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On the issue of loparite ore as a source of rare-metal and rare-earth elements and increasing its dressing efficiency

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A unique source of rare-metal and rare-earth elements is loparite ore, mining and processing of which are carried out at Lovozersky Mining and Processing Plant (MPP). The improvement of the enterprise's processing figures has to do with an increase in recovery of fine-graded particles, losses with which amount to 60–70% of the plant's overall loss. An increased load on the outmoded facilities and a low efficiency of slimes preparation to dressing are the causes of the losses such as these.
The implemented investigations are based on the optimization principle, consisting in well-directed forming the products, characterized by homogeneity of the particles on some physical attribute, and timely removing them from the process.
Proposed was a method of primary slimes separating from the feed at the 1st dressing stage by means of fine screening. An influence of slimes removal onto the indexes of spiral separation at the 1st dressing stage has been investigated. There has been shown a possibility of obtaining the final tailings with loparite content of about 0.1% at the yield up to 75% from the operation feed even at this stage. The granulometric characteristics of the screening product (feeding of a slime branch) as well as loparite distributuion and grains shape have been studied.
The indicators achieved in dressing of this product according to a gravity scheme with the use of spiral sluices and table concentrators are 1.5–2 times higher than that of processing the plant slimes of current production.
There has been developed a process flowsheet for primary slimes gravity processing, which comprise spiral separation at a sluice, cleaning of the obtained products on table concentrators and centrifugal concentrator. According to the proposed scheme, the expected loparite recovery into gravitation concentrate will be about 75% with loparite content not less than 51%. Overall loss with tailings will amount to 25% with loparite content of no more than 0.6%.

Key words: loparite, slimes, gravity concentration, fine screening, grain size grade, recovery, spiral sluice, concentration table, concentrate, tails.

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Introduction

Situated on Kola Peninsula Lovozersky MPP is carried out mining and processing of ores, the main ore mineral of which is loparite, comprising oxides of titanium, niobium, tantalum and some rare-earth elements (with predominance of oxides of cerium, lanthanum, strontium, thorium). Ore dressing at the plant is fulfilled according to the gravity scheme with gravity concentrate finishing to the qualified product (95% of loparite) by magnetic and electrical separation [1, 2]. The throughout loparite extraction doesn't exceed 80%. The plant operation analysis has shown that the main losses are related to the particles of the size less than 0.074 mm and reach 13% with loparite content of 1.7%, which makes 60–70 % of overall loss. Among primary reasons of the valuable component losses with slimes it is possible to emphasize the following:

1. Usage of the outdated equipment and an increased load on it.

2. Low efficiency of slimes preparation to dressing. At the plant, the existed special slime branch is fed by discharge of dehydrating hydrocyclones and hydraulic classifiers, where the small particles of light minerals are predominantly passed to. The main bulk of fine particles of a heavy mineral therewith fall into the sands products and after the whole cycle of cleaner operations on spiral separators and table concentrators are for the most part lost with tails.

As early as the 1980-ies, the leading institutes of the country (the Federal State Research and design institute of rare metal industry (Giredmet), the All-Union scientific research and design institute for mechanical processing of minerals (Mekhanobr), Mining institute of the Kola Science Centre of the Russian Academy of Sciences) have been deeply involved in attacking the problem of increasing the loparite fine particles recovery to concentrate at Lovozersky MPP enterprises. Investigations have been implemented in different directions with the use of flotation, gravity and magnetic separation methods.

Slimes processing by flotation technology has provided the highest figures of beneficiation; recovery to qualified loparite concentrate (94.5% of loparite) has been about 70-80%. However, an exclusive application of flotation technology to production has been restrained by a necessity to build up a shop for reagents preparation and a shop for effluent neutralization, which essentially raised the price of the project. Use of a combined technology with preliminary concentration by gravity and magnetic beneficiation methods followed by finishing by flotation has allowed decreasing the costs. The collapse of the Soviet Union and consequent perestroika (restructuring) have precluded none of the projects form realization, and the plant itself has been on the verge of survival.

Today, in connection with the changed rare-earth metals market conditions, a reviving of this industry in Russia is one of the most important tasks of domestic economy and the matter of the rare-metal ores beneficiation technology betterment is the topical problem.

Theoretical considerations on the issue

The research on a loparite ore separation mechanism carried out in the Mining institute of the Kola Science Centre of the Russian Academy of Sciences (KSC RAS) has enabled one to formulate an optimization principle, consisting in well-directed forming not only the exposed mineral but also the other products, characterized by homogeneity of the particles on some physical attribute and timely removing them from the process [3]. At the 1st stage, one of the main tasks in the process of ore preparation to further beneficiation is obtaining the final tailings, which should be also attributed as the above mentioned products.

During spiral separation, an essential part of slimes falls within a tail zone of a spiral stream and then is sent to the next beneficiation stage along with tails. Investigating the solid phase particles distribution across the width and the length of a spiral stream has made it possible to develop a means of an automated slimes withdrawal out of the stream of a spiral separator, based on the essential crushed ore density difference in the grained and slime zones. As this takes place, the fine-grained component removal at the end of the first turn of a spiral separator assists in obtaining the final tailings already at the 1st stage of beneficiation, since a zone with dump loparite content is being formed at the separator outlet in the middle part of a spiral stream. The separated slime stream is directed to the single concentration branch. Such a beneficiation method is protected by certificate of authorship [4] and has standed the commercial tests, but its realization has been restrained by complexity of automated control of the proposed process.

The advent of fine screens at the present-day mineral processing equipment market has opened up fresh opportunities for increasing the deep concentration efficiency. Substitution of hydraulic classifiers, which separates particles by an equal-setting factor, by the screens, separating them by coarseness directly on a sieve, permits one to lessen separation error and to ensure maximum output of productive classes thus bettering both qualitative and quantitative indicators of beneficiation operations. There exist a lot of positive examples of such screens application for various ores concentration on both domestic and foreign concentrating mills [5–8]. In the present investigations there are considered a possibility of using fine screening at the 1st stage of beneficiation for the purpose of primary slimes removal from the spiral separation feeding and its influence on separation indicators.

Use of an obsolete equipment at the operating mill is a factor of no small importance with relation to noneffective slime branch functioning. Moreover, the same apparatus are used for both granular and slime beneficiation, namely SSO-3-1500 (BCP-3-1500) spiral separators and TC-22 (CK-22) table concentrators.

For more efficient fine raw material beneficiation the proper equipment should be used – slime table concentrators and spiral machines. It should be noticed that the slime-sized material concentration process by spiral separation should be carried out at a laminar and the first transition periods of a water stream (Re < 1000), when turbulent velocity components either are absolutely absent, either are present, but in a weak state. Otherwise, particles of the valuable mineral would transform to a suspension state and wouldn't be extracted. The conditions required for the fine-graded products separation may be supported by spiral sluices with a chute cross-section shaped as a weakly slopping curve. These are precisely the ones which have been used for pursuance of research.

Procedure of studies

Investigations have been carried out on enlarged laboratory plant. Gravity method, which is used at operating concentrating mill, has been used as a principal separation method.

Prior to gravity benefitiation, the source ore of current production has been pound in a rod mill up to coarseness, incoming to the first stage (–1 mm) and corresponding to the upper size of loparite impregnation [9]. The grinded product has been supplied to screening on a sieve by size of 0.16 mm. Yield of the fraction with grain size grade of –0.16+0 mm has been amount to 41% and it has served as a feed for slime branch.

A SSO-500 spiral separator, instrumented at the output by a stream clipper to provide separation of the input stream into 8 close-cut fractions, has been used for the grainy product beneficiation.

Slime beneficiation has been implemented on a SS-500 spiral sluice. In a series of preliminary experiments there has been determined an optimum regime for the investigated material separation, corresponding to feeding density of 30–40% and productivity of 150 kg/h. The device has been fed through a conditioner, with the help of which the set points of crushed ore density and separator productivity has been ensured.

For cleaning the spiral separation concentrate an TC-0.5 table concentrator has been used in a slime mode, providing generation of a good choice of separation products.

The concentration products tests have been carried out by particle size analysis and mineralogical method; loparite detection has been fulfilled on an ARL Advant'X spectometer.

Discussion of results

The slime withdrawal influence on the spiral separation process at the first beneficiation stage has been estimated during implementation of comparative experiments with feeding of differing quality (Fig. 1). In the former case the separator has been fed by the product after pounding to coarseness of –1+0 mm, in the latter – after preliminary screening with coarseness of –1.0+0.16 mm. A stream clipper has divided the separator output stream into 8 products, each being analyzed separately.

In the course of the investigations it has been found the following:

- Removal of a slime component out of the spiral stream allows one to remove up to 75% of the product incoming to separator (scheme in Fig. 1, *b*) into the dump already at the first beneficiation stage. At that, the tailings zone is situated immediately beyond the middlings and its removal out of the process should present no problems. During the work in accordance with the scheme in Fig. 1, *a*, the dump product is also present, its yield makes up 26% of the separator feeding, but it is situated between middlings and slimes that's why it is quite difficult to lead it out to a separate stream.
- At the operating concentrating mill, the middlings revert to a head of the first beneficiation stage, therefore lessening the middlings quantity from 46% by the scheme in Fig. 1, *a* to 17 % by the scheme in Fig. 1, *b* will allow to essentially decrease circulating load.
- A fine-grained fraction removal out of feeding of the operation practically makes it possible to increase the valuable component recovery into the spiral separation concentrate from 54 up to 90% with corresponding enlargement of beneficiation efficiency from 49 to 84%.

It is obvious that slimes removal out of the spiral separation feeding is favorable to improving the beneficiation indicators.

Fraction with coarseness of –0.16+0 mm has served as a feeding of a slime branch (Fig. 1, *b*). About 60% of the product content is represented by classes more coarse than 0.045 mm, and they contain more than 65% of the valuable mineral, which is a favorable factor for gravity separation. Share of the most hard-torecover class of –0.028 mm constitutes an amount in the region of 20% and about 15% of loparite is contained there (Fig. 2).

Technological scheme of the fine-graded fraction (–0.16+0 mm) beneficiation has included two stages of screw separation (SS) and two cleaner operations on a table concentrator (TC) (Fig. 3).

During the first operation of spiral separation (SS-1) the emphasis has been on the concentrate obtaining (concentrate level was 6.4, loparite content was more than 15%) and removal from the process the finest particles (share of the class with coarseness of –0.028 mm in slime product has exceeded 40%). The middlings output during SS-1 has exceeded 60%, therefore its cleaning has been also fulfilled on a screw sluice (SS-2), at that the main task has lied in obtaining the final tailings (<0.5% of loparite): the tailings yield has formed about 45% with the valuable component content of 0.56% and extraction of 10.6%.

The difficulty of obtaining the final tailings (<0.5%) is partly connected with a shape of loparite grains: thought the mineral exists in a free form, it is represented by variously shaped wreckage. Table contains estimation of

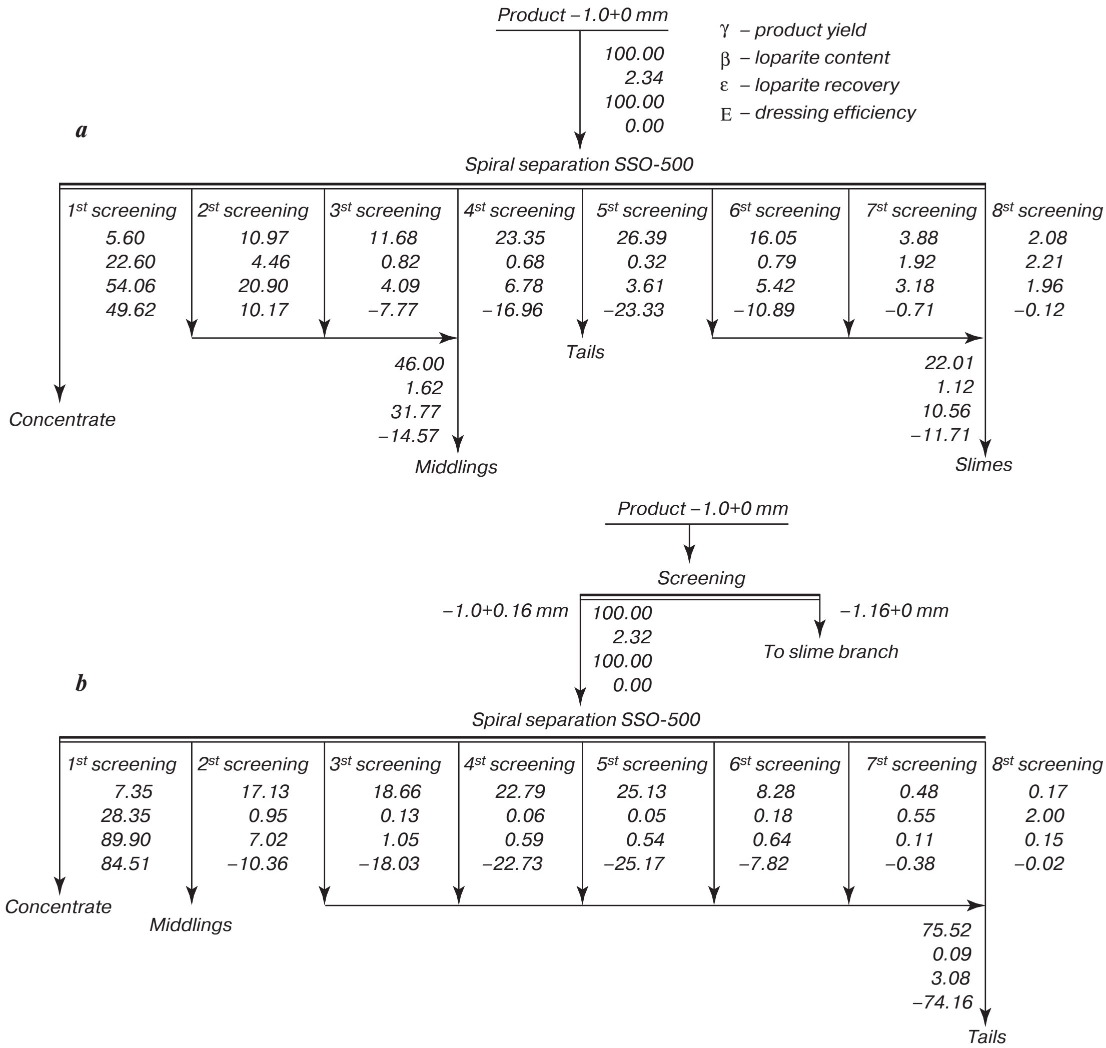

Fig. 1. The screw separation indices on feeding with an ordinary (*a*) and desliming (*b*) product

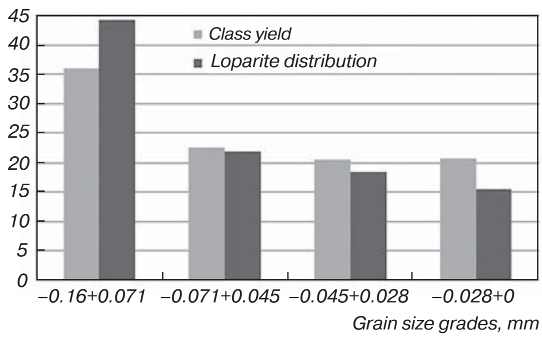

Fig. 2. The slime branch feeding characteristics

the shape of mineral grains, fulfilled by determining an oblongness coefficient as a ratio of the smallest particle size to the greatest: $\psi_y = L_{min}/L_{max}$.

Loparit is for the most part represented by grains with $\psi_y = 0.6–0.8$, in other words, it has various uneven shape, sometimes the pointed one. The number of such particles in all size grades is practically the same and equals to 50–60%. The particles of mineral with oblongness coefficient less than 0.6 are greatly elongated, some of them have

Loparite grains distribution according to oblongness coefficient in narrow grain size grades of the slime branch feeding

Grain size grade, mm	Distribution of loparite grains, %			Sum
	$\psi_y < 0.6$	$\psi_y = 0.6–0.8$	$\psi_y > 0.8$	
–0.16+0.1	13	57	30	100
–0.1+0.071	22	59	20	100
–0.071+0.045	35	50	14	100
–0.045+0	40	47	13	100

a distinctive crescent shape. Such grains are the most arduous object for gravity extraction. As a size grade is lessening, their number is rising three-fold from 13% in a size grade of –0.16+0.1 mm to 40% in a size grade of –0.045+0 mm. Loparite grains with c $\psi_y > 0.8$ are also characterized by shape diversity from a regular triangle to almost a ball, but they also fit the general tendency towards uneven and pointed edges. As a size grade is lessening, their number is gradually decreasing from 30 to 13%.

It should be pointed out that an oblongness coefficient doesn't take into account thickness of particles which also varies in perceptible limits: from practically ball-shaped to the flat ones. It is known from the literature, that the drop rate of particles in restrained conditions strongly depends upon their shape. At that, the roundish particles fall faster than the flat ones; the elongated particles have the highest drop rate; the rate of movement depends upon their sharpness and is higher in case of a drop tip down [10].

The process of stratification on a spiral chute is qualified as an intricate mass transfer processes with extremely varied movement of the particle under consideration in the intergrain channels. Therefore, grains of loparite being represented by so manifold shapes are distributed over the whole width of the chute and move over the chute of separator along various trajectories, often unpredictable. As a rule, the most coarse-grained and ball-shaped particles tend to pass into concentrate first, and check and cleaner operations should be organized to extract more small-sized and elongated particles of loparite.

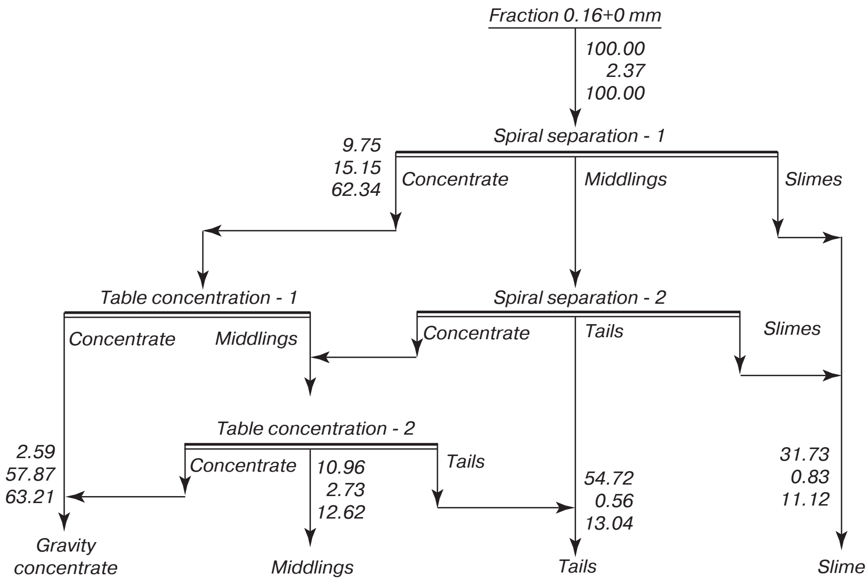

Fig. 3. The fine-grained loparite product beneficiation scheme

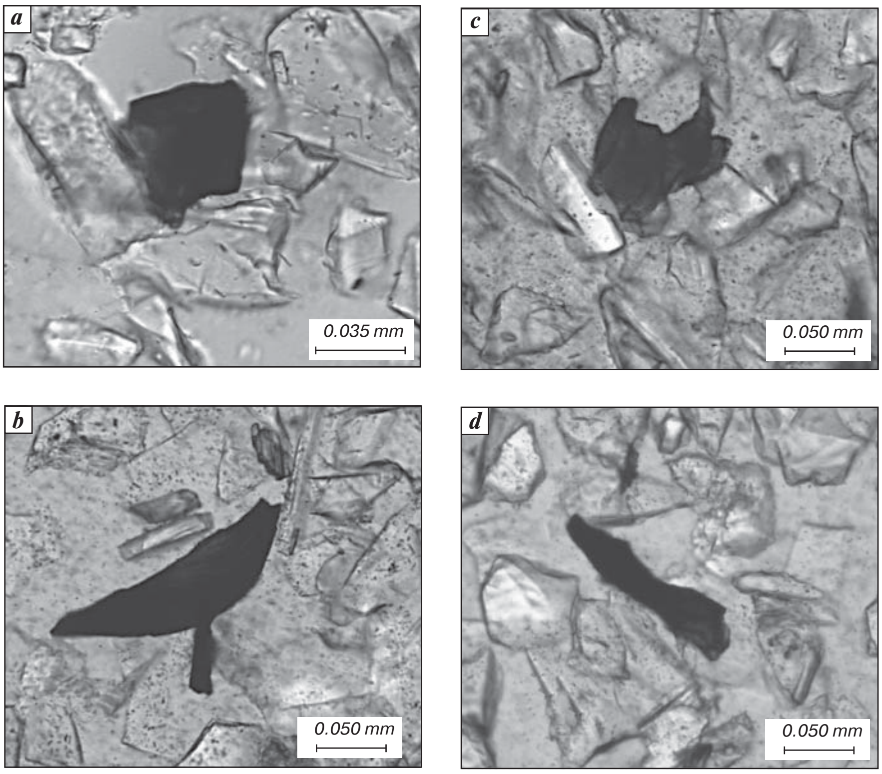

Fig. 4. Morphological varieties of loparite grains:
a — flat, close to isometric; *b* — crescent; *c* — cogged; *d* — spear-shaped

The concentration products mineralogical study has confirmed that loparite tailing loss in all size grades are connected either with flat grains (Fig. 4, *a*), either with various elongated and curved fine grades (Fig. 4, *b–d*). Overall loss in gravity scheme has amounted to 24.2%.

Loparite content in gravity concentrate has been more than 57% and recovery has been over 63%. The achieved results of primary slimes concentration significantly exceeds indicators, obtained by gravity concentration of the plant slimes of current production: gravity concentrate with the yield of 2%, recovery of 40.5% with the valuable component content of 29% was obtained of the product with initial loparite content of 1.44% [11, 12]. An essential recovery growth (by 23%) and raising the content of valuable component in gravity concentrate almost by 30% may be undoubtedly connected with the changes in quality of the slime branch feeding.

All final products obtained by gravity scheme (Fig. 3) have been analyzed by narrow size grades (Fig. 5). Loparite particles more coarse-grained than 0.045 mm have been most completely extracted to concentrate by gravity method; mineral extraction to a size grade has started from 68% for coarseness of –0.071+0.045 mm and has reached 91% for coarseness –0.16+0.1 mm. Content of the finest size grades of –0.028 mm has been the least with mineral extraction of 5% only. It have been the finest size grades with which the main losses of the mineral are bound up; about 40% of loparite with coarseness of –0.028 mm are wasted tails, about 50% of it remain in slimes.

For additional recovery of the mineral of such coarsenees a polygradient separator and Falcon concentrator were used. In both cases losses with final slime product has diminished by 2–3% and the valuable component content has reduced from 0.83 to 0.6–0.7%. Loparite content in concentration products returnable to beneficiation process has contained 3.1% on Falcon concentrator and 1.7% on polygradient separator. Such a difference is stipulated by the fact that practically all aegirite has passed into magnetic fraction of the polygradient separator due to more strong magnetic properties than that of loparite. That's why aegirite yield has been almost 3 times higher than on Falcon concentrator. Being compared with polygradient separation, centrifugal concentrator for slime fraction beneficiation seems to be preferable: with an equal content in dump product, more rich concentrate has been obtained and amount of the product returnable to beneficiation process has been substantially smaller.

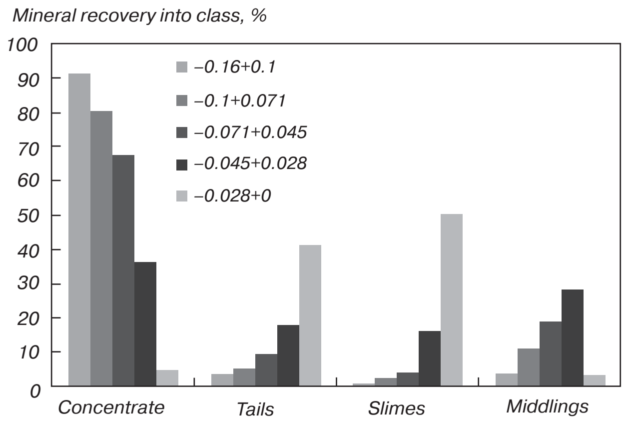

Fig. 5. The loparite balance distribution by size grades in the products of gravity beneficiation

Gravity middlings represent a reserve for increasing the recovery. Size grades with coarseness less than 0.028 mm are practically absent in it and all the other ones are present in approximately equal amounts. About 20% of loparite, containing in a size grade of –0.071+0.045 mm, and 30% of loparite, containing in a size grade of –0.045+0.028 mm, pass into the middlings (Fig. 5). Return of this product into recycle or cleaning at a separate operation will allow rising completeness of the valuable component extraction.

In that way, the recommended loparite slimes gravity beneficiation scheme (Fig. 6) comprises the fine screening operation by the size grade 0.16 mm, two stages of screw separation on a sluice, cleaning of the obtained products on table concentrators, lopparite additional recovery from gravity slimes on centrifugal concentrator. An expected loparite recovery to gravity concentrate will be about 75% with loparite content of about 51% and output of 3.4%. Overall loss with tailings will amount to 25% with loparite content in them of no more than 0.6%.

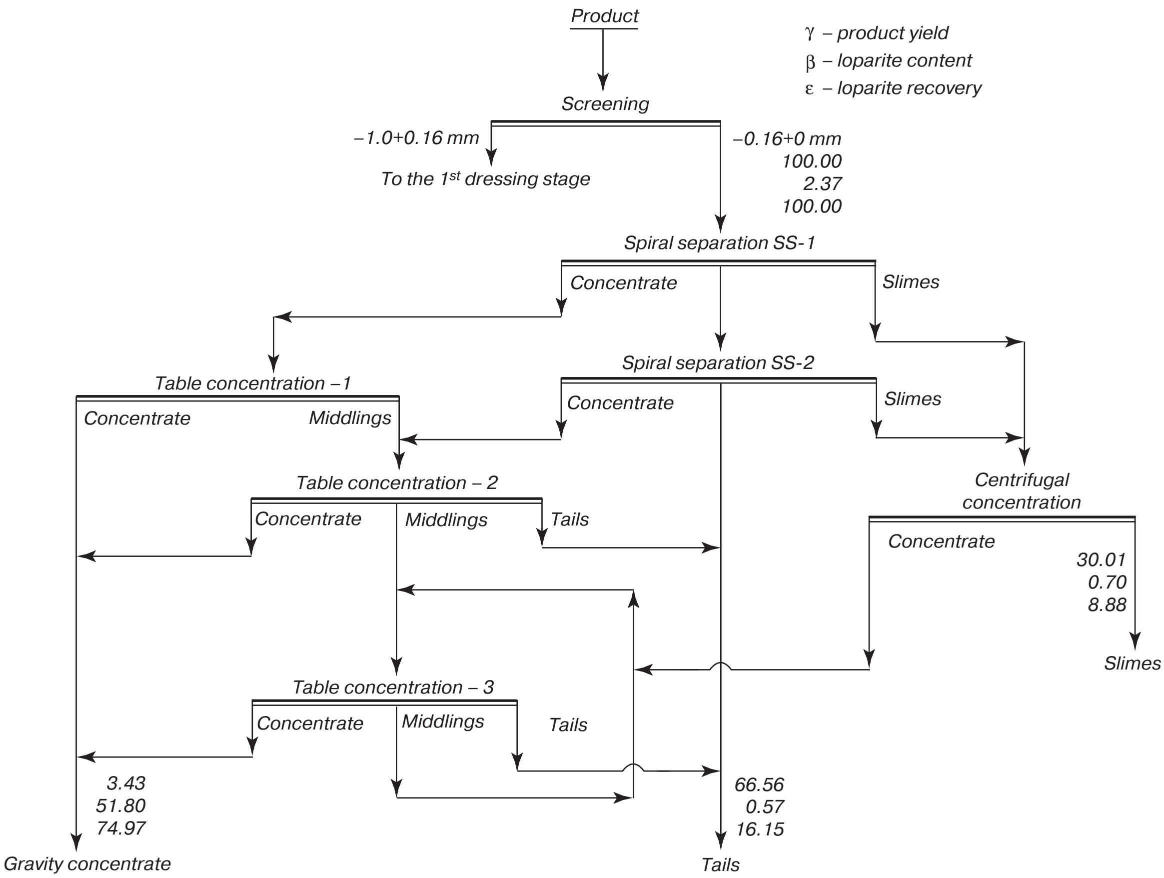

Fig. 6. The recommended gravity scheme of the loparite slimes beneficiation

Conclusion

The implemented investigations are based on the optimization principle, consisting in well-directed forming the products, characterized by the homogeneity of the particles on some physical attribute, and timely removing them from the process. Proposed was a method of primary slimes separating from the feed at the 1st dressing stage by the means of fine screening.

It has been found experimentally that removal of a fine-graded fraction of –0.16 mm from the feed of spiral separators at the 1st beneficiation stage allows one to obtain the final tailings with loparite content about 0.1% with the yield up to 75% of the operation feeding. Bedsides, the middling amount is lessened as compared with an ordinary separation mode. Under conditions of production this will lead to decrease of circulating load on equipment.

Use of fine screening makes a beneficial effect on the slime branch feeding, namely, a –0.16-mm fraction have quite regular granulometric composition, and more than 65% of loparite are located in the grades more coarse than 0.045 mm, recovery of which is still possible by gravity methods.

Research on the shape of loparite grains has showed that whole grains of the mineral are practically absent in a slime fraction. On the whole, the mineral is represented by wreckage of various types with an oblongness coefficient of 0.6–0.75; in other words, the particles are of various uneven shapes, sometimes pointed, for efficient extraction of which the check and cleaner operations should be organized.

The indicators, achieved in the process of a 0.16-mm fraction beneficiation by gravity scheme with the use of spiral sluices and table concentrators are 1.5–2 times higher than that of processing the plant slimes of current production. It has been found that the main losses of loparite are related with particles less than 0.028 mm. The grains of the mineral are of various comminuted shape and it is proposed to use centrifugal concentration for additional recovery.

Developed is a technological scheme of the fine-graded loparite product gravity processing, comprising two stages of spiral separation at a sluice, cleaner of the obtained products on table concentrators, and the valuable component additional recovery from gravity slimes on centrifugal concentrator. The scheme is fed by the slimes, withdrawn form the feed of the 1st beneficiation stage. According to the proposed scheme, an expected loparite recovery to gravity concentrate will be about 75% with loparite content not less than 51.8%. Overall loss with tailings will amount to 25% with loparite content in them of no more than 0.6%.

The implemented investigations provide strong evidence that fine screening is expedient to be used for increasing the efficiency of loparite ores dressing as a main source of rare-metal and rare-earth elements.

These investigations have been carried out in accordance with the Development program of the Federal state budgetary educational institution of higher education "Murmansk State Arctic University" and the Program of fundamental scientific research of state academies of science for 2013–2020 (Subsection 74 "The interior of the Earth integrated development and preservation, innovation processes of mineral deposits mining and minerals fine processing").

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