Prospect of preliminary beneficiation use in the poor tungsten ores processing practice

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Base tungsten ores involving into processing stipulates radically new strategy of their beneficiation. In contrast to the existing technologies, it allows for preliminary concentration (pre-concentration) of valuable component in the run-of-mine ore by use of radiometric methods of separation (RMS). Examined in the paper is a possibility in principal to separate base scheelite ores by use of different kinds of radiometric separation: *X*-ray adsorption method (XRT) on TOMRA Sorting GmbH (Germany) equipment and *X*-ray radiometric method (XRF) on RADOS Ltd. (ООО "РАДОС») equipment.

Results of the fulfilled research show high efficiency of the tungsten ore pre-concentration by both RMS methods. Thus, application of XRT method will permit to increase by the factor of 2.3 content of WO_3 in combined separation concentrate and riddling which is a feeding of subsequent flotation treatment as well as to provide high processing characteristics. Content increment in separation concentrates is connected with improvement of material composition of the primary ores owing to removal of sizeable rock amount and to growth of the ore material proportion.

Flotation of source samples with WO_3 content of 0.24–0.28% gives no scheelite concentrates of conditioned quality even in narrow terms of the rough concentrates finishing (liquid glass expenditure in steaming is 6–20 kg/t, residual concentration is 4.5–6.2%). Depending on oxidation level of mineral surfaces (limonite films formation and deeper limonite penetration in cracks) as well as ore contrast, extraction into final scheelite concentrate varies in a wide range and is present between 37(41) and 64.8%.

In flotation of separation concentrates with WO_3 content of 0.6–1.8% liquid glass consumption in finishing decreases up to 3.8–4.6 kg/t; in so doing quality of scheelite concentrate is 50–70%, extraction makes 83.5–89.3%.

Skarn ores of Vostok-2 deposit contain sulphide mineral complex: chalcopyrite, pyrrhotite, arseno-pyrite. Ores pre-concentration leads to some rise of copper (0.13–0.2%) and arsenic (0.1–0.44%) contents in separation concentrates. As a result of separation concentrates flotation, copper extraction increased by 10%, but obtained concentrate is ill-conditioned through arsenic as the main detrimental impurity.

Ore pre-concentration technology application at breaking and secondary crushing stages will allow to cut down operating costs, associated with expensive processes of grinding of the total volume of material meant for deep concentration stages. Use of RMS technologies will allow not only to reduce economic expenses but to lessen ecological load in the region owing to contraction of volume of filler tailing ponds. Lump separation tails may be used as a stowage material of mine waste, providing a complementary step in costs reduction for getting separation concentrates.

Thus, RMS technologies introduction into the process line of an enterprise with consideration for its declared advantages will ensure it a fundamental efficiency increasing in regard to use of subsoil and beneficiation. In the long-term prospect, these technologies will provide the enterprise with much more competitiveness than the other ones.

Key words: tungsten ore, scheelite, radiometric separation methods (RSM), *X*-ray adsorption separation (XRT), *X*-ray radiometric (roentgen fluorescent, XRF) separation, pre-concentration.

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In ore mining and processing industry one observes tendency of progressive deterioration of the ore resources quality over entire mineral spectrum, including tungsten. Decrease of the tungstic oxide content in ore, expansion of expolited deposits mining depth, increased part of ill-conditioned ore through detrimental impurities and dilution by rock require fundamentally new technological decisions. In regard of this, study of possibility of preliminary concentration of ores with diverse material mixture at crushing operations stage takes on great significance.

Methods based on interaction of different types of radiation with material are the most promising in this field. In the science practice of our country such beneficiation methods have taken the name of "radiometric separation methods" (RSM). Prominent Russian scientists and engineers have contributed significantly to the development of radiometric beneficiation theory and elaboration of the apparatus design philosophy. Among them are G. R. Golbek, V. A. Mokrousov, V. A. Lileev, O. A. Arkhipov, V. V. Novikov, B. S. Lagov, V. I. Revnivtsev, E. P. Leman, A. P. Tatarnikov, B. N. Kravets, E. G. Litvintsev, E. N. Gulin, L. Tch. Pukhalskyy, Yu. O. Fedorov, S. V. Tereshchenko and others. They have proved feasibility of using different radiation types in a wide energy range (from nuclear radiation to radio waves) for separating solid mineral raw material of different matter composition [1–6].

Radiometric separators' principle of operation and practice of use as applied to different ores is described in [1, 4, 7]. Presently, photometric, *X*-ray radiometric, *X*-ray luminescent and *X*-ray adsorption methods are the most-used among all known RSM techniques [1].

While ore blending is already widely used at operating plants, improvement of process flowsheets of poor lean ores treatment using radiometric separation technique as the base is the topical problem aimed to optimization of ore-preparation processes and efficient subsoil resources management [8–10]. Interest in radiometric concentration method and its possibilities has been considerably stimulated by tasks of mineral raw materials complex processing. Profitability of poor and lean ores of such deposits as Vostok-2 and Lermonovskoe as well as Skrytoe deposit in prospect, in many respects depends on applying an effective ore pre-concentration technology already at breaking and secondary crushing stages. The said interest is also keeping up by steady technical improvement of corresponding apparatus by both foreign and domestic manufacturers. This aspect is the most completely covered in the work of A. S. Kobzev [11]. Of all foreign papers the ones prepared by specialists of RWTH Aachen University are worthy of being noted. There are reviewed modern apparatuses of radiometric beneficiation and practice of radiometric beneficiation technologies usage as well as an economic evaluation of separators use on ores of different grades is also given [12, 13].

The present paper offers results of the tungsten ore of Vostok-2 and Skrytoe deposits examination by *X*-ray adsorption methods on TOMRA Sorting equipment and by *X*-ray radiometric separation on RADOS equipment.

The *X*-ray adsorption method (XRT) is based on the *X*-radiation flow difference between rock and ore lumps. This method is a penetrating one, thus it allows to discover lumps with hidden ore minerals [1, 12].

X-ray radiometric (roentgen fluorescent or XRF) method is based on registration of characteristic *X*-radiation of atoms of definable elements forming a part of the rocks, which has been excited by *X*-ray tubes or gamma radiation sources.

Applying technology of preliminary concentration will allow an enterprise to increase a valuable component content in the ore, sent to the deep concentration stages, and in doing so to essentially decrease its volume as well as to include into the mineral resources some ores considered unprofitable yet.

In the world practice, tungsten ores preliminary concentration with use of radiometric methods has been had a wide distribution in Australia and Austria for the ore processing schemes perfection.

In Australia, the *X*-ray adsorption method made it possible to obtain a beneficiated ore with 0.44% WO_3 and 97% extraction (33% yield of the concentrate) in concentrating 450 thousand tons per year of the ore with WO_3 amount of 0.15%, primary content. The ore feeding to separation is preliminary graded to size for machine classes as –100+40 mm, –40+20 mm, –20+10 mm and –10+5 mm. Plant capacity is 80–15 t/h depending on material size [14].

In Austria, the refining plant St. Martin of Wolfram Bergbau und hütten AG company uses the *X*-ray adsorption method for the concentrate with 0.37% WO_3 originated from the mining operations in Mittersill deposit (Salzburg). The result is as follows: 55.5% yield of the separation concentrate with 0.50–0.55% WO_3 and 94% recovery; separation tails contain 0.035% WO_3. Separation is feeded by –24+16 mm machine size grade. Plant capacity is 15–25 t/h. The company plans to increase size in use up to 32 mm and capacity up to 30 t/h [15].

Material composition of low-grade ores under consideration of Primorye Territory deposits is tabulated in Table 1.

Ores are of the same kind by mineral composition with significant content variation of tiff, pyrrhotite, pyroxene, amphibole, biotite and mica represented by muscovite. Tiff and mica are the minerals which make difficulties for subsequent ore flotation. Chemical composition of samples on which there were fulfilled investigations on separation and flotation is presented in Table 2. The samples assayed 97–98% scheelite according to the phase analysis.

Ore of Sample-1, in spite of low tungstic oxide content, is an exceptionally contrasting material. Scheelite-quarz and scheelite-sulphide types possess 10.9% at yield and 79.1% at metal distribution, WO_3 content in these types come to 0.94–5.55%, content in scarned hornfelses and diluent rock makes 0.07–0.05%. Oxidezied rocks (14.9% yeild) are represented by quartzites, sandstones; gritstones, rarely hornfelses, massive quartz, granodiorites with deep extent of surface oxidation. Limonite fragments are uncommon and amount to 3–5%.

High grade ore of Sample-2 in addition to the above mentioned types includes skarn scheelite-sulphide type. At that, total yield of high grade ore came to 15% with WO_3 content of 2.09%, Cu content of 0.70% as well as 75.9% of scheelite and 61.2% of chalcopyrite extraction. Vein-disseminated ore accounts for 39%, content of WO_3 is 0.15%, content of Cu is 0.11%, scheelite extraction makes 14.2%, chalcopyrite extraction comes to 25.2%. Gangue accounts for 42.5%, content of WO_3 is 0.07%, content of Cu is 0.004%. Sample-2 also represents contrasting ores due to ore types distribution. Scheelite occurs in quartz and sulphide thin threads and small clusters, grain size varies from 1(0.5) cm to 0.1(0.15) mm. In the vein-disseminated ores it is possible to observe an extremely small dispersed impregnation about 0.05–0.10 mm.

Sample-3 is represented by scheelite-carbonate ore type from Skrytoe deposit. Aposkarn mineralization type is applied to silicificated rocks: amphibole and pyroxene hornfelses which are greatly modified by secondary processes of carbonate formation and chloritization. Samples of rock have been possessing fine-grained constitution, massive, sometimes maculose or ribboned texture and horny structure. Mineral composition and texture-structure features of Sample-4 are close to that of Sample-3, but the former differs by quantitative proportion of minerals as well as slightly different ratio of textures and structures. Scheelite in samples is in a form of inclusions in quarz, amphiboles (tremolite), wollastonite, pyroxenes (diopside). Scheelite impregnation is extremely rare, nonuniform, in the form of thin interrupted threads and clusters with size from 0.001 to 0.2(0.4) mm.

To estimate a potential of radiometric technologies introducing into the working scheme of scheelite ores beneficiation, study of separation by use of two different technologies – XRT and XRF – has been conducted. Sampling points and equipment of the study are presented in Table 3.

Table 1
Main minerals of tungsten deposits low-grade ores

Minerals	Ore types by deposits				
	Skrytoe		Vostok-2		Lermontovskoe
	Scheelit carbonate	Scheelite quarzamphibole	Scheelite skarn	Scheelite horny	Scheelite skarn horny
Scheelite	0.6	0.5	0.5–0.8	0.1–0.3	0.5–0.7
Apatite	0.9	0.9	1.0–2.0	1.5–3.5	1.0–1.5
Tiff	18.0	10.0	8.0	12.0	3–5
Pyrrhotite	0.5	5	7.0–13.0	2.0–3.0	1–2
Chalcopyrite	Rare value	Rare value	0.3–0.5	0.2–0.4	Rare value
Arseno-pyrite	0.1	0.3	0.3	0.1–0.2	0.3–0.5
Pyrite	–	–	0.8	3.0	0.5–1.0
Magnetite	0.2	Unit value	Unit value	Unit value	–
Galena	–	–	Rare value	Rare value	–
Black jack	Rare value	Rare value	Rare value	Rare value	–
Iron hydroxides	Unit value	2.0	1.0	2.0	10–12
Quartz plagioclase	29.7	29.0	31–38	33–44	40–45
Pyroxenes	18.4	15.6	27.0	14.0	10–11
Amphiboles	17.1	10.4	4.2	4.0	3–4
Epidote	Unit value	0.5	0.1–0.3	0.6	Rare value
Garnet	Unit value	0.2	0.1	Rare value	1–2
Fluorite	1.4	1	Rare value	Unit value	Unit value
Biotite	–	–	3.0–5.0	5.0–15.0	2–3
Peach	7.5	11.6	0.5	1.7	Rare value
Muscovite (sericite)	4.2	8.3	2.5	5.0	10–11

Table 2
Chemical composition of separation feeding samples

Sample name	Sample type	Deposit	Percentage					
			WO_3	P	$CaCO_3$	Cu	As	S
Sample-1	Oxidized lean material	Vostok-2	0.24	0.15	1.95	0.04	0.26	0.73
Sample-2	Current production	Vostok-2	0.28	0.17	6.68	0.13	0.10	2.97
Sample-3	Carbonate ore	Skrytoe	0.34	0.13	14.6	0.01	0.17	0.49
Sample-4	Amphibole ore	Skrytoe	0.27	0.15	9.18	0.08	0.30	1.75

Table 3
Process characteristic of experiment conditions

Sample name	Sampling points	D_{max} of a piece, mm	Separation grade	Separator type
Sample 1-1	Belt conveyor of jaw cruhser discharge (8 t)	150	Sizing of half a sample 100–150, 50–100, 30–50 mm; laboratory re-crushing of half a sample 20–50, 10–20 mm	SRF 2-200
Sample 1-2	Sample mass 1 t		Post-crushing, sizing 20–50, 20–12, 12–6 mm	COM Tertiary XRT
Sample 2	Belt conveyor of secondary crushing cruhser discharge (1 t)	75	Sizing 30–70, 12–30, 5–12 mm; selection of lump material (by 100 pieces)	COM Tertiary XRT
Sample 3, 4	Core material		Laboratory crushing and sizing to classes 50–150, 25–50 mm	SRF 2-150

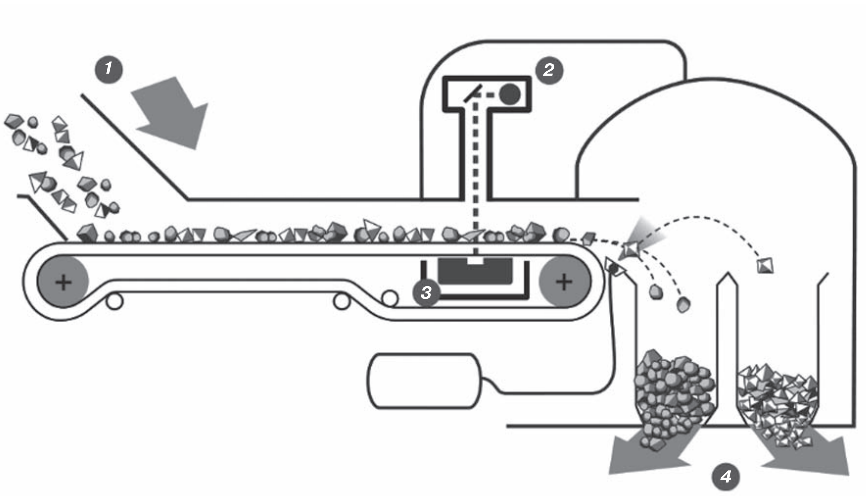
Tests of Samples 1-1, 3 and 4 have been carried out at SRF 2-150 (СРФ 2-150) and SRF 2-200 (СРФ 2-200) experimental-industrial *X*-ray radiometric separators, which are able to separate the ore within the size range from 10 to 200 mm and represent complete analogues of industrial separators (Technical Conditions ТУ 3132-015-058202239–2001 RADOS Ltd).

Tests of Samples 1-2 and 2 have been carried out in Germany in TOMRA Sorting Test centre at a COM Tertiary XRT separator [16].

TOMRA Sorting equipment allows to carry out a tungsten ore-dressing within the size range from 6 to 50 mm. Depending on separation tasks and source feeding size, maximum performance of one separator with the belt width of 1,200 mm amounts to 50 t/h. For separation it is recommended to feed classified by size grades material with gradation factor no more than 3. Principle of operation of a COM Tertiary XRT separator is the following: source material is feeded by vibrating feeder to a transport nodal point (conveyer belt) of separator, over which the ore is feeded to irradiation and registration zone. Obtained in so doing *X*-ray photographs of pieces are processed on computer of the separator by special algorithm, analyzed and then compared with preliminary specified threshold (limit) values. At the threshold crossing, computer gives the signal to an actuating mechanism, which picks out a piece from the motion path of general stream by pneumatic sprayers. The separator functioning scheme is shown in section in the Figure.

Discharge product of the SMD-110R (СМД-110Р) jaw crusher has been served as a feed for the SRF 2-150 (200) (СРФ 2-150(200)) separators; size of maximal piece in discharge is 150 mm, in a crushing feed — 500 mm. Discharge product of the KSD-1200 Gr (КСД-1200Гр) secondary crushing cone crusher has been served as a feed for the COM Tertiary XRT separator; size of maximal piece in discharge is 70 mm, in a crushing feed — 150 mm. Size chart of industrial crushed material after breaking and secondary crushing stages is represented.

According to the ore distribution by size grades, part of machine size grade in the feed of the SRF 2-200 separator have made 72.1%, the remained 27.9% of size –20+0 mm have comprised a screenings. As separated ore reduction range grows and size lessens, the COM Tertiary XRT equipment has achieved practically the same level of the oxidized inseparable lean ore as 26.8% (size grade –6+0 mm). Separation of size grade –12+6 mm from the secondary crushing product is complicated due to formation of aggregates of hardly-screened grains and fine material with size of –0.25+0 mm. Sizing has been fulfilled in laboratory environment after material drying and dry screening procedure.



A COM Tertiary XRT separator functioning scheme:
1 — a source material feeding; *2* — *X*-ray emitter; *3* — *X*-ray camera; *4* — separation camera

In the present paper it is carried out a comparison of SRF 2-200 and COM Tertiary XRT separation effectiveness on separation of one ore sample (Samples 1-1 and 1-2), testing results are tabulated in Table 4.

Material separation technological tests has been conducted in accordance with the guidlines [17, 18].

Investigation results shows that RADOS SRF 2-200 separator effectively operates on lumpy material –150+50 mm, while COM Tertiary XRT separator effectively operates on material with size class

–50+6 mm [19]. The fulfilled job aimed to increase of the tungsten ore separation size at the COM Tertiary XRT separator have given a demonstration of possibility of source feeding size growth to 70 mm, which permits to enlarge part of the ore sent to separation under high effectiveness of equipment operation.

The main advantage of the RADOS *X*-ray radiometric equipment is possibility of involving into processing of material with fragmentation size up to 150 mm, which corresponds to a discharge size of breaking crusher. At the same time, WO_3 losses with separation tails are higher than when using the TOMRA Sorting *X*-ray adsorption technology: 12.8–45.0% against 5.1–8.5%. It also should be noted that productivity of TOMRA Sorting separators exceeds that of the RADOS ones on the same machine classes. Results of samples separation are presented in Table 5.

Preliminary separation of the mined ore takes place only in case of blending separation concentrate (beneficiated ore) with inseparable size grade. This permits to send 34–55% of primary ore to flotation stage of ore-dressing with metal distribution by 80–95%.

Flotation investigating products of samples separation have showed that technology pf preliminary ore concentration by *X*-ray adsorption method increases content of the valuable component in flotation feeding and improves ore material composition due to removing an essential rock volume and increasing part of ore material. Table 6 comprises data on the scheelite concentrate obtained from primary samples and separation products with different scheelite concentration. Experiments has been carried out by standard scheme with preliminary sulphide concentrate isolation. Consumption of the main reagents is as follows: soda in flotation up to harshness in pulp less than 10 H, liquid glass –350+100 g/t, sodium oleate 250 + 50 + 30 g/t. In rough concentrates finishing: for primary ore of inseparable class –30+0 mm liquid glass consumption in steaming have made up 16–20 kg/t at residual concentration of 4.5–6.2%, and respectively 3.8–4.6 kg/t and 2.7–3.0% for separation concentrates and furnace charges. Time of steaming is one hour, temperature is 85 °C, T:H ratio is 1:1.

As may be seen from comparison of obtained figures of flotation beneficiation, concentrates of conditioned

Table 4
Separation effectiveness by different size grades

Parameter	Separation effectiveness, %				
Size grade, mm	–150+100	–100+50	–50+25(20)	–25(20)+10(12)	–12+6
Sample 1-1 SRF 2-200	87.2	87.7	55.0	15.1	–
Sample 1-2 COM Tertiary XRT	–	–	91.1	71.23	85.9

Note: separation effectiveness has been estimated by WO_3 extraction to beneficiated ore depending on size grade.

Table 5
Characteristics of the tungsten ore separation

Product name	Output, %	WO_3		Output, %	WO_3	
		Content, %	Extraction, %		Content, %	Extraction, %
Sample 1-1 SRF 2-200 Class –150+20 mm				Sample 1-2 COM Tertiary XRT Class –50+6 mm		
Concentrate	10.05	1.27	53.12	11.70	1.12	48.27
Tails	62.09	0.06	15.53	60.90	0.04	8.49
Screenings	27.86	0.27	31.35	27.40	0.43	43.24
Ore	100.00	0.24	100.00	100.00	0.27	100.00
Sample 3 SRF 2-200 Class –150+25 mm				Sample 4 SRF 2-200 Class –150+25 mm		
Concentrate	53.05	0.52	81.02	50.04	0.46	84.65
Tails	46.95	0.14	18.98	49.96	0.09	15.35
Ore	100.00	0.34	100.00	100.00	0.27	100.00
Sample 2 COM Tertiary XRT Class –70+5 mm						
Concentrate	24.92	0.77	68.54	–	–	–
Tails	58.87	0.02	5.13	–	–	–
Screenings	16.21	0.46	26.33	–	–	–
Ore	100.00	0.28	100.00	–	–	–

Note: Concentrate, tails — are the combined products over all machine classes.

Table 6
Data on scheelite concentrate for separation products

Flotation feed description	Content in ore, %			Content in concentrate, %			Extracted, %
	WO_3	$CaCO_3$	P	WO_3	$CaCO_3$	P	WO_3
Sample 1							
Source sample 1	0.24	1.95	0.15	39.60	30.20	2.63	37.20
Separation concentrate 1	1.15	3.13	0.17	70.40	5.66	0.10	85.90
Separation concentrate 2	0.59	2.75	0.13	64.50	6.20	0.19	83.50
Screenings –30+0	0.25	1.68	0.09	34.50	32.47	1.33	36.50
Charge: concentrate 1+screenings –60+40%	0.80	2.69	0.15	67.50	5.67	0.53	76.60
Sample 4							
Source sample 4	0.27	9.20	0.14	60.10	6.30	0.69	41.30
Separation concentrate 1	0.60	13.00	0.11	56.40	10.70	0.27	74.30
Sample 2							
Source sample 2	0.28	6.68	0.17	37.45	30.98	–	64.80
Separation concentrate 1	1.83	4.20	–	61.02	6.32	–	88.61
Separation concentrate 2	1.19	5.45	–	50.92	11.56	–	89.26
Screenings –5+0	0.45	6.48	–	36.00	19.93	–	84.15
Charge: concentrate 1+ screenings –20+80%	0.88	7.04	–	52.84	11.94	–	86.54

Table 7
Results of flotation beneficiation of copper separation products

Sample characteristics	Content in ore, %	Sulphide concentrate				Copper concentrate		
		Output	Extraction, %			Content, %		Extraction, %
	Cu – As – S		Cu	As	S	Cu	As	Cu
Initial sample 2	0.13 – 0.10 – 3.0	6.34	83.06	44.58	50.34	12.83	0.96	79.71
Inseparable class	0.17 – 0.12 – 3.1	10.33	87.69	61.49	64.88	17.35	0.51	75.32
Separation concentrate	0.20 – 0.44 – 3.4	3.95	90.04	14.83	27.74	15.63	2.38	87.08
Charge	0.19 – 0.39 – 3.4	5.88	88.82	23.78	39.56	15.18	2.09	85.70

quality couldn't be obtained from low-grade ores and screening of –30+0 mm with WO_3 content of 0.24–0.80% (see Table 6), extraction amounts to 37(41)–64%. Low level of scheelite extraction from the source samples 1 and 4 is caused by strong surface oxidation of the dump lean ore rocks owing to limonite films formation and deeper limonite penetration by cracks (Sample 1) and very thin scheelite impregnations in amphiboles and pyroxenes (Sample 4). Scheelite extraction from more contrasting ores (Sample 2) at the same initial content is 1.7 times larger.

Flotation beneficiation of separation concentrates with WO_3 content of 0.59–1.83% allows to produce conditioned scheelite concentrates; extraction level in flotation cycle is 83.5–88.6%.

Low-grade skarn ores of Vostok-2 deposit are the scheelite and sulfide mineralization carriers. Sulphides floatability from separation concentrates has been estimated in the course of studies. Corresponding data are tabulated in Table 7.

Data of Table 7 shows that some copper concentration is observed in the separation concentrates, but arsenic detrimental impurities exceed it. This makes difficulties for obtaining conditioned copper concentrates by majority impurity. Experiments with separation concentrate and charge have resulted in the copper recovery into copper concentrate growth by 10–11%.

Conclusion

Summarizing the presented above information it may be concluded the following:

1. Introduction of piece by piece separation into the process line of development of Vostok-2 and Skrytoe deposits, with consideration for declared technology advantages, will ensure them a fundamental efficiency increasing in regard to use of subsoil and beneficiation. In the long-term prospect, piece by piece separation will provide the deposits with much more competitiveness than other *technologies. Inasmuch as skarn scheelite-sulphide ores of Vostok-2 and Lermontovskoe deposits are of the same kind [20], one may assume feasibility of effective separation of the latter as well.*

2. To provide apparatus arrangement of an ore-picking complex it is necessary to fulfill integrated evaluation, including economic assessment of TOMRA Sorting and RADOS equipment usage.

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