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THE IMPACT OF THE COLLECTIVE CONCENTRATE FACTORY LOCATION ON THE CIRCULAR MINING TECHNOLOGY FOR TITANIUM-ZIRCONIUM DEPOSIT

Purpose. To determine the effective location of a collective concentrate enrichment plant (CCEP) when developing titanium-zirconium deposits using the principle of circular technology.

Methodology. The work used a set of research methods: graphical-analytical method – to determine the parameters of technological schemes using the principles of circular technologies, as well as the location of the collective concentrate enrichment factory when moving the mining front; analytical method – to establish the influence of the sequence of collective concentrate factory movements on the volumes of transport work in the pit and to substantiate the effective location of the elements of the enrichment complex.

Findings. The established dependence of the average pipeline length on the number of movements at the collective concentrate enrichment plant indicates that two factory movements are most effective during pit operation. It was determined that when the pit's productivity changes from 2.0 to 4.0 million m^3, the average annual volume of haulage work for moving pulp through pipelines can be reduced by 2.1 times, with a fivefold increase in the collective concentrate factory's output. The dependence of savings on operating costs for haulage work on the number of collective concentrate factory movements was established, thereby allowing us to determine the reduction in total economic costs. The results confirm the effectiveness of the proposed solutions, with one or two movements of the collective concentrate factory, depending on the pit's productivity and the cost of moving the elements of the enrichment complex.

Originality. The dependence of the average annual length of pipelines on the number of CCEP movements has been established, which allows us to determine that, during pit development with given parameters, pipeline length decreases by 23 %, with the greatest reduction occurring with three movements, amounting to 26 %. The influence of the number of CCEP movements on the weighted average annual volume of haulage work has been determined. According to the calculations, with a pit productivity of 2.0 million m^3, the optimal number of CCEP movements is up to two. At the same time, the volume of haulage work is reduced by 44 % during pit development. When the number of CCEP movements increases to 3–5, the volume of haulage work during pit operation decreases by only 8 % from 61.3 to 56.0 million km · t.

Practical value. Technological schemes for mining titanium-zirconium deposits have been developed using the principles of circular technology, with the CCEP moving relative to the advancement of the mining front, thereby allowing determination of the parameters of the pit haulage system and calculation of the volumes of haulage work. Technical and economic indicators have been established for the haulage of minerals using technological schemes based on circular technology principles. An assessment of the feasibility of periodic movement of the collective concentrate enrichment plant, considering the advancement of the mining front in the pit, has been carried out.

Keywords: *pit, titanium-zirconium deposits, haulage work, circular technology, enrichment plant, collective concentrate*

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Introduction. The implementation of technological solutions aimed at increasing resource conservation becomes particularly relevant in the work of mining enterprises with high annual productivity and production volumes of tens of millions of tons of man-made raw materials [1]. Such enterprises include mining and processing plants for the extraction and production of titanium-zirconium raw materials, for which Ukraine ranks first in Europe [2].

The main challenges facing the development of promising titanium-zirconium deposits are the high level of waterlogging in mining operations [3] and the high volume of haulage work, due to the need to move minerals with a high content of sand and clay to the enrichment plant [4]. Also, the imperfections of existing technological solutions lead to significant loss of valuable minerals [5], which end up in tailings dams along with host rocks [6].

The improvement of technological schemes [7] of the mining enterprises work for the extraction of titanium-zirconium ores consists in the implementation of technologies based on the principles of circularity [8], which provide for the separation of valuable minerals at the collective concentrate enrichment plant (CCEP) near the pit with subsequent transfer to a stationary enrichment plant [9]. When this technological scheme is applied, sandy and clayey rocks from the CCEP will be directed to internal dumps and used as a resource in the construction industry [1].

During the implementation of the above-mentioned technological solutions, a significant number of unresolved problems remain, the justification of which determines the effectiveness of the mining and processing plant. First, the use of circular technologies entails the complication of technological processes [10], the introduction of additional elements into the enrichment complex, and an increase in cargo flows during the transport of mineral-bearing rocks to the stationary enrichment plant [11].

The use of the concentrate enrichment plant on the slope of the pit also requires additional justification of

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the location parameters [12], since with its stationary placement of rocks with a capital trench, the length of the pipelines along which the entire volume of minerals is transported will gradually increase [13].

Collective concentrate enrichment plant worldwide is successfully used for placer deposits with a low initial content of heavy mineral fraction. The main function entrusted to them is to quickly clean large volumes of ore from the sand-clay mass directly near the front of mining operations. In such placer deposits, ores containing ilmenite, rutile, and zircon, with contents not exceeding 3–5 %, are often found; therefore, the effective implementation of these technologies can reduce transport work by up to 90 %.

These concentrate enrichment plant can also be effectively used not only on natural placer deposits but also on man-made formations formed earlier due to the imperfections of existing enrichment technologies. These objects are economically attractive from the point of view of re-mining, since they contain significant reserves of titanium and zircon, and their re-involvement does not require large capital expenditures compared to the development of a natural deposit. This is due to the lack of need to remove and move large volumes of overburden that were previously mined in the quarry to produce natural raw materials.

Considering the above, there is a need to justify the location of the collective concentrate enrichment plant relative to the boundaries of the pit field and the frequency of its movement when moving the front of mining operations during the working period.

Literature review. In [14], studies were conducted to analyze the effectiveness of implementing new digital tools that increase automation and artificial intelligence in circular mining technologies. The economic, environmental, and social advantages of the circular economy are well established, enabling sustainable mineral mining while minimizing the formation of man-made raw materials. The key problems limiting the use of circular technologies, including economic and regulatory barriers, are also presented, and recommendations are offered for ensuring a sustainable mining industry. However, the work does not pay sufficient attention to applied issues that enable the determination of the effective parameters of a mining and processing enterprise's operation.

In the studies conducted [15], it is proposed to consider the technogenic formations of the mining industry as a raw material resource for the development of ore deposits. The results of the analysis of practical obstacles to the use of technogenic raw materials from tailings impoundments are presented, which involve the principles of the circular economy. Examples of the use of tailings impoundment raw materials in the mining industry are given, emphasizing their significant future raw material potential. Factors influencing the circular economy of mining are determined, including technological, environmental, institutional, and economic components. At the same time, insufficient attention is paid in the work to the issues of organizing the enterprise's operations in line with the principles of the circular economy.

Research [16] identifies the main advantages and obstacles to the mining industry's transition to a circular economy. The authors consider several initiatives in the mining industry for the circular economy, using the example of three large companies. An assessment of the obstacles and advantages of these initiatives in the field of circular economy is made, and the experience of other industries will enable the timely promotion of initiatives and avoid repeating known mistakes. However, the work does not address issues related to determining the impact of circular-economy-based schemes on the operations of mining enterprises.

The authors of [17] focused on developing a basic technological scheme for extracting the rare-earth minerals monazite and zircon. The results of the research show that 97.9 % of monazite can be obtained from the initial sample when enriched using spiral, electrostatic, and magnetic separators, followed by flotation. At the same time, the work does not consider the possibility of using an additional collective concentrate factory, which would help reduce haulage volume at the enterprise.

Research on the main concepts of sustainable development in the circular economy was carried out in [18], confirming that the main efforts focus on increasing the efficiency of mining enterprises. An analysis of the approaches of leading mining companies was carried out, confirming that, in this industry, interest in sustainable development strategies is insignificant. The work also assesses the potential impact of information technologies on increasing the level of mineral raw materials development by mining enterprises, which emphasizes the importance of innovation in the development of the mining industry and a sustainable future. However, the work does not address the economic benefits enterprises achieve when introducing circular-economy-based technological schemes into their activities.

Unsolved aspects of the problem. The use of circular technologies in the development of titanium-zirconium deposits has several significant advantages compared to classical approaches; however, implementing improved technological schemes requires additional justification of the parameters of the elements of the pit development system and the organization of mining and haulage operations at the enterprise [19]. Since the application of cyclic technologies in the working cycle of a mining enterprise entails the introduction of additional enrichment equipment, it is necessary to study the location parameters to adjust the volumes of mining and haulage work. The established patterns will allow determining the effective parameters of the organization of mining and haulage works in the pit when using circular technology for the development of the deposit.

Purpose. To address the identified problems, the research goal was formulated: to determine the optimal location of the collective concentrate enrichment factory when developing titanium-zirconium deposits in line with the principles of circular technology. To achieve the set goal, the following tasks were solved: 1) to develop technological schemes for the development of titanium-zirconium deposits according to the principle of circular technology at different stages of pit operation; 2) to substantiate the methodology for determining the volume of mining and haulage work, taking into account the periodic transfer of the collective concentrate factory in accordance with the advancement of the mining front; 3) to determine the patterns of influence of the location and the number of collective concentrate factory movements during pit operation; 4) to develop rec-

ommendations on the sequence and order of collective concentrate factory movements during the main period of deposit development.

Methods. Improvements to the existing technologies for the development of titanium-zirconium ores should be based on the principles of minimizing the loss of valuable minerals, maximizing the use of associated minerals, and increasing the efficiency of moving the rock mass from the pit to the enrichment plant by reducing the volume of transported ore. In previous studies [4], significant advantages of using a collective concentrate enrichment plant on the pit slope to separate the containing rocks from the heavy fraction were identified.

Separating sandy-clayey-containing rocks from ore at the closest possible distance to the pit further minimizes the volume of clay sludge formed, which increases the viscosity of the pulp. In turn, this complicates gravitational enrichment processes when using screw separators or concentration tables, due to the obstruction of the sedimentation of heavy minerals such as zircon and ilmenite. In the future, the presence of sandy-clayey rocks in the enrichment technological cycle impedes the ingress of valuable raw materials into the enrichment finishing, necessitating the utilization and storage of significant volumes of technogenic raw materials in tailings, thereby increasing the environmental load on the mining region. Also, the future formation of tailings from these deposits necessitates their redevelopment as technogenic deposits, leading to additional costs and irrational use of resources.

According to classical technology, the entire sand-clay mixture contained in the mineral, constituting 92–95 % of its volume, is transported to a stationary enrichment plant (FG), thereby significantly increasing delivery costs. Therefore, separating host rocks at a minimum distance from mining operations will reduce haulage volume when moving the mineral, and the separated sand-clay mixture can be placed in dumps in the pit's mined space at the shortest distance [20].

To determine the effective parameters of the proposed technological solutions for organizing mining and haulage operations in the extraction of titanium-zirconium ores in accordance with the principles of circular technology, it is necessary to consider the dynamics of the mining front's development during the deposit's operation. Since the pits for the development of titanium-zirconium deposits have significant dimensions in plan, and the length of the pit can reach more than 5.0 km, there is a need to determine the influence of the location of the collective concentrate enrichment plant relative to the cutting trench, with the possibility of its periodic movement as the mining front advances.

Let us consider two basic schemes for developing a titanium-zirconium deposit using circular technology with a collective concentrate enrichment plant. The first technological scheme assumes a stationary location of the collective concentrate factory (Fig. 1, *a*) in the area of the pit's main trench throughout the entire period of deposit development. The second scheme (Fig. 1, *b*) proposes a periodic relocation of the CCEP during the operation of the deposit, considering the movement of the mining front, which will allow reducing the distance of transportation of the entire volume of titanium-zirconium ore with host rocks in comparison with the first scheme.

According to the analysis of the technological schemes presented in (Fig. 1), there are 6 main sections of the movement of the rock mass during the extraction of minerals and the delivery of the heavy mineral fraction to the enrichment plant. The second technological scheme is more complex in terms of the organization of the production process, as it provides for periodic movement of the CCEP in accordance with the specified parameters.

To minimize transportation costs, the most effective solution is to constantly move the collective concentrate enrichment plant behind the mining front, since in this case, only the collective concentrate, the mass of which is only a few percent of the total ore volume, will be sent a considerable distance to the enrichment plant.

Also, the location of the collective concentrate enrichment plant next to the cutting trench will significantly reduce water consumption for the gravitational enrichment of placers by using water directly from the pit drainage or water-reducing wells. At the same time, the volume of water consumption will significantly decrease on the section from the collective concentrate

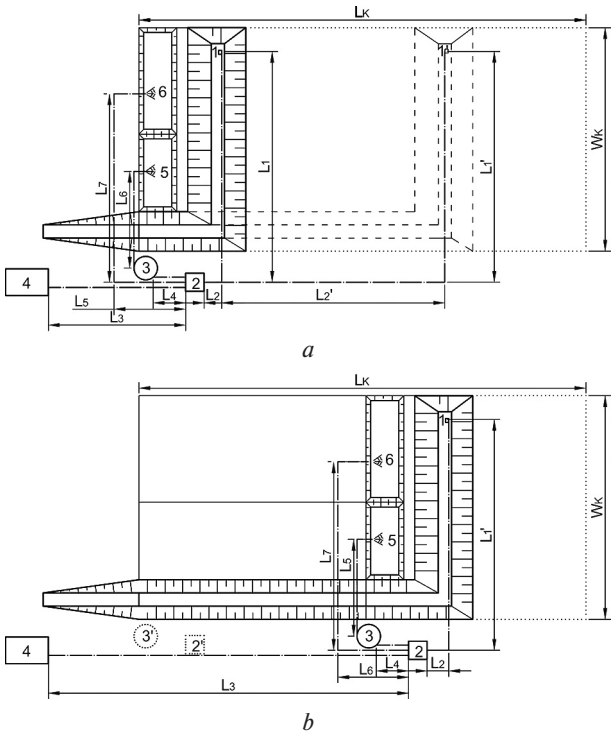

Fig. 1. Technological schemes for the development of a titanium-zirconium deposit according to the principle of circular technology:

a – stationary location of the collective concentrate enrichment plant; b – with periodic movement of the collective concentrate enrichment plant relative to the advance of the mining front; 1 – mining dredger; 2 – collective concentrate enrichment plant; 3 – thickener for clay rocks; 4 – stationary enrichment factory; 5 – hydraulic dump of clay rocks; 6 – hydraulic dump of sand rocks; L_K – length of the pit field; W_K – width of the pit field; L_1 – weighted average length of transportation by the bottomhole pipeline; L_2 – length of the pipeline on the surface of the pit to the CCEP; L_3 – length of the pipeline from the CCEP to the stationary enrichment factory; L_4 – length of the pipeline from the CCEP to the clay thickener; L_5 – length of the pipeline to the clay dump; L_6 – length of the pipeline on the surface of the pit from the CCEP to the dump; L_7 – length of the pipeline on the sand dump

enrichment plant to the stationary enrichment plant, since more than 90 % of the contained sandy-clay rocks will be directed to internal hydraulic dumps, which are located in a safe place of the mined pit space after the formation of the lower dump benches.

Placing the CCEP at a minimum distance from the mining front, with screw and cone separators, even without deep finishing installations, will allow for a significant reduction in the scale of the stationary enrichment plant in the future by reducing the volume of raw ore acceptance while maintaining the enterprise's productivity indicators.

In the case of low productivity of the pit, up to 1 million m^3, a single modular mobile enrichment plant can be used as a CCEP. It can be moved at the speed of the mining front on a sled or pontoon, since it has relatively small overall dimensions. The main difficulty arises when increasing the pit's productivity to 2–4 million m^3/year, since the collective concentrate enrichment plant dimensions must be significantly increased, making it impossible to move it quickly. Therefore, this factory can be built as a semi-stationary structure, the movement of which will take some time, with production processes at the enterprise ceasing.

Therefore, to develop titanium-zirconium pits with high productivity, it is necessary to solve a multifactor problem that involves determining the appropriate number of collective concentrate enrichment plant movements for further comparison of savings from reducing haulage volume with the costs of moving a semi-stationary factory.

In the case of using a stationary CCEP at the final stage of pit development when mining a titanium-zirconium deposit, the distance from the face to it will approach the length of the pit field. In this case, the effect of the proposed solution will be mitigated due to the lack of a reduction in the volume of haulage work.

First, to justify the effective number of movements of the location of the collective concentrate enrichment plant during the operation of the pit, as well as to determine the distance of its movement along the mining front, it is necessary to determine the impact of the movement step on the weighted average volumes of mining and haulage work.

When conducting research, the following initial data are accepted, which correspond to the averaged indicators of the size of the pits during the development of titanium-zirconium deposits: the length of the pit field L_K – 5.0 km; the width of the pit field W_K – 1.5 km; the number of movements of the CCEP during the operation of the pit from 0 to 5, where the absence of movements corresponds to the first technological scheme (Fig. 1, *a*). The calculated parameters of remaining indicators L_1–L_7 shown in (Table 1).

When calculating pipeline lengths for transporting titanium-zirconium ore from the pit to the collective concentrate enrichment plant and further to the stationary enrichment plant (Table 1), the parameters of the technological scheme (Fig. 1, *b*) and the graph-analytical research method were used.

To determine the patterns of haulage work volume distribution from the frequency of collective concentrate enrichment plant movement, the pit productivity by mineral is considered in the range of 2.0 to 4.0 million m^3. The initial data for calculations are taken in accordance with the composition of the mineral of the Malyshivske deposit of titanium-zirconium ores, which, on average, consists of 8 % heavy mineral fraction, 20 % clay, and 72 % sand. Considering the density of each rock and heavy minerals, the total and individual volumes of pulp to be moved through pipelines during pit operation are determined (Table 2).

The calculation method for determining the volume of haulage work according to various schemes has the following sequence:

1. We determine the total length of pipelines for further comparison of capital investments in the operation of a mining enterprise under different technological schemes, km/year

$$\sum L_{TR} = \sum_{i=1}^{n} L_i,$$

where L_i is the length of the pipeline section i, m; i is the number of the pipeline section L_1–L_7 when using a technological scheme with periodic movement of the collective concentrate enrichment plant.

2. We establish the total average annual volume of transport work, considering the workload of all pipeline sections during the operation of the pit, when using a technological scheme with periodic movement of the CCEP, in accordance with the proposed expression, km m^3/year

$$\sum V_{TR} = \sum_{i=1}^{n} V_i \cdot L_i + V_1\left(L_1 + L_2\right) + V_6\left(L_6 + L_7\right).$$

Calculation of the total average annual volume of haulage work when moving minerals in a mine allows

Table 1

Distance of rock mass haulage during titanium-zirconium deposit development according to the principle of circular technology with the movement of collective concentrate enrichment plant

CCEP movements, units	Pipeline length using circular technology						
	L_1, m	L_2, m	L_3, m	L_4, m	L_5, m	L_6, m	L_7, m
0	750	2,500	10,000	100	3,095	2,600	930
1		1,250	10,500		1,845	1,350	
2		833	11,000		1,428	933	
3		625	11,500		1,220	725	
4		500	12,000		1,095	600	
5		417	12,500		1,012	517	

Table 2

Annual volume of movements on different sections of pipelines using circular technology and variable pit productivity Q_K from 2.0 to 4.0 million m^3

Slurry volume in the pipeline when moving	Volume of haulage work, million tons		
	$Q_k = 2$ million m^3	$Q_k = 3$ million m^3	$Q_k = 4$ million m^3
- heavy minerals, V_3	1.28	1.92	2.56
- clay to the thickener, V_4	3.20	4.80	6.40
- thickened clay, V_5	2.00	3.00	4.00
- sand, V_6	11.52	17.28	23.04
- general, V_1	16.00	24.00	32.00

you to compare options with different numbers of CCEP movements, since the redistribution of volumes of heavy minerals and host rocks in all sections of the pit L_1–L_7 is considered. The results obtained allow you to establish technical and economic indicators for each scheme, thereby identifying the most effective solution.

3. We calculate the savings in operating costs when implementing the proposed solutions by comparing the technical and economic indicators of technological schemes with the stationary placement of the CCEP and its periodic movement, Euro/year

$$\sum Å_{TR_i} = C \cdot V_M - C\sum_{i=1}^{n}(V_{S_i} + V_{C_i} + V_{T_i}),$$

where C is the cost of pulp transportation, Euro/t km; V_M is the annual volume of transportation of minerals in pulp, km · t; V_S is the annual volume of transportation of containing sandy rocks in pulp, km · t; V_C is the annual volume of transportation of containing clay rocks in pulp, km·t; V_T is the annual volume of transportation of heavy minerals in pulp, km · t; i is the number of movements of the collective concentrate enrichment plant during the deposit development.

When performing calculations, the average cost of transporting mineralized pulp during the development of the titanium-zirconium deposit by the Vilnohirskyi Mining Processing Plant is used. The average calculations indicate that, when transporting 40 million tons of pulp, the costs amounted to 5.1 million Euros [4]. According to the indicated parameters, the cost of haulage work for moving pulp (t km) is calculated.

4. We determine the total cost savings considering the costs of periodic movement of CCEP relative to the advancement of the mining front, Euro/year

$$\sum P_{TR} = C \cdot V_M - \sum E_{TR_i}.$$

The developed methodological recommendations enable the determination of the technical and economic feasibility of moving the CCEP during deposit development. In the case of a negative value of the cost-saving indicator, the effectiveness of periodic transfer of collective concentrate enrichment plant loses its relevance to changes in the technological parameters of mining and haulage operations in the pit.

Findings. Determination of the influence of the number of collective concentrate enrichment plant movements on the transportation distance of mining mass during the development of a titanium-zirconium deposit, according to the principle of circular technology, made it possible to determine the annual weighted-average length of pipelines for the movement of minerals (Fig. 2).

According to the established dependence (Fig. 2), increasing the number of collective concentrate enrichment plant movements from 0 to 5 during pit operation allows reducing the length of pipelines for moving minerals during the development of a titanium-zirconium deposit with given parameters by 23 %. In comparison, the greatest reduction in pipeline length occurs with three collective concentrate enrichment plant movements and amounts to 26 %.

A general analysis of mineral transportation in sections L_1–L_7 allows us to establish that with five CCEP movements during pit development, the greatest reduction in transportation occurs in section L_2 by 6 times from 2,500 to 417 m. Also, a significant change in the pipeline length occurs in section L_6, and under the same conditions, it decreases by a factor of 5 to 517 m. The length of section L_5 with five collective concentrate enrichment plant movements decreases by 3.1 times to 1,012 m. Sections L_1 and L_7 have a constant length and do not change with an increase in the number of CCEP movements. Only in section L_3 does an increase in the number of collective concentrate enrichment plant movements increase the pipeline length by 25 % to 12.5 km.

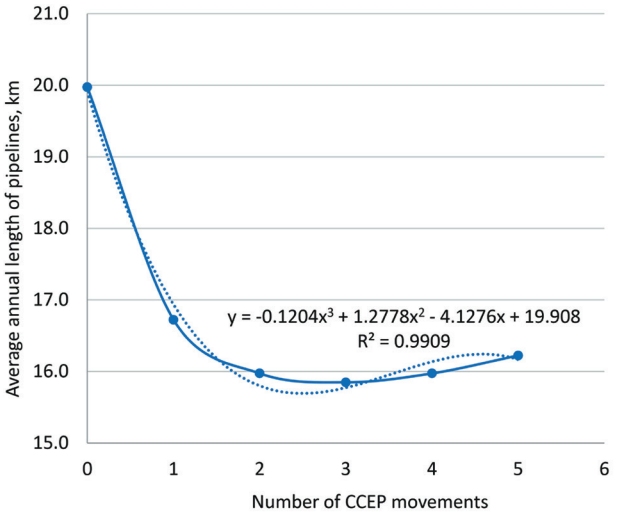

Fig. 2. The influence of the number of CCEP movements on the average annual length of pipelines for haulage minerals during the development of a titanium-zirconium deposit using the principle of circular technology

The established dependence of the average pipeline length on the number of collective concentrate enrichment plant movements allows us to conclude that three factory movements are most effective during pit operation. However, as previously determined, different volumes of mineral resources are moved on each section of the pipelines L_1–L_7; therefore, to perform the feasibility analysis, the average annual haulage volumes were determined in accordance with the initial data in Tables 1 and 2.

When determining the impact of the number of collective concentrate enrichment plant movements on the volume of haulage work of the enterprise, the annual productivity of the pit for the mineral was assumed to be 2.0–4.0 million m^3. The obtained results of the dependencies are shown in Fig. 3.

The obtained dependences of the average annual volume of haulage work on the number of movements of the collective concentrate enrichment plant when moving the front of mining works (Fig. 3) allow us to state that an increase in the number of movements of the CCEP in all considered cases leads to a decrease in the volume of haulage work.

With a pit productivity of 2.0 million m^3, the average annual haulage volume for moving pulp through pipelines can be reduced by 2.1 times, from 118.5 to 56.0 million km·t. However, as can be seen from the graph (Fig. 3), the most rapid decrease in the volume of haulage work by 44 % occurs with 1–2 movements of the collective concentrate enrichment plant, and with 3–5 movements, the volume of haulage work decreases

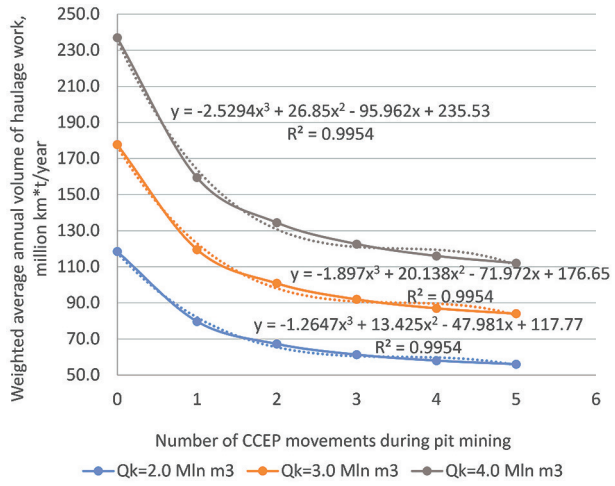

Fig. 3. The impact of the number of CCEP movements on the weighted average annual volume of haulage work during the development of a titanium-zirconium deposit according to the principle of circular technology, considering the productivity of the pit

by only 8 % from 61.3 to 56.0 million km·t.

With an increase in the pit's productivity to 3.0 million m^3, similar patterns are observed as in the previous case. Increasing the number of CCEP movements to 5 reduces the average annual volume of haulage work from 177.7 to 84.0 million km·t. It is worth noting that even with one collective concentrate enrichment plant movement during the pit's operating period, the average annual haulage volume will decrease by 32 % to 119.6 million km · t. The choice of one CCEP movement during the pit's operating period may be justified by the high costs of installation and auxiliary work for moving the factory and the clay thickener.

Analysis of indicators of the average annual volume of haulage work, with an annual mineral extraction of 4.0 million m^3, shows that with five movements of the CCEP, the annual haulage volume decreases from 237.0 to 112.0 million m^3. However, as in previous cases, without accounting for the costs of auxiliary work for moving the CCEP and the clay thickener, it is impossible to recommend an effective number of their movements along the pit.

To establish the effective number of collective concentrate enrichment plant movements during the pit's operational life, it is necessary to take into account the reduction in costs due to the reduction in the average annual volumes of mineral transportation, as well as to predict the allowable cost of moving CCEP and clay thickener, taking into account the advancement of the mining front.

The obtained calculation results allowed us to determine the cost savings achieved by reducing the average annual volume of haulage work when moving minerals according to the proposed scheme with periodic movement of the collective concentrate factory relative to the advance of the mining front (Fig. 4).

According to the obtained dependencies (Fig. 4), the greatest cost savings are observed at a pit productivity of 4.0 million m^3/year. The annual operating cost savings when applying the proposed technological solutions for a pit with the specified parameters are 1.6 million Euro/year. Even with one movement of the collective concentrate enrichment plant and clay thickener throughout the pit's operating period, an average annual operating cost savings of 1.0 million Euro/year is achieved. These savings indicators will change during the pit operation period and will be calculated depending on the number of years of field development.

When reducing pit productivity to 3.0 million m^3/year, significant savings will also be achieved due to lower operating costs, with 5 CCEP movements being the most effective in this regard. In this case, the savings in operating costs will be 1.2 million Euros/year. When comparing the effectiveness of increasing CCEP movements from one to two, it is worth noting that savings increase by 32 % from 0.7 to 1.0 million Euros/year, while increasing movements from one to five increases operating cost savings by 61 %. That is, a further increase in the number of CCEP movements leads to a decrease in the dynamics of cost savings.

At the lowest pit productivity of 2.0 million m^3/year, the lowest efficiency is observed from moving the CCEP and clay thickener in accordance with the advancement of the mining front. With five-fold movement of the collective concentrate enrichment plant during the pit development period, the average annual saving in operating costs for transporting useful material is 0.8 million Euro/year. If CCEP is moved 2 times during the pit operation, cost savings will reach 0.5 million Euro/year, which is comparable to the cost of moving the collective concentrate enrichment plant and the clay thickener as the work front advances.

To develop recommendations for selecting the appropriate number of CCEP and clay thickener movements over the life of the pit, the indicative total cost savings are determined, which considers the periodic cost of moving the specified elements of the enrichment complex.

Since the cost of moving the CCEP and the clay thickener can vary significantly depending on the modifications and standard sizes of the structures, a range of possible costs from 1.0 to 11.0 million Euros was considered for one cycle of dismantling, moving, and reinstalling the equipment at the new site.

When conducting the research, the average pit productivity for the mineral was assumed to be 3.0 million m^3/year, and the pit's operating life was 25 years, which corresponds to the previously defined ranges and prac-

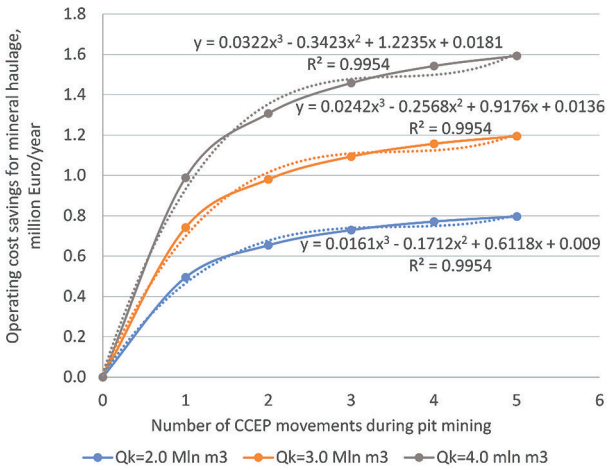

Fig. 4. Dependence of operating cost savings for mineral transportation on the number of collective concentrate enrichment plant movements with pit productivity from 2.0 to 4.0 million m^3/year

tices of open-pit mining in deposits of the specified type.

The results of calculations of total cost savings from implementing the proposed technological scheme, with periodic movement of the collective concentrate factory relative to the advance of the mining front, are shown in Fig. 5.

The obtained dependence of cost savings in mineral transportation on the number of CCEP movements (Fig. 5) indicates that, for a movement cost of up to 1.0 million Euros, three movements are most effective. Compared to a single movement, the efficiency of this work will increase by 38 %, guaranteeing annual cost savings of 0.27 million Euros during the development of the deposit. With a further increase in the number of CCEP movements from 3 to 5, cost savings will increase by 2 %, which is within the error range.

If the cost of the work on the transfer of the CCEP and the clay thickener increases to 6.0 million Euros, it is established that one or two transfers of the enrichment complex elements are most effective. Under such conditions, the annual cost savings will be 0.5 million Euros. Of course, if the same economic effect can be achieved with one or two transfers of the CCEP, a single transfer will be most appropriate, thereby preventing an increase in the volume of additional work. With a further increase in the number of transfers between CCEP and the clay thickener 3–4 times, the effectiveness of the proposed solutions will decrease, and the savings will be 0.20–0.37 million Euros, which is 1.3–2.5 times less than a double transfer. If the number of transfers of the enrichment complex elements to 5 is increased, there will be no cost savings, which makes the proposed solution impractical under the existing initial conditions.

Further increase in the cost of the CCEP relocation to 11 million Euros reduces the attractiveness of the proposed technological scheme. First, this is due to the level of cost savings, which has reduced the cost of auxiliary works. The best option in this case is a single relocation of the enrichment complex elements, which will allow achieving annual cost savings of 0.3 million Euros during the development of the deposit. When choosing a double relocation of the CCEP and clay thickener, cost savings are reduced by a factor of 3 to 0.1 million Euros/year, which is a significantly worse option than a single relocation. Moving CCEP more than 3–5 times is not economically feasible and results in additional annual costs of 0.2 to 1.0 million Euros.

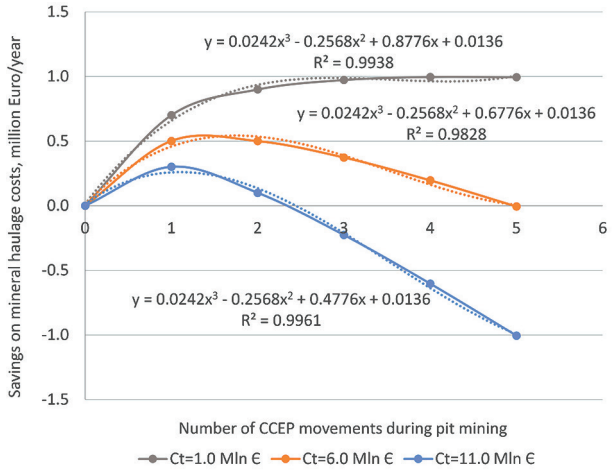

Fig. 5. Savings on mineral haulage costs when changing the number of CCEP movements in a pit with a capacity of 3.0 million m³/year, considering the change in costs for CCEP movement from 1.0 to 11 million Euros

According to the established dependencies, it can be stated that the movement of CCEP and clay thickener during pit operation under certain conditions has technical and economic feasibility, and the benefits obtained consist of reducing haulage work at the mining enterprise and achieving the basic principles of developing a titanium-zirconium deposit according to the principle of circular technology.

Conclusions. Technological schemes for the development of a titanium-zirconium deposit based on the principles of circular technology, with the CCEP moving relative to the advance of the mining front, have been developed, which allows determining the parameters of the elements of the pit haulage system and calculating the volumes of haulage work.

The dependence of the average annual length of pipelines on the number of CCEP movements has been established, which allows us to determine that, during the development of a pit with given parameters, the pipeline length decreases by 23 %, with the greatest reduction occurring with three movements, amounting to 26 %.

The influence of the number of CCEP movements on the weighted average annual volume of haulage work has been determined, which allows us to establish that with a pit productivity of 2.0 million m³, the largest reduction in the volume of haulage work by 44 % occurs with 1–2 CCEP movements, and with 3–5 movements, the volume of haulage work decreases by only 8 % from 61.3 to 56.0 million km · t.

The dependence of savings on haulage operating costs on the number of CCEP movements was established, allowing us to determine the reduction in total economic costs. The results confirm the effectiveness of the proposed solutions for 1–2 CCEP movements, depending on pit productivity and the cost of moving enrichment complex elements.

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Вплив розташування фабрики колективного концентрату на циркулярну технологію розробки титан-цирконієвих родовищ

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Мета. Визначення ефективного місця розташування збагачувальної фабрики колективного концентрату (ЗФКК) при розробці титан-цирконієвих родовищ за принципом циркулярної технології.

Методика. У роботі використано комплекс методів досліджень: графоаналітичний для визначення параметрів технологічних схем із використанням принципів циркулярних технологій, а також місця розташування збагачувальної фабрики колективного концентрату при переміщенні фронту гірничих робіт; аналітичний – для встановлення впливу послідовності переміщень фабрики колективного концентрату на об'єми транспортної роботи в кар'єрі й обґрунтування місця розташування комплексу збагачення.

Результати. Встановлені залежності середньої довжини трубопроводів від кількості переміщень збагачувальної фабрики колективного концентрату дозволяють стверджувати, що найбільш ефективним є два переміщення фабрики протягом експлуатації кар'єру. Визначено, що при зміні продуктивності кар'єру від 2,0 до 4,0 млн м^3 середньорічний об'єм транспортної роботи із переміщення пульпи трубопроводами може бути зменшено у 2,1 рази за п'ятикратного переміщення фабрики колективного концентрату. Встановлена залежність економії експлуатаційних витрат на транспортні роботи від кількості переміщень ЗФКК, що дозволила визначити скорочення загальних економічних витрат. Отримані результати підтверджують ефективність запропонованих рішень за одного або двох переміщеннях ЗФКК, у залежності від продуктивності кар'єру і вартості переміщення комплексу збагачення.

Наукова новизна. Встановлена залежність середньорічної довжини трубопроводів від кількості переміщень ЗФКК, яка дозволяє визначити, що довжина трубопроводів при розробці кар'єру із заданими параметрами зменшується на 23 %, при цьому найбільше скорочення відбувається при трьох переміщеннях і складає 26 %. Визначено вплив кількості переміщень ЗФКК на середньозважений річний об'єм транспортної роботи. Відповідно до розрахункових даних, при продуктивності кар'єру 2,0 млн м^3, найбільш ефективна кількість переміщень ЗФКК складає два рази, при цьому об'єм транспортної роботи скорочується на 44 % за час розробки кар'єру. При збільшенні кількості переміщень ЗФКК до 3–5, об'єм транспортної роботи протягом роботи кар'єру зменшується лише на 8 % з 61,3 до 56,0 млн км · т.

Практична значимість. Розроблені технологічні схеми освоєння титан-цирконієвого родовища за принципом циркулярної технології при переміщенням ЗФКК відносно до посування фронту гірничих робіт, що дозволяють визначити параметри транспортної системи кар'єру й виконати розрахунок об'ємів транспортної роботи. Встановлені техніко-економічні показники при транспортуванні корисних копалин із використанням технологічних схем із принципами циркулярної технології. Виконана оцінка доцільності періодичного переміщення збагачувальної фабрики колективного концентрату при посуванні фронту робіт.

Ключові слова: *кар'єр, титан-цирконієві родовища, транспортна робота, циркулярна технологія, збагачувальна фабрика, колективний концентрат*