Properties-based identification and separation of rocks in the drilling process and shipment

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Abstract The development of a dynamic technology for monitoring and controlling the quality of the extraction and processing mineral raw materials based on deposit modeling and ore flow control is relevant for large mining and metallurgical plants, where ore from several mines is sent to the processing plant. There exists a problem connected with all parts coordination of the technological process from the geological model of the deposit, mining faces, ore depots, and the shipment system to the concentrating mill and metallurgical plant. By assessing the physicomechanical properties of rocks and their ratios during the drilling of blastholes, it is possible to determine the composition of the rock mass. The scheduling system monitors the movement of rock mass components from blasting to shipment to ore passes. An intelligent rig system identifies the properties of certain rocks according to their properties and their combination. With the help of the dispatching system, a portioned controlled ore shipment occurs with the ore accumulation of the particular composition.

Keywords Types of polymetallic ores, Physical properties, Identification, Portioned shipment.

1. Introduction

The development of a dynamic technology for monitoring and controlling the quality of the extraction and processing mineral raw materials based on deposit modeling and ore flow control [1,2] is relevant for large mining and metallurgical plants [3], where ore from several mines is sent to the processing plant [4]. There exists a problem connected with all parts coordination of the technological process from the geological model of the deposit, mining faces, ore depots, and the shipment system to the concentrating mill and metallurgical plant. A representative object for the implementation of such a system is the Polar Division of PJSC MMC Norilsk Nickel, one of the largest mining enterprises in Russia and the world [4]. For this plant, the development of the effective technology for controling ore flows [4] is especially important, since multicomponent ores are mined and processed at its deposits and there is a need to maintain the targets for some metals [5]. A separate problem is the dilution of mined ores [6]. It should be solved by separating the host ore or filling mixtures from the ore starting from mining faces, so that the waste rock does not fall into one ore pass with the ore, reducing its quality. Separation of ores and gangue at the drilling and shipment stages of ores from the mining face is a complex problem that should be solved using intelligent systems that evaluate the characteristics of the rocks directly while drilling [7,8].

The development of the intelligent technology for monitoring and controlling the quality of ore flows in the extraction and processing of multicomponent ores [2] involves achieving the main goal. It is the development of the system for evaluating the mineral composition of rocks in real time while drilling, their movement during the blasting process and the portioned shipment of ore portions to ore passes with the ore shipment of the particular quality to specialized processing plants. The following tasks should be solved for this goal achievement:

1. Study conditions for the rocks separation in mines of the Polar Division of JSC MMC Norilsk Nickel [9], including the study of the ore flow formation. Study of the composition and physical and mechanical properties of the mined ores and contained minerals;
2. Study the structure of the operating unit and the automation system of the Sandvik DL-430 drilling machine, equipped with a hydraulic perforator and hydraulic feed mechanism [10, 11] with an evaluation of the

possibility of measuring the mechanical properties of the rock using standard equipment and standard measuring tools;

3. Development of principles for determining the strength and density of drill rocks using the operating unit and sensors of the drilling machine;
4. Development of the methodology for determining rocks while drilling, casting [12] and shipment;
5. Development of methods for digital control of the separation accuracy of ore flows with the formation of ore passes of the necessary quality and composition.

2. Analysis of the problem of useful ore components loss and dilution at extremely different ore quality

Ores mined at the mining enterprises of the Polar Division of MMC Norilsk Nickel PJSC are multicomponent [13] and they can significantly differ both in the content of useful components (Fig. 1) and in mineral composition that determines the efficient concentrating technology.

Minerals reserves and resourses as at December 31, 2018	Ore kt	Metal grade						Contained metal					
		Ni %	Cu %	Pd g/t	Pt g/t	Au g/t	6 PGM g/t	Ni kt	Cu kt	Pd koz	Pt koz	Au koz	6 PGM koz
TAIMYR PENINSULA													
Proven and probable reserves	683,625	0.92	1.73	4.23	1.12	0.24	5.60	6,286	11,858	92,864	24,600	5,331	122,982
Proven reserves													
Talnakh ore field, including	328,571	0.79	1.55	3.84	1.04	0.23	5.08	2,600	5,080	40,582	10,938	2,398	53,664
rich	51,627	2.52	3.10	6.25	1.30	0.23	7.89	1,299	1,603	10,380	2,156	385	13,100
cuprous	19,770	0.97	3.93	9.56	2.32	0.64	12.01	192	776	6,073	1,472	405	7,633
disseminated	257,174	0.43	1.05	2.92	0.88	0.19	3.98	1,109	2,701	24,129	7,310	1,608	32,931
Norilsk-1 deposit (disseminated ore)	21,628	0.35	0.51	3,95	1.58	0.18	5.82	76	110	2,744	1,101	122	4,045
Probable reserves													
Talnakh ore field, including	311,622	1.14	2.11	4.64	1.13	0.27	6.07	3,549	6,588	46,529	11,347	2,676	60,828
rich	79,629	2.90	3.95	7.11	1.40	0.26	9.05	2,308	3,145	18,199	3,581	664	23,160
cuprous	61,380	0.75	3.17	7.12	1.86	0.52	9.20	461	1,944	14,057	3,666	1,017	18,153
disseminated	170,613	0.46	0.88	2.60	0.75	0.18	3.56	780	1,499	14,273	4,100	995	19,515
Norilsk-1 deposit (disseminated ore)	21,804	0.28	0.37	4.29	1.73	0.19	6.34	61	80	3,009	1,214	135	4,445

Fig. 1. The content of useful components in the extracted ores.

Mining enterprises of the JSC MMC Nornickel are developing three deposits of sulfide copper-nickel ores [2]:

1. Norilsk - 1 (underground mine “Zapolyarny”, open-pit mine “Medvezhy Ruchey);
2. Talnakhskoye (underground mine “Komsomolsky” including “Komsomolskaya”, “Skalistaya” and “Mayak” mines);
3. "Oktyabrskoye" (underground mines "Taimyrsky" and "Oktyabrsky").

Ores of various quality and composition are processed in two mills. At the Norilsk Concentrating Mill (NCM), ore concentrating is carried out according to gravity-flotation technology according to three technological schemes [2]. At the Talnakh Concentrating Mill (TCM), ore concentrating is carried out by the flotation method [2]. Rich ores are from “Oktyabrsky”, “Taimyrsky”, and “Skalisty” mines. Moreover, any deviations from the required content of useful components in the ore and its mineral composition lead to significant losses of metals.

So with a decrease in the mass share of nickel in ore from 4.5% to 1%, an average decrease occurs [14]:

- Quality of the same name concentrate decreases from 13% to 8.2%;
- Extraction of nickel in a concentrate decreases from 77.5% to57%;
- Yield of nickel concentrate decreases from 27% to 7%. At the same time, the yield of tailings increases from 30% to 75%.

To increase the efficiency of the technology, ores are averaged and the mixture of the required quality is prepared [15,16]. It requires energy-intensive, capital-intensive and labor-intensive resources. At the same time, significant losses of useful components are inevitable. Obtaining ores with previously known characteristics from mining enterprises will avoid significant losses of metals.

A significant impact on the decrease in the ores quality is exerted by the inevitable ingress of enclosing rocks into the ore using the technology of mining a deposit with explosion of overlying rocks [6,17] and filling mixtures using the technology with a hardening tab [6,17]. At the same time, up to 17% of the gangue can enter the ore [6]. In the absence of intelligent automated technology for the gangue separation in the mine, the latter inevitably falls into ore passes and goes to the mill. This reduces the efficiency of mining enterprises and processing plants.

3. Evaluation of the ores identification possibility for further separation of various physical and mechanical properties

Depending on the structure and mineral composition, as well as the content of non-ferrous and precious metals [18], ores are divided into:

- disseminated ore (average composition of Ni 0,4–0,5 %, Cu 0,7–0,8 %),
- Cupriferous (average composition of Ni 0,9–1,5 %, Cu 2,0–3,2 %), coppery (average content
- rich (average composition of Ni 2,5–3,5 %, Cu 3,5–4,5 %),
- selective ores (the richest in the composition of non-ferrous and precious metals are ores from the "Oktyabrsky" mine).

Ore mining is carried out at seven mining enterprises [2], which process three deposits and produce commodity ores of various compositions. Salable production and consumers of mining enterprises are given in Table. 1.

Table 1. Production Consumers.

Mining enterprise	Salable production	Consumer
"Zapolyarny" mine	Disseminated ore	Norilsk concentrating mill
"Medvezhy ruchey" pit	Disseminated ore	Norilsk concentrating mill
"Komsomollyskaya" mine	Cupriferous and disseminated ores	Norilsk concentrating mill
"Skalistaya" mine	Rich ore	Talnakh concentrating mill
"Mayak" mine	Disseminated and rich ores	Norilsk concentrating mill Copper plant
"Taymirsky" mine	Rich ore	Talnakh concentrating mill, Copper plant
"Oktyabrsky" mine	Rich, Cupriferous and disseminated ore	Talnakh concentrating mill, Norilsk concentrating mill

According to Table 1 it is clear that the capabilities and technologies of the concentrating mills differ significantly and it is necessary to separate the ore flows at the exits from the mines. Studies have shown that the physical and mechanical properties of ores and enclosing rocks differ significantly [19] and can be fairly accurately identified by two parameters: strength and density. These parameters are often inversely related. This allows one to obtain important digital markers [20] for identifying ore components with sharply different combinations and property values. The physical and mechanical properties of ores are well studied [21]. The density of ores has the following values:

- Density of rich ores is 4.1 t/m^3;
- Density of disseminated ores is 3.05 t/m^3;

- Density of cupriferous ore is 3.3 t/m^3;

The value of the rock strength ratio according to the M.M. Protodyakonov scale is as follows:

- For rich ores is from 5 to 7;
- For cupriferous ores is from 10 to 12 (up to 16);
- For disseminated ores is from 5 to 10;
- For enclosing rocks is from 5 to 10.

Thus, ores are determined by the following property ratios:

- rich ores are identified by a combination of the following properties: high density, low strength;
- cupriferous ores are identified by a combination of the following properties: low density, high and very high strength;
- disseminated ores are identified by a combination of the following properties: low density, average strength values.

The enclosing rocks have similar strength values. To distinguish disseminated ores from gangue, one should take into account that gangue has a slightly lower density of 2.5 - 2.8 t/m^3. An intelligent system installed in the on-board computer of a drilling machine, using these digital markers, distinguishes in the rock mass and builds a map of the ores location with the necessary properties on the well grid by combining identified fields with a specific ore composition.

4. Development of principles for evaluating the strength and density of drilled rocks

Sandvik DL-430 drilling rigs are used at the mining enterprises of the JSC MMC Nornickel for drilling blast holes (Fig. 2). This is a single boom electro-hydraulic drilling rig for extensive underground sewage processing and deep drilling. The robust boom has three meter parallel drilling coverage. Using the 360° rotation mechanism, full parallelism is achieved, and the wide coverage of the tilt forward and backward provides the ability to perform a variety of drilling tasks. It is equipped with an automation system and an on-board computer. This machine uses a hydraulic hammer for drilling.

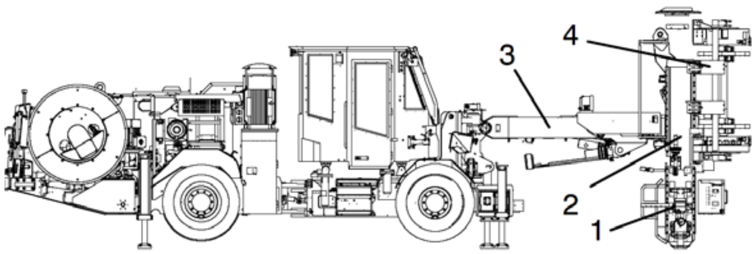

Fig. 2. Drilling module Sandvik-430. (1-punch; 2-feeder; 3-boom; 4-pipe manipulator).

While drilling, the automated system maintains pressure on the discharge line of the hammer drill at a constant level. It is necessary to measure the feed rate of the operating unit in discrete time intervals to evaluate the strength of rock in real time. For this, it is necessary to measure the flow rate of hydraulic fluid on the discharge line of the hydraulic cylinder of the feed mechanism using a flow meter (Fig. 3). The feed rate is directly dependent on the flow rate of the fluid supplied to the hydraulic cylinder of the feed mechanism and is inversely proportional to the strength of the drill rock. Thus, the strength of the drill rock in real time is determined according to the formula (1).

$$\sigma_{t.r} = \frac{k}{v_d} = k \cdot \frac{S}{Q_{g.f}},\ MPa \tag{1}$$

Here $\sigma_{c.r}$ is compressive strength of the rock, MPa; v_d is drilling speed, m/min; S is cross-sectional area of the hydraulic cylinder of the feed mechanism, m^2; $Q_{g.f}$ is flow rate of the hydraulic fluid of the pump in the hydraulic cylinder of the feed mechanism, m^3/min; k is design coefficient, depending on the design of the drilling tool and perforator.

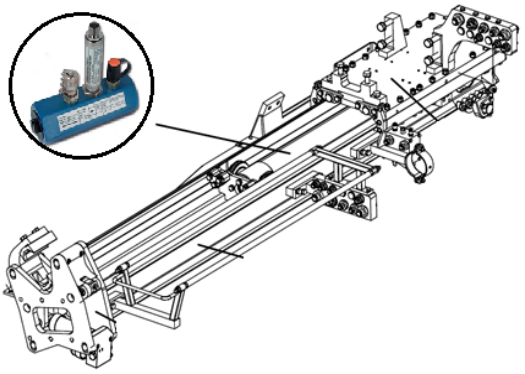

Fig. 3. Drilling speed meter (flow meter) for indirect evaluation of rock strength, subject to constant pressure of the feed mechanism.

To maintain a constant pressure level in the perforator while drilling, a pressure manometer is installed in the hydraulic system of the drilling rig; its readings are duplicated in an automated system. It is necessary to measure a parameter characterizing the recoil energy to evaluate the density of the drill rock. It is necessary to use a shock sensor installed in the hydraulic system of the hydraulic perforator to measure the shock pressure (Fig. 4).

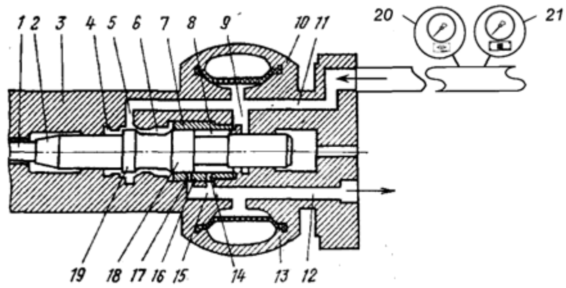

Fig. 4. Mechanism for evaluating the characteristics of the rocks based on the standard hydraulic perforator drilling rig Sandvik-430. (1 - shank; 2 - piston; 3 - case; 4.6 - chambers; 5.11 - pressure head highway; 7 - spool; 8 - chamber; 9 - channel; 10,13 - hydraulic accumulator; 12,15 - drain highway ; 14 - hole in the spool; 16.17 - channels; 18.19 - piston shoulder; 20 - pressure manometer of the feed line for indirect determination of rock strength. 21 - pressure manometer measuring impact pressure for indirect evaluation of rock density).

The sensor measures pressure fluctuations when a hammer is hit. At the moment of impact, a sensor shows a peak value. Peak values in different cycles of the drill differ depending on the density and strength of the rock being destroyed (Fig. 5).

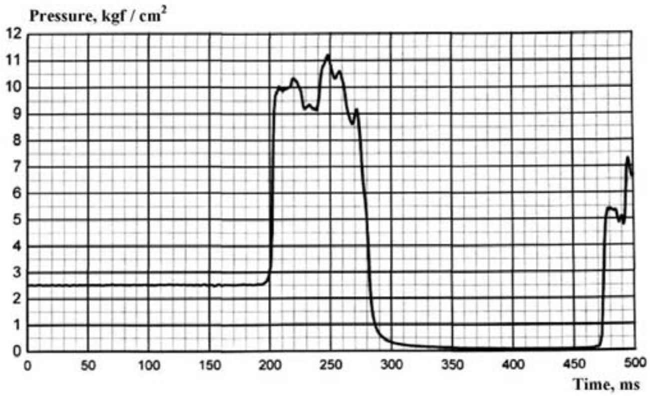

Fig. 5. The graph of the pressure of the impact of the hammer while drilling.

In this case, the averaged strength of drill rocks is determined by measuring the drilling speed using a flow meter (Fig. 3). By comparing the strength measured through the drilling speed and the impact pressure measured through the impact sensor with reference values, the system evaluates the relative value of the rock density. By the ratio of the calculated strength and relative density of the rock, the system evaluates and fixes the pass of a certain type of ore or gangue.

5. Methodology for evaluating areas of specific types of rocks while drilling, milling (explosion) and shipment

Using the big data analysis on the properties of drill rocks and comparing combinations of strength and density of drill rocks at certain time intervals with digital markers, the on-board computer accurately determines the location of rock types along the depth of the well (Fig. 6). The coordinates of the beginning and end of the areas of certain types of rocks are determined.

Fig. 6. Fixing the alternation of certain types of rocks in the well while drilling.

While drilling a grid of wells, the coordinates of the beginning and end of the regions of certain types of rocks are combined into the boundaries of the volume regions of certain types of rocks. The union of these regions makes up a volumetric tomogram of the rock mass (Fig. 7).

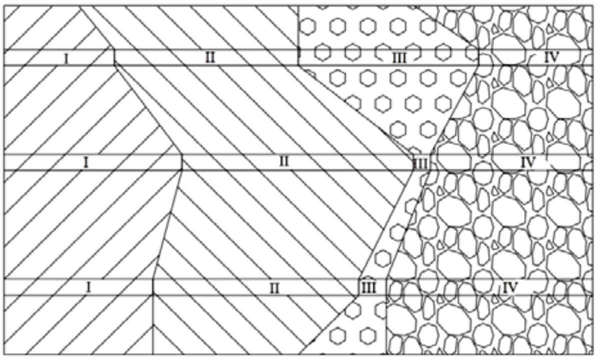

Fig. 7. Building a tomogram of the rock mass while drilling a grid of wells.

According to mining technology, explosives are calculated. This calculation is advisable to perform an intelligent system taking into account certain strength characteristics and areas of certain types of rocks.

Explosion of the rock mass with predetermined properties and structure will help to get a controlled explosion to obtain the optimal size of the pieces and minimal expansion of the rock with the formation of explosion with a known structure and location of areas with the known types of rocks. As a result of the calculation of explosives and the application of the rock mass transformation algorithm in the explosion, the intelligent system builds an explosion diagram (Fig. 8). Thus, the intelligent system of the on-board computer based on the drilling rig receives a tomogram of the rock mass along the grid of wells. On its basis it determines the quantitative content of individual types of ores. The system performs automatic calculation of explosives, simulates the transformation of rock mass after an explosion, and determines the explosion scheme with the determination of the accumulation areas of the certain types of rocks. The system determines a specific ore pass into which it is necessary to ship the ore and remembers the corresponding digital marks for each area of accumulation of the same type of rocks.

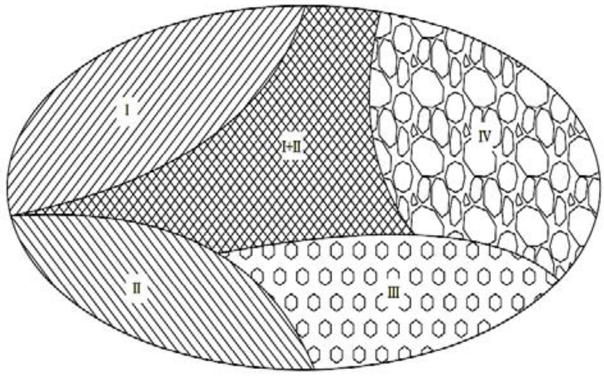

Fig. 8. Digital diagram of the explosion of the rock mass after detonation with the determination of accumulation areas of certain types rocks.

5. Control system of the addressed portioned shipment of various types of rocks

It is necessary to use a transport complex and digital communications on-board computers of a drilling rig and load-haul-dump (LHD) to develop of a comprehensive technology for pre-concentration by separating different types of ores, starting from the drift with the loading of some passages with ore with the particular characteristics and quality. There are no any opportunities to organize free wireless communication in the cramped conditions of the mine and its constant transformation. In this regard, it is necessary to organize wireless communication by installing wireless communication units at forks in the mine close to the drift and at the LHD unloading points. Fixed wireless communication units are necessary for the control system of address portioned shipment of various types of rocks (CSAPS dispatching system). This system operates as follows. It is necessary to complete the calculation of the digital scheme of the explosion of the rock mass at the moment of drilling completion in the on-board computer of the drilling rig. Then, the intelligent drilling rig system transmits the received information to CSAPS. This system is pre-connected with LHD, digitally attached to the drift for further unloading the rock mass. CSAPS transmits a rock diagram of the rock mass explosion and a loading command to the LHD on-board computer.

In the on-board computer of the LHD, an explosion scheme and the placement of the LHD in the mine with digital marks of the drift and ore passes appear. The camber scheme is displayed on the PDM operator monitor and the remote control monitor. An operator of the LHD focuses on the unloading of certain areas of the explosion using augmented reality video displayed on the monitor. Certain rocks types are shown by lightening in the form of various colors shading on the video from the LHD video camera, which removes rock mass explosion in real time (Fig. 9).

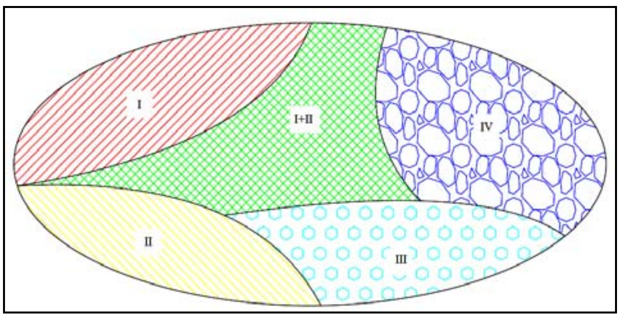

Fig. 9. Lightening of the rock mass explosion on the LHD monitor determining accumulation areas of certain type rocks.

Having loaded the ore, an on-board computer displays a digital mark of the ore pass where the loaded ore must be shipped. This digital mark is pre-attached to the submerged part of the explosion by an intelligent rig system. When passing the wireless unit near the drift, the LHD transmits information about the shipped part of the explosion to CSAPS. Then a computer adjusts the digital explosion scheme based on the shipped part. The next LHD loads the updated digital explosion scheme to the on-board computer with the help of the wireless unit and it is sent for loading.

The loaded LHD delivers the rock to a specific ore passage to which the loaded rock is attached with a digital mark. A driver of certain LHD sees on the screen with these digital marks a number of the ore run to which the ore must be delivered. Along the route to the ore pass, the LHD passes by a wireless stationary electronic receiver-transmitter, while the map of the rock mass explosion is updated taking into account the shipped portion.

6. Quality of addressed portioned shipment of certain types of rocks

6.1. CSAPS performance verification system

A system for monitoring the correctness of ore uploading is required to ensure the reliability of CSAPS. This system operates as follows. In the on-board LHD system, the next to be shipped, a specific ore pass, a digital mark is fixed with a number of the ore pass. Approaching the appropriate ore pass, the LHD unloads the bucket, while the on-board system reads the wireless digital ore pass mark and remembers it to confirm the shipment. In case of compliance with the digital mark of the ore and LHD, the information is updated and the LHD should be slaughtered for the next shipment. In the case of a mismatch of digital marks (LHD arrived at an inappropriate ore pass), a system captures and remembers the error, ties it to the driver's personality to control the quality of operation. The error is duplicated on the screen and the light signal. If it arrives at the wrong ore pass, the system can block the unloading of the bucket into the wrong ore pass and signals to follow the previously defined ore pass. As a result, the system controls the shipment of the ore with the particular properties to certain ore passes.

6.2. Intelligent system performance evaluation

The evaluation of the developed system should be done to reduce the loss of recoverable useful components and reduce dilution. The extraction of nickel is the most indicative for the processing of copper-nickel ores. It is known that with an increase in the nickel content in ore from 1% to 2%, a substantial increase in recovery occurs from 56% to 72% [15]. A system that determines the composition and quality of the ore obtained will avoid accidental contact with the concentrating mill of raw materials with characteristics that do not correspond to the technology and avoid metal losses of up to 22%.

Monitoring the process of loading and unloading certain portions of ore from the explosion of the rock mass will eliminate the ingress of gangue into the ore pass with ore of known quality and composition. The hit of waste rock taking into account the error of the system within 6% is possible. The ore processing at the concentration plants will decrease to 11% decreases in concentrating mills from 17% to 6%.

Taking into account the output volumes of mining enterprises of the JSC MMC Norilsk Nickel (Fig. 10), the reduction in ore processing while maintaining the plant's productivity is 1.9 million tons per year. Taking into account the released capacities of concentration mills the output of the mineral processing plant of JSC MMC Norilsk Nickel may grow by the appropriate value.

Ore output *(mt)*

Deposit/Mine, ore type	2016	2017	2018
Total ore	**17.24**	**17.38**	**17.32**
rich	6.19	6.59	6.76
cupriferous	7.08	7.17	6.79
disseminated	3.97	3.62	3.78

Fig. 10. Extraction volume of various types of ores by mining enterprises of the JSC MMC Norilsk Nickel.

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