grade ore bodies in the cross-sections are relatively thin, setting a large thickness for barren rock layers or non-typical layers reduces the ore content in the cross-section. Therefore, we carefully selected a value of 4.0 m to minimise any excessive impact [[10], [11]].

Taking into account the above research and analysis results, the conditional indicators used in the resource calculation were as follows:

- Cutoff grades for delineating ore intervals – 10%, 15%, 20%
- Minimum industrial grade within a block – 15%
- Minimum ore body thickness – 2.0 m
- Thickness of barren rock and sub-economic layers – 4.0 m
- Bulk density of ore – 4.91%
- Minimum mineralization coefficient – 0.8

Using the key conditional indicators described above, the central part of the ore body was estimated as measured reserves (denoted by the letter B), while the marginal parts of the ore body were estimated as indicated reserves (denoted by the letter C). The remaining parts—namely, the northern, eastern, western, and southern sections of the ore body as defined by the magnetic anomalies identified during exploration, along with the deeper part of the deposit—were classified as inferred resources (denoted by P1).

The Kharganat deposit's ore body is geologically simple, with minimal variation in ore body thickness, uniform distribution of the main mineral components, and no fragmentation or significant internal alteration. Therefore, in accordance with the classification system of mineral deposits, it was categorized as Group II [[12], [13]].

After studying the rock samples and other materials collected during the Kharganat exploration, along with laboratory analysis results and ore distribution characteristics in the deposit area, it was concluded that the ore has no clearly defined distribution criteria or geological boundaries. Therefore, the boundaries of the ore body were defined solely based on drilling data and sample analysis results.

The boundary of the measured reserves (B) was delineated based on sample analysis results, conditional indicators, and constrained by exploration workings and boreholes. Since geological and geophysical indicators, along with some mine workings and boreholes, confirm that the ore body extends toward the margin, limited extrapolation methods were used on exploration lines X, V, I-1, and VIII. The indicated reserves (C) were also defined using the extrapolation method.

The ore body of the Kharganat iron ore deposit is a stable, massive body with consistent thickness, starting from the surface and extending to shallow depths. Fracturing across the deposit does not generally exceed 5–10 meters and significantly decreases with depth. Although the ore body is hard, slightly weathered and crumbled sections occur near the surface.

The Kharganat iron ore body extends from the southeast to the northwest, with a total length of approximately 1,100 meters. Its width is about 160-240 meters in the southeastern section, 80-170 meters in the northwestern section, and 160-200 meters in the central section, with an average width of 150.9 meters. The surface relief of the ore body gradually slopes downward from southeast to northwest, making the northwestern side especially suitable for mining operations.

In the blocks classified as measured reserves (denoted by B), the overburden thickness ranges from 0.0 to 17.5 meters, averaging 3.5 meters, while the ore body thickness ranges from 5 to 40 meters, with an average of 23 meters.

In the resource estimation, the average bulk density of the ore body was taken as 4.91 t/m³, as determined in 2010.

Iron ore can be mined using drilling and blasting methods, and it is fully feasible to selectively extract slightly weathered and fragmented sections near the surface. Within the deposit area, groundwater was encountered at a depth of 29.0 meters in the borehole drilled at the lowest point. Therefore, drainage measures will need to be implemented in the later years of operation. During the initial years of mining, the hydrogeological conditions are not problematic, as there is no groundwater or surface water, and the terrain is elevated, meaning that water accumulation in the open-pit is not expected [[14], [15]].

Considering the mining and technical conditions of the deposit, the structure and location of the ore body, and the volume of overburden removal, it was determined that open-pit mining would be appropriate. This report includes a preliminary technical and economic estimate for operating the deposit as an open-pit mine.

The boundaries of the open-pit were established based on the ratio of economically viable ore and waste in the measured reserves. The slope angle of the pit wall at a mining depth of 40-60 meters was determined to be 70 per mille ‰), taking into account the natural, climatic, hydrogeological conditions, and rock hardness characteristics during mining. Depending on the mining and technical conditions, during the first nine years, the slope angle in the upper 20-30 meters of depth may be close to 0°.

An open-pit mine with an annual capacity of 500,000 tons of ore is planned. The parameters for exploiting the Kharganat iron deposit via open-pit mining have been optimised, suitable mining machinery has been selected based on operational parameters, and the production cost has been calculated. The cost of mining 1 ton of ore (production cost) is estimated to be 4,312.8 MNT.

In the beneficiation cost estimate, the ore was first crushed to less than 30 mm and then processed by dry magnetic separation. The remaining low-grade portion was ground and also processed using a dry method. This selected technology was used to calculate the beneficiation cost. The cost of beneficiating 1 ton of ore (production cost) is 10,388.98 MNT [16].

The reserves of economically exploitable and geologically proven mineral resources are presented in the table below. The quantity of measured reserves selected for exploitation (denoted by B) amounts to 10.8 million tons of ore.

Table 1 - Reserves prepared for exploitation and identified through geological exploration [17]

No	Reserve Category	Average Thickness of Ore Body (m)	Volume (m³)	Bulk Density (t/m³)	Total Geological Reserves (million tons)
1	B	23	2.186.67 9.0	4.91	10.8
2	C	—	695.002	4.91	3.41
3	P1	—	72.000	4.91	11.74
	Total				25.94

When extracting mineral resources, it is not possible to recover the entire geological reserve identified through exploration, and to some extent, loss and dilution occur during mining. Factors such as geological-mining conditions, technical-technological limitations, and organizational factors contribute to the occurrence of loss and dilution of mineral resources.

During mining operations, the ore loss rate was estimated at 3%, and the dilution rate at 2.5%. Using these indicators, the production (exploitable) reserves were calculated as follows:

Table 2 - Ore Loss During Mining [18]

Reserve Category	Geological Reserves (million tons)	Loss (3%) (million tons)	Dilution (2.5%) (million tons)	Production Reserves (million tons)
B	10.8	0.324	0.27	10.7
C	3.41	0.102	—	3.3
Total	14.2	0.426	0.27	14.0

Discussion of the results

Within the area covered by Mining License No. 13766A, the Kharganat iron ore deposit was explored in 2010 by ELGT LLC using its own funds. The exploration work included core drilling, magnetic surveying, topographic and geodetic surveys, various types of sampling, and laboratory analyses.

The drilling was carried out by the drilling team of Naran Talst LLC, magnetic surveying by Geo Oron LLC, topographic and geodetic work by ATPP LLC, laboratory testing by the Central Geological Laboratory in Ulaanbaatar, external quality control by SGS Laboratory, geological studies by a team of geologists from ShShDB LLC, and the hydrogeological work was performed under contract by Dr. Professor M. Alei and others. It is important to note their contributions.

The results of trenches and boreholes excavated during previous exploration phases by researchers such as N.I. Modnova (1950) and O. Khongor (1990)—including channel and core sample chemical analyses—were reprocessed and integrated with the results from the complementary exploration conducted by ELGT LLC. This included magnetic surveys, geological traverses, borehole data, and laboratory test results. Based on these combined outcomes, this reserve report has been compiled.

The complementary exploration work carried out at the Kharganat deposit fully meets the requirements of the standard.

The Kharganat deposit is located at the margin of a 1,200 x 500 m xenolith body of the Tsagaanshiveet Formation, consisting of Lower to Middle Devonian volcanogenic-sedimentary rocks, which formed as a result of the intrusion of leucogranitic rocks from the Dulaanuushig intrusive complex of Late Devonian–Early Carboniferous age.

The ore body is hosted in a skarn formation that is intensely silicified and hornfelsed, containing actinolite-epidote minerals.

The ore body is concordantly hosted within skarn-altered volcanogenic-sedimentary rocks, trending northwest. Its strike length is 1,100 m. The width of the ore body varies: in the southeast it ranges from 160–240 m, in the central section from 110–160 m, and in the northwest from 90–120 m, with an average width of 151 m.

Morphologically, the iron ore body is continuous with no apophyses or significant disruptions, extending in a northwest direction both horizontally and vertically.

The total iron content in the ore ranges from 20.3-60.8% in exploration trenches, with an average of 44.26%, and from 10.28–62.0% in drill holes, with an average of 36.93%. Sampling has confirmed that the iron content is uniformly distributed along both the strike and vertical direction of the ore body.

The mineral composition of the Kharganat iron ore consists mainly of magnetite, with smaller amounts of martite, hydrogoethite, pyrite, malachite, millerite, hematite, chalcopyrite, and other minerals. Magnetite accounts for 80–85% of the iron ore, martite 5–10%, and the rest are minor minerals. The ore is classified as skarn-type magnetite.

For technological testing and the development of a beneficiation process flow, a 180 kg technological sample was processed at the Central Geological Laboratory using both dry and wet magnetic separation. The dry magnetic separation yielded a concentrate with 66.7% iron content and 95.88% metal recovery, while wet magnetic separation resulted in 65.71% iron content and 95.42% metal recovery.

The iron content in the tailings was about 14%, which chemical analysis confirmed to be low-magnetic martite.

Based on these results, two beneficiation flowsheets using dry and wet magnetic separation were developed, and due to the high-water consumption of the wet process, the dry magnetic separation process was recommended for industrial application [19].

The hydrogeological conditions of the deposit are very simple.

The southeastern part of the ore body will remain dry during operation, while groundwater will begin to seep only in the northwestern part of the mine at depths below 25 m (elevation 1,498 m). The water inflow is estimated at 676 m^3 per day, or 28.2 m^3 per hour, which will not pose any difficulties for mining operations.

The mining and technical conditions of the Kharganat deposit are simple.

Most of the ore body is exposed at the surface, with the deepest part located at 17.5 m depth. The stripping ratio is 0.05 m^3/ton.

As a result of the complementary exploration work conducted at the Kharganat deposit in 2024, the classification of the iron ore production reserves was upgraded, and the quantity of ore contained within the ore body was redefined. The figures are shown in the table below:

Table 3 - Reserves prepared for exploitation and identified through geological exploration [20]

No	Indicators	Unit	Ore Reserves and Cutoff Grade		
			10%	15%	20%
1	Measured reserves (Category B) Total iron average grade	Million.t %	10.82 41.9	9.87 44.96	9.33 46.08
2	Measured reserves (Category C) Total iron average grade	Million.t %	3.41 27.82	2.15 39.41	1.33 42.35
3	Inferred resources (Category P1)	Million.t	11.74	12.61	13.52
4	Total ore reserves, B+C Total resources B+C+P1	Million.t Million.t	14.2 26.8	12.02 24.63	10.67 24.19

It is planned to develop the deposit through open-pit mining and to construct a beneficiation plant capable of processing 500,000 tons of ore per year. A preliminary economic assessment has shown that the exploitation of the Kharganat iron ore deposit would be economically viable. Bringing this deposit into economic circulation would not only contribute to the development of the local economy but also help to reduce unemployment to some extent.

Conclusion

Beneficiation tests conducted on samples from the Kharganat iron ore deposit confirmed that both dry and wet magnetic separation technologies are effective. Dry beneficiation produced concentrates with iron content ranging from 60.28% to 66.7%, while wet beneficiation yielded a concentrate with 67.71% iron content, demonstrating high technological efficiency. Since wet beneficiation requires significant water consumption, it is recommended to apply dry beneficiation technology in production.

The geological structure of the ore body is simple, and the ore distribution is consistent. The deposit is suitable for open-pit mining, with a planned annual production capacity of 500,000 tons of ore. From an economic perspective, calculating reserves at a 10% cutoff grade is considered appropriate, and the cost of mining is within a feasible range.

Thus, based on technical-economic indicators and beneficiation results, the Kharganat iron ore deposit has been confirmed to be suitable for industrial exploitation.

Conflict of interest. On behalf of all the authors, the corresponding author declares that there is no conflict of interest.

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Харганат темір кенін құрғақ магниттік бөлу арқылы эксперименттік зерттеу

[1] Хусан Б., [1] Есендосова А.Н., [1] Кенетаева А. А., [1] Рабатұлы М., [2] Матаев Ж.Ш., [3] Дуйсен Ж., [4] Тошов Ж.Б.

[1] *Ә. Сағынов атындағы Қарағанды техникалық университеті, Қарағанды, Қазақстан*
[2] *Тимерлан-2011 ЖШС оқу орталығы, Қарағанды, Қазақстан*
[3] *Моңғолия ұлттық Университеті, Ұлан-Батор, Моңғолия*
[4] *Ислам Кәрім атындағы Ташкент Мемлекеттік Техникалық Университеті, Ташкент, Өзбекстан*

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ТҮЙІНДЕМЕ
Харганат кен орнынан алынған темір кенінің сынамасы 3 мм-ге дейін ұсақталып, құрғақ магниттік бөлінуге ұшырап, құрамында 60,28% темір бар концентрат және 98,92% металл алынды. Үлгіні одан әрі 1 мм-ге дейін ұсақтап, қайта өңдеген кезде құрамында 66,7% темір және 95,88% метал болатын концентрат алынды. Ылғалды магниттік сепарацияны қолдана отырып, құрамында темір мөлшері 67,71% және металл экстракциясы 96,9% болатын концентрат алынды. Сынақтар ең тиімді әдіс 1 мм-ден төмен ұсақталғаннан кейін және 40 минут бойы ұнтақталғаннан кейін ылғалды бөлу екенін растады. Кен орнын байыту технологиясына келетін болсақ, екі технологиялық схема әзірленді—құрғақ және дымқыл магнитті бөлу. Өндірісте суды көп қажет ететін дымқыл әдістің орнына құрғақ байытуды қолдану ұсынылды. Технологиялық үлгілердегі күкірт пен фосфордың мөлшері стандартты талаптарға сай болды. Ресурстарды бағалау кезінде алдыңғы зерттеулер де, геологиялық барлаудың жаңа нәтижелері де пайдаланылды. Ресурстарды есептеу үшін шекті бағаны 10% пайдалану экономикалық тұрғыдан тиімді екендігі расталды. Кен денелерінің минималды қалыңдығы 2,0 метр, ал қалдық жыныстардың максималды қалыңдығы 4,0 метр болып белгіленді. Ресурстар Өлшенген (B), Көрсетілген (C) және Болжамды (P1) санаттарға жіктелді. Кен орнының геологиялық құрылымы қарапайым, кен денелері тұрақты таралған. Кен денесінің қалыңдығы 5-тен 40 метрге дейін, орташа есеппен 23 метрді құрайды. Кен орны ашық әдіспен өндіруге жарамды және алғашқы жылдары суды ағызуда қиындықтар күтілмейді. Қуаттылығы жылына 500 000 тонна кенді құрайтын ашық кеніш салу жоспарлануда, бұл ретте бір тонна кенді өндіру құны 4 312,8 млн тугрикке бағаланады.

Түйін сөздер: темір кені, кен орны, тау-кен гидрогеологиялық жағдайы, геологиялық барлау.

Авторлар туралы ақпарат:

Хусан Болатхан	*PhD докторы, Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Пайдалы қазбалар кенорындарын өндіру кафедрасының доцент м.а., 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: h.bolathan@ktu.edu.kz; ORCID ID: https://orcid.org/ 0000-0003-0996-348X*
Есендосова Айнель Нуртасовна	*PhD докторы, Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Пайдалы қазбалар кенорындарын өндіру кафедрасының аға оқытушысы, 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: a.yesendosova@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0001-7415-3630*
Кенетаева Айгуль Акановна	*Техника ғылымдарының магистрі, Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының оқытушысы, 100027, Нұрсұлтан Назарбаев 56, Қарағанды, Қазақстан. E-mail: aigul_tate@bk.ru; ORCID ID: https://orcid.org/0000-0001-7943-3279*
Рабатұлы Мұхаммедрахым	*PhD докторы, Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Пайдалы қазбалар кенорындарын өндіру кафедрасының доцент м.а., 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: mukhammedrakhym@mail.ru; ORCID ID: https://orcid.org/0000-0002-7558-128X*
Матаев Жанмурат Шагизатович	*Тимерлан-2011 Жауапкершілігі шектеулі серіктестігі оқу орталығының директоры, 100000, Ермеков к-сі, 102/1, Қарағанды, Қазақстан. E-mail: too-timerlan-2011@bk.ru; ORCID ID: https://orcid.org/0009-0000-9839-7170*
Дуйсен Жанат	*PhD докторанты, Геология және геофизика факультеті, Жаратылыстану ғылымдары мектебі, Моңғолия Ұлттық университеті, 14201, Моңғолия, Ұлан-Батор, Университет көшесі-1. E-mail: d_jagii@yahoo.com; ORCID ID: https://orcid.org/0000-0001-8757-5525*
Тошов Жавохир Буриевич	*Техника ғылымдарының докторы, Ислам Карим атындағы Ташкент мемлекеттік техникалық университетінің профессоры, 100095, Алмазар ауданы Университетская көшесі 2, Ташкент, Өзбекстан. E-mail: j.toshov@tdtu.uz; ORCID ID: https://orcid.org/0000-0003-4278-1557*

Экспериментальное исследование по сухой магнитной сепарации Харганатской железной руды

[1] Хусан Б., [1] Есендосова А.Н., [1] Кенетаева А. А., [1] Рабатұлы М., [2] Матаев Ж.Ш., [3] Дуйсен Ж., [4] Тошов Ж.Б.

[1] Карагандинский технический университет имени А. Сагинова, Караганда, Казахстан
[2] ТОО Учебный центр Тимерлан-2011, Караганда, Казахстан
[3] Национальный университет Монголии, Улан-Батор, Монголия
[4] Ташкентский государственный технический университет имени Ислама Карима, Ташкент, Узбекистан

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АННОТАЦИЯ
Образец железной руды с месторождения Харганат был измельчен до размера менее 3 мм и подвергнут сухой магнитной сепарации, в результате чего был получен концентрат с содержанием железа 60,28% и извлечением металла 98,92%. Когда образец был дополнительно измельчен до размера менее 1 мм и подвергнут повторной обработке, был получен концентрат с содержанием железа 66,7% и извлечением металла 95,88%. С помощью мокрой магнитной сепарации был получен концентрат с содержанием железа 67,71% и извлечением металла 96,9%. Испытания подтвердили, что наиболее эффективным методом является мокрая сепарация после дробления до размера менее 1 мм и измельчения в течение 40 минут. Что касается технологии обогащения для месторождения, то были разработаны две технологические схемы — сухая и мокрая магнитная сепарация. Было рекомендовано использовать сухое обогащение в производстве вместо водоемкого мокрого метода. Содержание серы и фосфора в технологических образцах соответствовало стандартным требованиям. При оценке ресурсов были использованы как предыдущие исследования, так и новые результаты геологоразведочных работ. Было подтверждено, что использование 10%-ной нормы отсечения для расчета ресурсов является экономически эффективным. Минимальная толщина рудных тел была установлена на уровне 2,0 метров, а максимальная толщина пустой породы - 4,0 метра. Ресурсы были классифицированы на категории "Измеренные" (B), "Указанные" (C) и "предполагаемые" (P1). Геологическое строение месторождения простое, со стабильным распределением рудных тел. Мощность рудного тела колеблется от 5 до 40 метров, в среднем 23 метра. Месторождение подходит для разработки открытым способом, и в первые годы не ожидается проблем с отводом воды. Планируется строительство открытого месторождения мощностью 500 000 тонн руды в год, при этом стоимость добычи одной тонны руды оценивается в 4 312,8 млн тугриков.

Ключевые слова: железная руда, рудное месторождение, горно-гидрогеологические условия, геологоразведка.

Хусан Болатхан — *Доктор PhD, и.о. доцента кафедры Разработки месторождений полезных ископаемых Карагандинского технического университета имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: h.bolathan@ktu.edu.kz; ORCID ID: https://orcid.org/ 0000-0003-0996-348X*

Есендосова Айнель Нуртасовна — *Доктор PhD, старший преподаватель кафедры Разработки месторождений полезных ископаемых Карагандинского технического университета имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: a.yesendosova@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0001-7415-3630*

Кенетаева Айгуль Акановна — *Магистр технических наук кафедры Геология и разведка месторождений полезных ископаемых Карагандинского технического университета имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: aigul_tate@bk.ru; ORCID ID: https://orcid.org/0000-0001-7943-3279*

Рабатулы Мухаммедрахым — *Доктор PhD, и.о. доцента кафедры Разработки месторождений полезных ископаемых Карагандинского технического университета имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: mukhammedrakhym@mail.ru; ORCID ID: https://orcid.org/0000-0002-7558-128X*

Матаев Жанмурат Шагизатович — *Директор Учебного центра Товарищество с ограниченной ответственностью Тимерлан-2011, 100000, ул. Ермекова, 102/1. Караганда, Казахстан. E-mail: too-timerlan-2011@bk.ru; ORCID ID: https://orcid.org/0009-0000-9839-7170*

Дуйсен Жанат — *PhD докторант, Факультет геологии и геофизики, Школа естественных наук, Национальный университет Монголии, 14201, улица Университетская 1. Улан-Батор, Монголия. E-mail: d_jagii@yahoo.com; ORCID ID: https://orcid.org/0000-0001-8757-5525*

Тошов Жавохир Буриевич — *Доктор технических наук, профессор Ташкентского государственного технического университета имени Ислама Карима, 100095, Алмазарский район, улица Университетская 2, Ташкент, Узбекистан. E-mail: j.toshov@tdtu.uz; ORCID ID: https://orcid.org/0000-0003-4278-1557*

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