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PROCESSING OF RARE EARTH ORE OF WEATHERING CRUST

Rapid development of high-tech industries is due to the rare and rare-earth metals used in instrumentation and radio electronics. Their materials are used primarily in the military-industrial and aerospace industries and are of strategic importance for the state.

Purpose. To develop a technology of enrichment of difficult-to-enrich rare-earth ore of weathering crust on the basis of combined gravity and flotation enrichment scheme.

Methodology. Studies on processing of this mineral raw material were carried out on the basis of gravity-flotation enrichment with obtaining rare-earth concentrate. The enrichment studies were carried out on a selected sample of ore from the deposit. On the basis of sieve and sedimentation analyses, the distribution of the sum of rare-earth elements ($\sum REE$) in ore size classes and enrichment products was studied. Gravity enrichability of ore was determined by fractional analysis.

Findings. A method of gravity enrichment using the developed gravity apparatus and flotation enrichment of sand and clay fraction of the studied ore has been developed. Gravity enrichment produced a concentrate containing 1,053.76 g/t of rare-earth elements ($\sum REE$), flotation enrichment of the clay fraction of the ore produced a concentrate containing 590.0 g/t of rare-earth elements ($\sum REE$).

Originality. The developed ultrasonic aerohydrodeslimator was used for ore desliming. The gravitational technology for processing hard-to-enrich rare-earth ore of weathering crust with the use of vibrocentrifugal frequency apparatus, which allows intensifying the extraction of fine ore particles, is developed. Rare earth ore of size class –0.045 + 0 mm (clay fraction) and class –2.5 + + 0.045 mm (sand fraction) was subjected to flotation beneficiation.

Practical value. The results of the research can be used in technological processes of processing of stubborn difficult-to-enrich rare-earth and other ores of weathering crust.

Keywords: *rare-earth ore, size class, gravity-flotation enrichment, concentrate, enrichment waste*

Introduction. The object of the study is the rare earth ore of the weathering crust of the Kundybay deposit located in Kazakhstan.

The mineralogical composition of the studied sample is represented by the following minerals: quartz SiO_2, oligoclase $KAlSi_3O_8$, calcite $CaCO_3$, hematite Fe_2O_3, iron hydroxides (goethite) $HFeO_2$, muscovite $KAl_2Si_3AlO_{10}(OH)_2$ is present in the form of a fine powder on grains of quartz and feldspar; kaolinite $Al_4Si_4O_{10}(OH)_8$.

The content of $\sum REE$ in the studied ore sample according to the results of chemical analysis is 320.45 g/t. REE content in the initial ore sample, are g/t: Dy – 9.175; Er – 3.93; Eu – 0.874; Gd – 6.8; Ho – 1.03; La – 48.0; Lu – 0.6; Nd – 26.09; Pr – 41.8; Sm – 3.89; Tb – 0.722; Tm – 6.524; Y – 14.12; Yb – 2.78; Ce – 155.765. From rare-earth elements in the studied ore the most contained cerium – 155.765 g/t, somewhat in smaller amounts can be noted as La, Pr, Nd and Y.

Granulometric analysis of the initial ore of Kundybay deposit crushed to –2.5 mm showed that 70.65 % of $\sum REE$ is contained in fine classes –0.02 + 0.01 mm, –0.01 + 0.005 mm, 0.005 + 0 mm. The total yield of these classes is 32.65 %. The average content of $\sum REE$ in these classes is 667 g/t.

There are four deposits with rare earth mineralization. The first is the largest, including 64.9 % of reserves, the second – 78 %, the third – 4.3 % and the fourth – 23 % [1].

The main carriers of rare earth elements (*REE*) are clay minerals of the weathering crust, accounting for 58.1 %. A distinctive feature of this ore, unlike others, is the absence of radioactivity, loose sandy-clayey granulometric composition, which neutralizes the process of ore preparation before beneficiation processes. The presence of yttrium, europium and other lanthanides in it. The ores of the deposit can be considered promising for their processing to produce rare earth metal (REM) concentrates. In this regard, the need arose to conduct technological research in order to study the material composition of ore with the establishment of variability in the distribution of useful components in them and the technological properties of their processing.

Rare earths include a group of 17 elements, including: scandium (Sc), yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu). Rare earth elements are used in instrument making, radio electronics, mechanical engineering, nuclear engineering, the chemical industry, metallurgy and other various industries. Based on Nd, Y, Sm, Er, Eu with Fe-B (iron boride), alloys with high magnetizing and coercive forces are obtained to create permanent magnets, used, in particular, in wind generators and electric vehicle engines [2].

Literature review. Mineral reserves of rare earth metals are estimated at about 110 million tons, of which China accounts for about 50 % of all rare earth metal reserves in the world [3–5].

The main value in the weathering crust are the secondary rare earth minerals bastnäsite, cherchite and rhabdophonite. Cherchit is the most common mineral in the deposit. Rhabdophanite in composition is a close analogue of churchite $\sum TR_2O_3$ – 42.57 %, it is characterized by a high yttrium content (4.76 %).

From a review [6–8] of literary and patent studies in the field of enrichment and hydrometallurgical processing of difficult-to-enrich rare-earth weathering crusts, it was established that when processing these ores, three processing methods are used: gravity-magnetic, flotation and hydrometallurgical ones.

Unresolved aspects of the problem. Currently, only three major REE-containing minerals (bastnaesite, monazite and xinotime) are used in industrial processing. We utilize 15 rare earth elements (Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, Y, Yb, Ce) in the processing of rare earth ore based on gravity-flotation beneficiation. The main separation processes used in the beneficiation of rare earth minerals include gravity-magnetic separation and froth flotation [9–11]. From the mineralogical composition of the investigated ore sample, there are no minerals with magnetic properties, so this paper does not consider the magnetic processing method.

In this regard, we [12–14] carried out studies of the ores of the weathering crust of the Kundybay deposit using physicochemical methods of analysis to further determine the ore's processability and establish the pattern of distribution of rare earth metals in the studied ore: size and density, separation of the clay fraction of the ore by both gravity, flotation enrichment.

Purpose. The main value in the ore are the secondary rare earth minerals bastnäsite, cherchite and rhabdophonite. Cherchit is the most common mineral in the deposit. Rhabdophanite in composition is a close analogue of churchite, $\sum$REE is 42.57 %, it is characterized by a high yttrium content (4.756 %). Particularly noteworthy are the most important and valuable differences in comparison with ores from other deposits of rare earth mineral raw materials – the absence of radioactivity and, accordingly, in the resulting commercial products. Loose sandy-clayey granulometric composition of ores, which eliminates partly expensive ore preparation operations (crushing and grinding). An unusual lanthanide composition containing deficient yttrium, europium and other heavy lanthanides.

The current practice of processing difficult-to-process rare earth ores requires the use of combined schemes that combine the processes of gravity, flotation concentration, hydrometallurgy and pyrometallurgy. This is due to the fact that rare earth elements in these ores are represented in more diverse forms and are distributed in both the clayey and granular parts of the ore [1].

To conduct research on the processing of the studied ore, a representative sample of rare earth ore was selected. To analyze the material composition of the ore and enrichment products, the following methods of physical and chemical analysis were used: spectral, mineralogical, chemical, X-ray phase analysis and scanning electron microscopy.

Atomic emission qualitative spectral analysis of samples of the studied ore and enrichment products was carried out on a DFS-13 diffraction spectrograph, mineralogical analysis using a MIN-8 microscope (transmitted light) and an inverted Deica microscope (reflected light). X-ray phase analysis using the "D8 Advance (Bruker)" apparatus.

The ore was analyzed by infrared spectroscopy using an Avatar 370 IR-Fourier spectrometer.

In order to determine the particle size distribution and the nature of the distribution of rare earth elements by size class, sieve analyzes were performed on ore of initial size –80 + + 0.0 mm and crushed to a size of 2.5 mm.

Sieve analysis consisted of sifting an ore sample through a set of sieves and washing each size class, followed by determining the percentage of product on each sieve, relative to the weight of the original sample. To determine the particle size distribution of the sample, a set of sieves was used up to a particle size of 0.05 mm, and a class with a particle size of less than 0.05 mm was subjected to sedimentation analysis.

Analysis of the results of the granulometric composition showed that the number of large classes with a particle size from 80 to 2.5 mm in the ore of the original size is insignificant. Thus, the yields of classes with sizes –80 + 40, –40 + 20 and –20 + 10 mm were 1.44, 1.21 and 1.61 %, respectively, with their total yield of 4.26 %. It can also be noted that in these size classes the lowest $\sum$REE contents are observed, with their total extraction of 0.608 %.

The yield of classes with size –10 + 5 and –5 + 2.5 mm was 2.60 and 4.43 % and the REE content was 97.499 and 83.673 g/t, respectively, with a total recovery of $\sum$REE per class with size –10 + 2.5 mm 1.948 %.

The total yield of the –80 + 2.5 mm size class was 11.29 % with an average $\sum$REE content of 73.434 g/t and a total $\sum$REE recovery of 2.556 %. Based on this, we can say that in the total class with a particle size of –80 + 2.5 mm, a small amount of REE is concentrated and, accordingly, it is not advisable to subject it to separate enrichment.

In general, the distribution of total REE contents by size class in the original ore is uneven. At the same time, the lowest content of $\sum$REE is observed in the largest classes and the highest contents in fine size classes. Thus, the $\sum$REE content in the –80 + 40 mm size class was 22.055 g/t, and in the –0.02 + + 0.01 and –0.01 + 0.05 mm size classes it was 609.981 and + 821.597 g/t accordingly. At the same time, the overall yield of these size classes was 31.49 % with an average $\sum$REE content of 694.318 g/t and a total extraction of $\sum$REE of 68.229 %. This allows us to assert that most of the REE are concentrated in the size class –0.02 + 0.005 mm.

The yield of the finest class with a particle size of less than 5 microns was only 1.14 %. However, in this size class, the highest content of $\sum$REE is observed, which amounted to 890.639 g/t, with an extraction of $\sum$REE of 3.168 %. The weighted average content of $\sum$REE in the ore sample of the original size was 320 g/t.

Methods. The work examined methods of chemical, mineralogical, granulometric and fractional analyses. Experimental studies of the beneficiation of a selected representative sample of rare earth ore of the weathering crust based on gravitational and flotation enrichment.

A sample of rare earth ore containing total rare earth elements ($\sum$REE) was received for research – 308.18 g/t.

The initial ore size is –80 + 0.0 mm, with a total weight of 220 kg. In order to determine the particle size distribution and the nature of the distribution of rare earth elements by size class, sieve analyzes were performed on ore of original size and crushed to a size of 2.5 mm.

The distribution of $\sum$REE content by size class is uneven. The lowest $\sum$REE content is observed in the largest classes and the highest in fine size classes.

According to the results of sieve analysis, the weighted average $\sum$REE content was 308.18 g/t of ore.

The results of the sieve analysis of the ore of the original size predetermined the need to determine the particle size distribution and the nature of the distribution of $\sum$REE when crushing the original ore to a size of 2.5 mm.

Analysis of the results of the granulometric composition by size class showed that the highest yields correspond to the size classes –0.02 + 0.01 and –0.01 + 0.005 mm, while their total yield is 30.76 % with an average content of $\sum$REE 655.291 g/t.

The distribution of content by size class, when crushing the original ore to 2.5 mm, is also uneven, with the lowest content corresponding to the largest size class –2.5 + 1.25 mm and amounting to 93.225 g/t, and the highest to the finest size class –0.005 + 0.0 mm and 856.297 g/t.

The nature of the distribution of $\sum$REE extracts by size class is similar to their distribution in the ore of the original size. The highest extraction of $\sum$REE in two classes with sizes of –0.02 + 0.01 and –0.01 + 0.005 mm is also observed, which amounted to 34.011 % and 31.393, respectively. At the same time, the total extraction of $\sum$REE in these classes was 65.404 % (68.229 % in the ore of the original size), i. e., most of the REE are concentrated in these size classes. It has been established that 70.65 % of $\sum$REE is contained in thin classes –0.02 + 0.01, –0.01 + 0.005, 0.005 + 0 mm. The total yield of these classes is 32.65 %. The average $\sum$REE content for these classes is 667 g/t. According to the results of the sieve analysis, the weighted average content of $\sum$REE was 308.18 g/t.

In order to study the gravity concentration of the studied ore, a fractional analysis was carried out.

Studying the nature of the distribution of $\sum$REE by density fractions makes it possible to determine the possibility of separating heavy (concentrate) and light (waste) fractions from the studied size classes and from the ore in general, i. e., its gravitational concentration.

The studied classes with sizes –2.5 + 0.315, –0.315 + 0.1 mm were subjected to stratification in solutions of heavy liquid M-45 into fractions with a density (kg/m^3): less than 2,550; 2,550–2,650; 2,650–2,750; 2,750–2,850; 2,850–2,950 and more than 2,950. Class coarseness –0.10 + 0.0 mm was subjected to stratification only in density 2,850 kg/m^3 under dynamic conditions using centrifugal force, obtaining two fractions of density less and more than 2,850 kg/m^3.

Results. According to the results of the particle size distribution, the weighted average content of $\sum$REE in the studied ore sample was 307.73 g/t. Analysis of the results of the granulometric composition of the ore sample showed that the yield of the –2.5 + 0.315 mm size class is 31.37 % with a $\sum$REE content of 92.35 g/t and an extraction of 9.414 %. The yield of the class size –0.315 + 0.0 mm was 19.82 % with a $\sum$REE content of 146.96 g/t with a recovery of 9.465 %.

The highest yield and recovery is observed in the finest class with a particle size of –0.1 + 0.0 mm. Its yield was 48.81 % with a $\sum$REE content of 511.44 g/t with an recovery of 81.121 %. According to the results of fractional analysis, the weighted average content of $\sum$REE in the studied ore sample was 307.83 g/t.

Analysis of the results of studies of the fractional composition showed that from the size class –2.5 + 0.315 mm, it is theoretically possible to isolate heavy concentrate fractions with a density of 2,850–2,950 kg/m^3 and more than 2,950 kg/m^3, in which the highest concentration of rare earth elements is observed. Thus, the yield of the fraction with a density of 2,850–2,950 kg/m^3 was 0.58 %, and the fraction with a density of more than 2,950 kg/m^3 was 1.13 %, with a $\sum$REE content of 432.96 and 490.22 g/t, respectively , with the initial content of $\sum$REE in this size class being 92.34 %. In the case of joint isolation of these density fractions, their total yield will be 1.71 % with an average $\sum$REE content of 470.80 g/t.

The theoretically possible yield of light fractions with a density of less than 2,550 and 2,550–2,650 kg/m^3, in which the lowest content of rare earth elements is observed, was 2.96 and 18.92 %, with a $\sum$REE content of 68.10 and 42.93 g/t, respectively, when they are separated together into one common fraction with a density of less than 2,650 kg/m^3, their total yield will be 21.88 % with an average $\sum$REE content of 46.385 g/t.

At the same time, the studied size class contains intermediate fractions with a density of 2,650–2,750 and 2,750–2,850 kg/m^3, the yield of which was 4.71 and 3.07 % with a $\sum$REE content of 145.75 and 128.17 g/t respectively. In the case of joint isolation of fractions of intermediate density (2,650–2,850 kg/m^3), their total yield will be 7.78 %, with an average $\sum$REE content of 128.53 g/t.

Based on the analysis of the results of the fractional composition of the class with a particle size of 2.5–0.315 mm, with its gravitational enrichment, it is possible to isolate three products: concentrate, middlings and tailings. In the case of dividing this size class only by density of 2,850 kg/m^3, with the separation of fractions with a density of less than 2,850 kg/m^3 into a light product, their total yield will be 29.66 % with an average $\sum$REE content of 67.895 g/t. The fractional composition of the 0.315–0.10 mm size class shows that it is theoretically possible to isolate heavy concentrate fractions with a density of 2,850–2,950 kg/m^3 and more than 2,950 kg/m^3, in which a significant concentration of rare earth elements is observed. Thus, the yield of fractions with a density of 2,850–2,950 kg/m^3 and more than 2,950 kg/m^3 was 0.47 and 1.17 %, with a $\sum$REE content of 643.937 and 1,112.162 g/t, with the initial content of $\sum$REE in this size class is 146.95 g/t. The total yield of these density fractions will be 1.64 %, with an average $\sum$REE content of 977.95 g/t.

Analysis of the results shows that in the class with a particle size of –0.315 + 0.10 mm, in all fractions with a density of less than 2,850 kg/m^3, almost the same $\sum$REE contents are observed, and which are in the range of 191.343–47.876 g/t. Based on this, it can be noted that in this size class there is no clear boundary between light and intermediate fractions. Accordingly, with the joint isolation of fractions with a density of less than 2,850 kg/m^3, their total yield will be 18.18 %, with an average $\sum$REE content of 72.436 g/t. It should be noted that in a fraction of similar density, but in the size class –2.5 + + 0.315 mm, the content of $\sum$REE is almost the same and equal to 67.895 g/t.

Based on the above assertion, it can be stated that from both size clases it is necessary to separate fractions with a density of more than 2,850 kg/m^3 into the heavy (concentrate) fraction. In accordance with this, the required separation density for isolating concentrate fractions of both size classes is 2,850 kg/m^3. In the case of dividing both classes with a particle size of –2.5 + 0.315 and –0.315 + 0.10 mm by density of 2,850 kg/m^3, the theoretically possible total yield of the heavy concentrate fraction will be 3.35 %, with an average $\sum$REE content of 719.088 g/t . Based on this, we can say that the average degree of concentration of $\sum$REE in the concentrate fractions was 6.34 times.

Accordingly, the yield of all light fractions with gravitational separation at a density of 2,850 kg/m^3 will be 47.84 %, with an average $\sum$REE content of 69.620 g/t.

Fractional analysis of the –0.10 + 0.00 mm size class was performed using centrifugal force in a centrifuge at a density of 2,850 kg/m^3.

The results of fractional analysis of the 0.10–0.00 mm class are shown in Table 1.

The fractional composition of the class with a particle size of –0.10 + 0.00 mm showed that at a separation density of 2,850 kg/m^3, a concentration of rare earth elements at a density of more than 2,850 kg/m^3 is also observed. At the same time, an increased content of rare earth elements is observed in the fraction with a density of less than 2,850 kg/m^3. This can be explained by the fact that in this size class there is a significant amount of fine and slurry classes, which are difficult to

Table 1

Fractional composition of class size 0.10–0.00 mm

Size class, mm	Density of fractions, kg/m^3	Output, % of		Content $\sum$REE, %	Extraction, % of	
		class	ore		class	ore
0.10–0.00	–2,850	73.96	36.10	369.090	53.37	43.296
	+2,850	26.04	12.71	915.792	46.63	37.825
	Total	100.0	48.81	511.450	100.0	81.121

separate in a heavy liquid with a relatively high viscosity, even using centrifugal force.

The results obtained from studying the fractional composition of the ore showed that the studied ore and, in particular, size classes larger than 0.10 mm can be enriched using gravitational processes.

The presence of a high amount of sludge fraction (more than 30 % of the ore) led to the conclusion that this ore cannot be subjected to enrichment processes without preliminary desliming.

The desliming process was carried out using a system developed at KazNRTU named after. K. I. Satpayev ultrasonic aerohydrodeshludger (UAGD), which makes it possible to remove up to 90 % of fine clay-sludge material with a particle size (–2 mm) from the process. The UAGD scheme is presented in Fig. 1.

The process of desliming the feedstock is carried out in sequentially separate UAGD chambers. In the turbulent countercurrent of air and water jets (chamber *1*), coarse aggregates and heavy minerals are separated from the pulp, then in the subsequent chamber *2*, due to ultrasonic activation of the laminar flow of the pulp, fine and finely dispersed particles are separated. Hydraulic classification in the apparatus is carried out in continuous, alternatingly outgoing and ascending, curvilinearly flowing flows and occurs from large class to small class.

In the first chamber, the size and density of the separated particles are of great importance; in the second chamber, the main thing is the size and shape of the particles and the nature of their structure; in the drain, the size of the particles is important. Due to the aeration of the pulp in the first chamber, the mineralization of air bubbles occurs, the fixation of fine sludge (clayey) particles on them as the bubble moves from bottom to top and the particle falls down. Secondly, ultrasonic activation destroys air bubbles and opens (“cleanses”) grains from films and crusts of other minerals, performs fine disintegration (1–10 microns) of mineral suspension and promotes the sedimentation of larger grains. Finely disintegrated, purified (ennobled) material suitable for hydrometallurgical processing and gravity-flotation enrichment enters the deslimer drain.

Mixing of the pulp and separation of solid particles are carried out by bubbling, that is, by passing small air bubbles through the pulp. For this purpose, an air bubbler is installed in the first chamber, which consists of three horizontally located pipes ($d = 21$ mm) fastened together with 56 holes ($d = 1$ mm) in the lower part of each. Due to this, the air from the holes overcomes the same hydraulic resistance and comes out evenly from the holes, which contributes to better mixing of the sediment in the conical funnel, and the lower location of the holes protects them from clogging with sand. The air is supplied under pressure. Particles of minerals that are poorly wetted by water (sulfur, talc, graphite, sulfides, and in some cases native metals) adhere to air bubbles and float with them to the surface of the pulp. Particles well wetted by water, surrounded by a strong hydration shell, do not stick to air bubbles and remain in the aqueous environment.

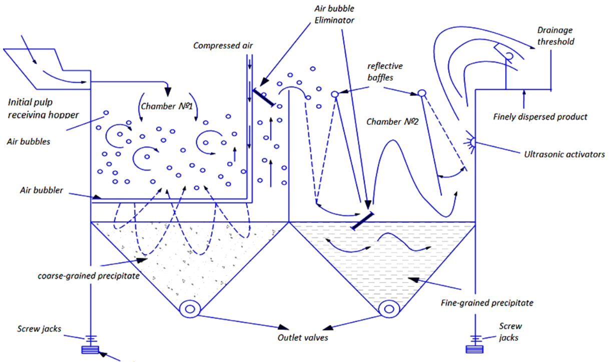

Fig. 1. Diagram of ultrasonic aerohydrodeshlamator

Table 2

Results of desliming crushed ore up to 2.5 mm

Size class, mm	Output, %	$\sum$REE content, g/t	$\sum$REE extraction, %
–2.5 + 0.1	53.75	108.09	18.88
–0.1 + 0.0	41.25	534.02	81.12
Ore	100	307.78	100

The addition of foaming agents (pine oil, etc.) to the pulp ensures the stability and duration of existence of air bubbles in the pulp.

The release of settled sediment is carried out using ball valves located in the conical bottoms of the chambers; the drain is sent through a drain threshold, through which sludge is removed.

The separation of sands in UAGD by ascending water flows is carried out in chamber classifiers, the performance of which is calculated based on the performance of the last chamber, from which fine particles are removed into the drain. With a large content of fine sludge, due to the insufficient settling area (water surface) of particles in the last chamber, the classification performance decreases. De-sliming in UAGD is carried out at a cut-off size of 0.04 mm.

The required ore size for carrying out large-scale laboratory tests, determined by preliminary studies, was 2.5 mm.

A sample of the original ore –80 + 0.0 mm – was crushed and ground to a particle size of 2.5 mm. The resulting size class –2.5 + 0.0 mm was sent for desliming at the UAGD in order to separate the sludge fraction –0.1 + 0.0 mm. The resulting two size classes –2.5 + 0.1 and –0.1 + 0.0 mm were sent for experiments on gravitational enrichment.

Before conducting large-scale laboratory tests, the ore, crushed to 2.5 mm, was subjected to desliming according to the size class –0.1 + 0.0 mm. The results of desliming are presented in Table 2.

According to the results of desliming, the weighted average content of $\sum$REE in the studied ore sample was 307.78 g/t, Table 2.

Analysis of the results of desliming of the original ore, crushed to 2.5 mm, showed that the yield of class –2.5 + 0.1 mm was 53.75 % with a $\sum$REE content of 108.09 g/t with an extraction of 18.88 %.

The yield of the –0.1+0.0 mm class was 41.25 % with a $\sum$REE content of 534.02 g/t with a recovery of 81.12 %.

It should be noted that the content of $\sum$REE in the size class – 2.5 +0.0 mm is almost three times lower than the content of $\sum$REE in ore and has a low extraction of $\sum$REE in this class (18.88 %). From this we can state that the main amount of $\sum$REE is extracted into the size class –0.1 + 0.0 mm (81.12 %) and there is an increased content of $\sum$REE in relation to the content of $\sum$REE in the original ore by 1.73 times (534.02 g/t).

Large-scale laboratory tests were carried out on the gravitational enrichment of fine particles of rare earth elements from the studied ore using a developed vibrocentrifugal bowl apparatus of various capacities.

Enrichment of class –2.5 + 0.1 mm was carried out using a screw separator and a developed vibrating centrifugal bowl apparatus [12–14].

Technical characteristics of vibration centrifugal bowl apparatus
Basic parameters and dimensions.
Technical performance at
pre-processing
prepared (disintegrated)
samples (processed material), kg/h. 40–100

Sample weight by material per cycle, kg, no more than	25
Feed size, mm, no more than	2
Concentrate yield, g	9–60
Gold recovery by size class, %, no less	
larger than 0.1 mm	95
size 0.05–0.1 mm	80
size 0.01–0.05 mm	50
Concentration degree	100–200
Electric drive of the executive body	
Type of current alternating single-phase	
Frequency, Hz	50±0.2
Voltage, V	2
Total installed capacity electric motor, kW	0.75–1.1
Water consumption, l/min	2
Overall dimensions, mm, no more	
length	750
width	290
height	410
Weight, kg, no more than	10

The vibrating bowl apparatus, in its design parameters and operating principle, is an analogue of the developed hydraulic concentrators [12–14]. A distinctive feature of the device: no additional water supply to the concentrator bowl (rotor), a high degree of concentration (up to 200) of useful components in the enrichment products and the ability to work with small samples of the material under study. Loosening of the material in the bed of the concentrator bowl is carried out due to its vibration (3,000–6,000 counts/min).

Gravity enrichment of the studied ore was carried out on a developed enlarged technological installation.

Enrichment of class –2.5 + 0.1 mm on a screw separator was carried out with the following parameters: ratio $W:T = 3:1$.

The finishing of the screw separator concentrate in a vibrating bowl apparatus was carried out with the following parameters: $W:T$ ratio = 3 : 1, bowl rotation speed 500 rpm.

Analysis of the results of enlarged laboratory tests of gravity enrichment of the –2.5 + 0.1 mm size class showed the possibility of obtaining a concentrate, two industrial products (industrial product – 1 and industrial product – 2) and tailings.

The concentrate yield was 3.76 % of the ore (7.00 % of the class) with a $\sum$REE content of 640.68 g/t, with an extraction of $\sum$REE of 7.83 % of the ore (41.47 % of the class).

The yield of middling product – 1 was 8.17 % of the ore (15.2 % of the class) with a $\sum$REE content of 122.61 g/t with an extraction of $\sum$REE of 3.25 % of the ore (17.21 % of the class). The yield of middling product – 2 was 9.48 % of the ore (17.45 % of the class) with a $\sum$REE content of 95.15 g/t, with an extraction of $\sum$REE of 2.90 % of the ore (15.36 % of the class). The yield of the total middling product (middling product – 1 plus middling product – 2 was 17.55 % of the ore (32.65 % of the class) with a $\sum$REE content of 107.93 g/t, with a total extraction of $\sum$REE 6.15 % of the ore (32.57 % of the class).

The yield of enrichment tailings with a size of –2.5 + + 0.1 mm was 32.44 % of the ore (60.35 % of the class) with a $\sum$REE content of 46.44 g/t with an extraction of $\sum$REE 4.90 % of the ore (25.96 % of the class).

Class enrichment –0.1 + 0.0 mm on a vibrating bowl apparatus.

Enrichment of class –0.1 + 0.0 mm on a vibrating bowl apparatus was carried out with the following parameters: ratio $W:T = 3:1$, bowl rotation speed 500 rpm.

The obtained results of enlarged laboratory tests of gravity enrichment of the size class – 0.1 + 0.0 indicate the possibility of obtaining concentrate and tailings.

Thus, the concentrate yield was 11.05 % of the ore (23.89 % of the class) with a $\sum$REE content of 1,053.76 g/t, with an extraction of $\sum$REE of 37.83 % of the ore (46.63 % of the class).

The yield of enrichment tailings with a size of 0.1 + 0.0 mm was 35.2 % of the ore (76.11 % of the class) with a $\sum$REE content of 378.53 g/t with an extraction of $\sum$REE 43.29 % of the ore (53.37 % of the class). Based on the $\sum$REE content, these tailings should be considered an industrial product.

According to the results of enlarged laboratory tests, the yield of total gravity concentrate when enriching ore with a size of –2.5 + 0.0 mm was 14.81 %, with an average $\sum$REE content of 948.89 g/t and an $\sum$REE extraction of 45.66 %.

The yield of the total middling product of class –2.5 + 0.1 mm combined with tailings of class – 0.1 + 0.0 mm was 52.75 %, with an average $\sum$REE content of 208.5 g/t and recovery of 49.44 %.

Tailings stand out from the class –2.5 + 0.1 mm, their yield was 32.44 %, with an average $\sum$REE content of 46.44 g/t and extraction of 4.90 %.

The resulting middling product must be subjected to additional concentration in order to increase the $\sum$REE content. When combined with enrichment tailings of all size classes, their total yield is 85.19 % with an average $\sum$REE content of 146.79 g/t and a total recovery of 54.34 %.

Research has been carried out on flotation enrichment of the ore under study. The flotation scheme is shown in Fig. 2.

The scheme for carrying out flotation experiments is presented in Fig. 2.

Rare earth flotation was carried out on particle size classes –0.045 + 0 mm (clay fraction) and class –2.5 + 0.045 mm (sand fraction).

The distribution of rare earth elements by fraction is presented in Table 3.

From the results in Table 3 it is seen that the bulk of rare earth elements are in the –0.045 + 0 mm class and amount to ~60.25 %.

The results of flotation enrichment of the sand (–2.5 + + 0.045) mm fraction are presented in Table 4.

The results of flotation enrichment of the sand part show the possibility of obtaining a concentrate with a $\sum$REE content of up to 400.7 g/t with a recovery of 16.96 % of the operation.

Rare earth flotation of the clay fraction was carried out according to a scheme including desliming according to class –0.045 mm, agitation of the pulp with reagents, main flotation using IM-50 reagent and a modifier – soda and liquid glass as a collector, thickening and steaming of the rough rare earth concentrate at a temperature of 60–90 °C, re-cleaning of rough of rough rare earth concentrate at a low mass fraction of solids (5–12 %). The results of flotation enrichment of the clay fraction are presented in Table 5.

The obtained results of flotation enrichment of the clay fraction show the possibility of obtaining a concentrate with a $\sum$REE content of 590.0 g/t, with a recovery of 17.48 % of the operation.

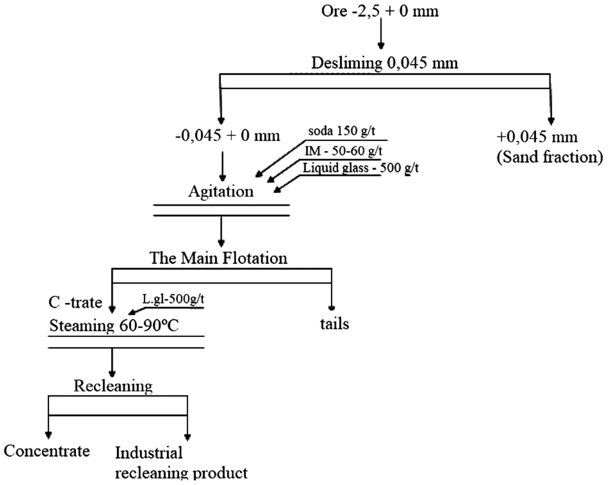

Fig. 2. Scheme of flotation experiments

Table 3

Distribution of rare earth elements by fractions

Product Name	Output, %	Content, g/t	Extraction, %
Sand fraction (–2.5 + 0.045) mm	62.8	215.0	39.75
Clay fraction (– 0.045 + 0) mm	37.2	550.0	60.25
Total	100.0	339.62	100.0

Table 4

Results of flotation enrichment of sand fraction

Product Name	Output, %		Total REE content, g/t	REE extraction, %	
	From operations	From ore		From operations	From ore
Concentrate	9.1	5.71	400.7	16.96	6.74
Industrial product	8.3	5.22	270.1	10.43	4.14
Flotation tailings	82.6	51.87	189	72.61	28.87
Total	100.0	62.8	215.0	100.0	39.75

Table 5

Results of flotation enrichment of the clay fraction

Product Name	Output, %		Total REE content, g/t	REE extraction, %	
	From operations	From ore		From operations	From ore
Concentrate	16.1	5.99	590.0	17.48	10.54
Industrial product	15.9	5.91	510	14.92	8.98
Flotation tailings	68.0	25.3	540.0	67.6	40.73
Total	100.0	37.2	543.0	100.0	60.25

The results of flotation enrichment of the sand (–2.5 + + 0.045) mm fraction are presented in Table 6.

The results of flotation enrichment of the sand part show the possibility of obtaining a concentrate with a $\sum$REE content of up to 400.7 g/t with a recovery of 16.96 % of the operation.

Since the ore, according to the results of X-ray diffraction and IR analysis, contains a significant amount of mica and feldspar, studies were carried out on the flotation extraction of feldspathic and mica minerals. Mica flotation was carried out using a cationic collector ANP (200 g/t) in an acidic environment created by sulfuric acid pH 5–5.5. Flotation tailings, after mixing with hydrofluoric acid (pH 3–4), cationic collector ANP (100 g/t), were sent to feldspathic flotation. Flotation enrichment experiments using the cationic collector ANP showed the concentration of $\sum$REE in mica concentrate up to 327 g/t, in feldspathic concentrate 314 g/t, with recovery of 16.46 and 6.22 %, respectively.

Table 6

Results of flotation enrichment of sand fraction

Product Name	Output, %		Total REE content, g/t	REE extraction, %	
	From operations	From ore		From operations	From ore
Concentrate	9.1	5.71	400.7	16.96	6.74
Industrial product	8.3	5,22	270.1	10.43	4.14
Flotation tailings	82.6	51.87	189	72,61	28.87
Total	100.0	62.8	215.0	100.0	39.75

The distribution of $\sum$REE by size class of the ore under consideration was studied. The yield of the sand fraction with a particle size of –2.5 + 0.5 mm was 62.76 %; 24.984 % of the total rare earth elements (REE) are extracted into this fraction; the yield of sludge fraction with a particle size of –0.05 + + 0.0 mm is 37.24 % with $\sum$REE 74.06 %. The weighted average content of $\sum$REE was 300.18 g/t.

The resulting gravity and flotation concentrates, as a rule, in world practice should be sent to hydrometallurgical processing in order to increase the content of the amount of rare earth metals.

Conclusions. Distribution of REE by size classes of initial ore was studied.

1. On the basis of fractional analysis, the gravity enrichability of the ore was also studied.

2. A UAGD apparatus was developed for the removal of fine flake material.

3. The results of gravitational enrichment of ore with the use of the developed vibrocentrifugal, more frequent apparatus allowed more gravitational concentrate with an average grade $\sum$REE 948.89 g/t and recovery of $\sum$REE 45.66 %.

4. The results of flotation enrichment of clay fraction of ore showed the possibility of obtaining flotation concentrate with content $\sum$RZE 590.0 g/t, with recovery of 17.48 % of the operation. Sand fraction showed the possibility of obtaining concentrate with content $\sum$RZE up to 400.7 g/t with recovery of 16.96 % of the operation.

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Переробка рідкісноземельної руди кори вивітрювання

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Швидкий розвиток високотехнологічних галузей промисловості відбувається за рахунок рідкісних і рідкісноземельних металів, що використовуються у приладобудуванні, радіоелектроніці тощо. Матеріали з них знаходять застосування насамперед у військово-промисловій та авіаційно-космічній галузях і мають стратегічне значення для держави.

Мета. Розробка технології збагачення важкозбагачуваної рідкісноземельної руди кори вивітрювання на основі комбінованої гравітаційно-флотаційної схеми збагачення.

Методика. Дослідження з переробки даної мінеральної сировини здійснювалося на основі гравітаційно-флотаційного збагачення з отриманням рідкісноземельного концентрату. Дослідження зі збагачення виконувалися на відібраній пробі руди з родовища. На підставі виконання ситового й седиментаційного аналізів вивчено розподіл суми рідкісноземельних елементів ($\sum$РЗЕ) у класах крупності руди та продуктах збагачення. Фракційним аналізом визначена гравітаційна збагачуваність руди.

Результати. Розроблено метод гравітаційного збагачення з використанням розробленого гравітаційного апарату та флотаційного збагачення піскової та глинистої фракцій досліджуваної руди. Гравітаційним збагаченням отримано концентрат зі вмістом суми рідкісноземельних елементів ($\sum$РЗЕ) 1053,76 г/т, флотаційним збагаченням глинистої фракції руди отримано концентрат зі вмістом $\sum$РЗЕ 590,0 г/т.

Наукова новизна. Для знешламлювання руди використано розроблений ультразвуковий аерогідродешламатор. Розроблена гравітаційна технологія переробки важкозбагачуваної рідкісноземельної руди кори вивітрювання з використанням віброцентробіжного чашевого апарату, що дає змогу інтенсифікувати вилучення тонкодисперсних частинок руди. Рідкісноземельна руда класу крупності –0,045 + 0 мм (глиниста фракція) і класу –2,5 + 0,045 мм (піщана фракція) піддавалася флотаційному збагаченню.

Практична значимість. Результати досліджень можуть бути використані в технологічних процесах переробки важкозбагачуваних рідкісноземельних та інших руд кори вивітрювання.

Ключові слова: *рідкісноземельна руда, клас крупності, гравітаційно-флотаційне збагачення, концентрат, відходи збагачення*

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