Materials of devices and equipment for deep-sea mining of manganese resources

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Abstract. The extraction of oceanic ores will make it possible to extract a complex of strategic metals: manganese, nickel, copper, cobalt, molybdenum, zinc. The following materials are considered as cost-effective mineral raw in the ocean: manganese nodules – MN (Mn, Ni, Cu, Co), cobalt-rich manganese crusts – CMC (Co, Mn, Ni), deep-sea polymetallic sulfides – DPS (Cu, Zn, Au, Ag). As an example, the Indian concept of deepwater development is described, which proposes to use the pipeline as a transport of minerals from the bottom. The calculation of the pipeline transportation system with the indication of shortcomings is given. As an alternative, it is proposed to use a lift of a self-propelled device for minerals on a cable made of special material. The article presents a device for deep-sea mining of MN with pressure drop chambers. The method of application of this device for collecting CMC is replacing the pressure drop chambers with the clamshell type device. The grab must be made of strong and at the same time light material and can be equipped with a hydraulic hammer for preliminary destruction. Elements of the shock system of the hydraulic hammer must also be adapted to the conditions of deep-sea mining by using special metal alloys for manufacturing. The destroyed mass is temporarily stored in a hopper mounted on a collector, which can be made of nylon mesh stretched between plates of titanium alloys. The calculation of the performance of the device for deep-sea mining from is presented.

1. Introduction
In the world there are several concepts for the development of underwater mineral deposits, which are developed by the largest mining countries (USA, India, China, Germany, Russia, etc.).

Russia has already passed the stages of geological exploration of known deposits and is at the stage of forming its own concept of their development. The complex nature of the problem of development of the seabed of the oceans determines the diversity of the main tasks:

• providing geological exploration in the ocean with a modern scientific and methodological knowledge base;
• conducting exploration work on promising mineral deposits;
• development and provision of all works highly efficient and economical technical means and ships, long-term autonomous power plants;
• justification of structural materials from which technical means will be made for conditions of deep-sea mining;
• development of technologies for the enrichment of oceanic ores, ensuring the extraction of a wide range of useful components and their non-waste processing [7].
For example, the Indian concept [2] of a deep-sea mining system (Figure 1) proposes the use of a support ship, a lifting unit with a pipeline and a pump, as well as a self-propelled device for collecting minerals. Depending on the geotechnical characteristics of each type of mineral, the parameters of this system may vary. The disadvantages of this concept will be associated with the use of hydraulic transport, which entails high energy cost for transporting minerals from a depth of more than 5000 m.

Therefore, consideration should be given to using the transportation method similar to the ground-based development systems, namely cable winch transport, including an analogue of skip hoisting. The main problems of the latter will be the use of an additional vessel with a pile driver and an unloading and reloading system, devices for underwater unloading and reloading. Therefore, simplifying this method, it is proposed to raise the collector or only the hopper mounted on the collector. Then the task is reduced to the selection of the optimal material for the manufacture of the cable, on which the lowering and lifting device for deep-sea mining will be made. Preliminary strength calculations show that the optimal options may be varieties of materials based on Kevlar [14].

![Figure 1. The concept of deep-sea mining using a self-propelled collector.](image)

2. Types of deep-sea mineral resources

For several decades, intensive exploration and exploration work is conducted in the Pacific Ocean. In the process of these studies, three dominant types of solid minerals were identified [13]. Manganese nodules (MN) usually occur at the bottom of the ocean at depths of 4000–6000 m. The explored sites in the Clarion – Clipperton Fault (CCFZ) in the Pacific Ocean are known for their rich deposits with a distribution of up to 40 kg/m² [11]. Nodules are typically 1–15 cm in diameter and partially submerged in soft, deep-sea sediments. In their composition, they contain Mn <35 %, Fe <25 %, Cu <2 %, Ni <2 %, Co <0.5 % [7].

The main parameter for the design of devices for collection and executive bodies of collectors (miners) (Figure 1) is the geotechnical characteristics of the deposits. At the moment, both towed and self-propelled types of mining machines are being developed [2].

Based on the results of experiments on the development of MN, the key factors were determined that affect the performance of all systems for underwater mining of minerals:

- the values of pressing and immersion of the miner in soft deposits formed on the bottom surface;
- the magnitude of the created sea loop at the bottom from the movements of the miners;
- the level of the sea plume in the surface layers from the discharge of sediments and mineral fragments that cannot be separated from water [9];
minimization of labor costs for transportation of minerals from the bottom to the surface.

The results of experimental studies and practical applications of the devices showed the main ways of developing deep-sea deposits. For example, the location of the support ship is as close as possible to the development site, the discharge of waste into the deep layers [9], the use of self-propelled vehicles with the least number of movements per cycle with protection against pressing against soft bottom sediments.

Massive sulfides of the seabed are formed as a result of hydrothermal processes, namely plate tectonic shifts at water depths of about 1200–3500 m [10]. Sulfide deposits (Kuroko deposit, Japan) with topographic data in the form of seamounts that contain gold up to 20 ppm and silver up to 1 % were discovered at a depth of the Pacific Ocean water of 700–1800 m. Massive sulphide mountain ranges are of great interest for development, since they mainly consist of demanded metals: Fe <40 %, Zn <25 %, Pb <25 % and Cu: <15 % [4].

Cobalt-rich manganese crusts (CMC) are common on seamount slopes and guyots at a depth of 800–2500 m. Usually they occur in the form of crusts up to 20 cm thick covering slopes and mountains, but can also be crumby nodules. The equatorial part of the Pacific Ocean is considered a zone of high potential with a distribution density of up to 200 kg/m2. They are valuable because of the constituent metals such as Fe <25%, Mn <35 %, Cu <0.5 %, Co <2 %, Ni <1 % and Pt <2 ppm.

The selection of rational parameters of equipment and materials from which devices will be made to implement the presented concept is an important task. Its solution will largely depend on the geotechnical characteristics of not only crusts and their substrates, but also other deep-sea mineral deposits. The results of research voyages establish that the crusts have a specific gravity of 1.65 –2.17 g/cm3, porosity can vary between 43-74 %, and the compressive and tensile strengths are 0.5–16.8 MPa and 0.1–2.3 MPa, respectively.

**Figure 2.** Schematic distribution aspect of cobalt-rich manganese crust. 1 – devices for deep-sea mining; 2 – thrusters; 3 – pick-up devices; 4 – device for destruction; 5 – cobalt-rich manganese crusts; 6 – storage bunker; 7 – loosened rock; 8 – seamount sediments; 9 – substrate; 10 – cable winch; 11 – mother vessel; 12 – cable.
CMC are also located at great depths – in the area of high static pressure. The linear compressive strength of materials in a high pressure medium is known [13]. Nevertheless, the effect of pressure on the tensile and shear strength [6], which play a decisive role in the destruction of the material, is not observed or does not affect. Therefore, the refinement of the tensile and shear strength of rock materials and deposits is the most important for the geotechnical understanding and adaptation of the structures of the mechanisms of destruction of the earth's crust. Knowledge of these parameters will be the basis for the selection and justification of the materials from which destructive devices will be made.

3. Layout schemes for the extraction

Our proposed concept is based on the use of a support vessel with a bunker and unloading and overload mechanisms, as well as a winch (Figure 3) for lowering and raising a self-propelled device for collecting minerals (Figure 4). As shown in Figure 3, the deep-sea apparatus for collecting the CMC descends initially to a certain point in the bottom region, from which, collecting minerals, it moves along a certain trajectory, thereby passing a certain area at the bottom.

![Figure 3. Schematic area of mining.](image)

The device for collecting (miner) is an assembly with 4 manipulators, at the ends of which an executive body is fixed for trapping minerals. Depending on the type of mineral (MN or CMC), the executive body for capture may vary. So, for MN, a device with an executive body in the form of pressure drop chambers was proposed and patented (Figure 4). The capture of nodules in this case occurs due to the pressure difference between the internal (in the chamber) and external (at the bottom of the ocean) (Figure 5.1). The device sinks to the bottom from a support vessel on a specialized winch with a Kevlar cable. Further, a vacuum of 3–4 atm is created in the chambers. Manipulators plates are pressed to the bottom and nodules are captured by suction cups. Unloading takes place in a storage hopper with a volume of 40–85 m³. After collecting nodules from one point, the device is moved by “walking” to another place of collection using manipulators [15].

Since cobalt-manganese crusts differ in hardness and difficult bedding conditions in the form of a homogeneous mass, they require preliminary loosening. This problem can be solved by replacing the pressure drop chambers with a clamshell type device (Figure 4). One or two of the manipulators can be equipped with a grab with a hammer (Figure 5), which should have increased destruction efficiency of the CMC with small dimensions. This can be achieved through the use of shock systems “piston-striker-tool”, in which due to the rattling of the striker between the peak and the piston, an increase in the intensity of destruction of the massif is realized [3, 5, 16]. As a grab, you can use a hydraulic grab with a closed bucket for liquid bulk materials (Figure 6).
Figure 4. Proposed model of self-propulsive types of underwater mining machine for manganese nodule.

Figure 5. Pick-up devices for self-propulsive types of underwater mining machine: 1 – discharge chamber; 2 – device of grab type; 3 – device of grab type with hummer; 4 – hydraulic grab with a closed bucket for liquid bulk materials.

4. Transportation systems

Most world concepts consider the use of hydraulic lifting technology to be effective, in which the extracted minerals are transported to the water surface through a vertical flexible pipeline in the form of hydraulic mixtures due to the operation of soil pumps [1, 12]. When lifting from great depths, it is necessary to install several pumps in series (Figure 6). There are also theoretical developments of complexes, which include an intermediate capsule with atmospheric pressure and pulp transfer equipment, which allows reducing the energy consumption of the process of hydraulic lifting of minerals and reducing the number of installed pumps [12].

The power expended in transporting the slurry is determined by the parameters of the pumped slurry stream [1], namely, the slurry density $\rho_{sm}$, slurry flow rate $Q_{sm}$ and the required pressure of the hydrotransport system $H$:

$$N = \frac{\rho_{sm} \cdot g \cdot Q_{sm} \cdot H}{1000},$$

where $g$ – acceleration of gravity, m/s$^2$. 
Figure 6. Diagram of the deep-water hydraulic lift of minerals by ground pumps; 1 – watercraft, 2 – power plant, supplying electric power to electric motors of ground pumps, 3 – ground pumps, 4 – bunker, 5 – underwater mining machine, 6 – vertical pipeline, 7 – flexible pipeline of positive buoyancy

Pressure losses during transportation of the slurry will be made up of the pressure losses along the length and local, determined by the Darcy-Weisbach formula, as well as additional pressure losses to overcome the resistance of solid particles in the vertical pipeline and to weigh the slurry column [12].

For the approximate determination of the required power for transporting the hydraulic mixture through a conventionally vertical pipeline without the use of a capsule, the following hydraulic transport parameters were obtained:

\[
\begin{align*}
Q_{cm} &= 0.44 \text{ m}^3 / \text{s} \\
\rho_{cm} &= 1120 \text{ kg/m}^3 \\
H &= 215 \text{ m}
\end{align*}
\]

\[
\Rightarrow N = \frac{1120 \cdot 9.81 \cdot 0.44 \cdot 215}{1000} = 1040 \text{ kW}.
\]

Even according to rough calculations, it is clear that a large amount of power needs to be spent on hydraulic transport, which entails the use of special expensive overall installations. This technical solution becomes difficult to implement in conditions of deep-sea mining for the following reasons:

- requires preliminary crushing to particles no larger than 0.5 cm in size;
- requires the installation of intermediate chambers with pumps, the design of which has not been worked out;
- the material (multilayer) from which the pipeline is made is not known, which should not collapse under the influence of its own weight and deep-sea currents, as well as natural mechanical stresses, the inner surface of which should have minimal resistance to the movement of the pulp.

To date, there is no detailed technical solution for the implementation of hydrotransport from a depth of more than 5 km.

It is proposed to replace the hydrotransport with a cable-skip transportation system using a cable made of special Kevlar material. Calculations performed on cables made according to
German and Chinese technologies showed that 48 mm (solid line, fig. 7) allowable tension is 1500 MPa and the safety factor is 2.2, and the maximum net mass of the ore being lifted is 109 t. Given the density of MN and CMC t/m$^3$, the reservoir volume should be 40 m$^3$. In Figure 7, the dashed line shows the dependence for the diameter of 40 mm, and the dotted line shows the dependence for the diameter of 32 mm. Depending on the chosen development system, it is possible to achieve the most cost-effective combinations of reservoir volume and skip lift.

**Figure 7.** The dependence of the diameter of the cable from the net weight of the lifted ore.

5. **Method of calculating the performance**

The performance of the device for collecting MN or CMC can be considered by the example of the operation of the device shown in Figure 5.1. It depends on the following parameters: speed of descent to the seabed, time for preparatory and basic operations, speed of movement of hydraulic cylinder rods, trapping coefficient (pressure drop chambers or clamshell type device), geotechnical characteristics of occurrence of minerals. Knowing the performance of one device for mining, you can identify the required number to meet the conditions of annual productivity.

The basis of the calculation is the determination of the total cycle time ($T_{cycle}$). It consists of the following operations:

1. Basic operations:
   1.1. The time of the descent of the installation to the bottom $T_{descen}$.
   1.2. Collector fill time $T_{load}$.
   1.3. The time of moving the unit from one place to another $T_{motive}$.
   1.4. Collector unloading time to skip $T_{scip\ load}$.

2. Auxiliary operations:
   2.1. The time for moving the paws to the position of capturing minerals.
   2.2. Mineral crushing time (if necessary).
   2.3. Paw raising time for dropping minerals into the collector.
   2.4. PI dropping time (pump station stop).
   2.5. Stock movement time.
The time of the descent of the unit depends on the buoyancy and mass of the unit and ranges from 30 to 40 minutes at a speed of 3 m/s.

The time of loading the minerals into the collector \( T_{\text{load}} \) depends on the time of moving the paws to the position of picking up the minerals, the time the minerals is crushed, if necessary, the time of picking up the minerals, the time it takes the paws to drop the minerals into the collector and the minerals itself.

The estimated performance of one unit will be calculated by the formula:

\[
Q = \frac{\rho \cdot E}{T_u}.
\]

Under the best environmental conditions, the productivity of one unit will increase to 68 t/h. Consequently, to ensure an annual productivity of about 1 million tons/year, 3–6 production units will be required.

Depending on the development system and the diameter of the discharge chambers, rational parameters of devices for collecting manganese nodules or cobalt-manganese crusts can be obtained (figure 8).

Figure 8. The dependence of the productivity rate of the unit from the diameter of the cameras.

6. Method of calculating the performance

The development of mankind and its life activity every day increases the relevance of the extraction of submarine mineral deposits. Iron-manganese nodules turned out to be the most favorable for development and less laborious, therefore, the technical equipment for the development of this type of minerals is higher today. But the most valuable in their composition are cobalt-manganese crusts. A long-term study of deposits and the proposal of new methods and devices for the extraction of deep-sea deposits did not solve a large number of problems. One of the main problems, in our opinion, necessitates the use of new materials:

- Kevlar-based joints for the manufacture of a cable that will lift the vessel to transport minerals from the bottom;
- alloys of titanium and aluminum, with great strength and lower mass, for use in the manufacture of elements of the shock system, cleaving nodes;
- compounds based on polymers (capron), which can be used for the manufacture of vessels for the intermediate collection of underwater minerals.

Other sets of tasks will be technical solutions and the development of a cost-effective production system. This article proposes the use of a system based on a generally accepted concept using a mother vessel, a self-propelled collector and a cable-skip transport system, which is a distinctive feature. This system is calculated and assumed as the most appropriate.
Also checked by theoretical and practical calculations, the optimal distance from the collection point to the lifting system, the trajectory of the optimal number of self-propelled collectors from one collection point to another with minimization of areas left due to inappropriate collection. The developed prototype design of the collector, presented in the article, can be used for most types of subsea deposits, such as KMK and MN, adapted for cable-skip hoisting transport and uses universal interchangeable units and assemblies that can be replaced in the process of studying the issue, thereby improving profitability deep-sea mining.

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