Calculation of parameters of technological equipment for deep-sea mining

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Abstract. The actual problem of extracting minerals from the bottom of the world ocean is considered. On the ocean floor, three types of minerals are of interest: iron-manganese concretions (IMC), cobalt-manganese crusts (CMC) and sulphides. The analysis of known designs of machines and complexes for the extraction of IMC is performed. These machines are based on the principle of excavating the bottom surface; however, such methods do not always correspond to "gentle" methods of mining. The ecological purity of such mining methods does not meet the necessary requirements. Such machines require the transmission of high electric power through the water column, which in some cases is a significant challenge. The authors analyzed the options of transportation of the extracted mineral from the bottom. The paper describes the design of machines that collect IMC by the method of vacuum suction. In this method, the gripping plates or drums are provided with cavities in which a vacuum is created and individual IMC are attracted to the devices by a pressure drop. The work of such machines can be called "gentle" processing technology of the bottom areas. Their environmental impact is significantly lower than mechanical devices that carry out the raking of IMC. The parameters of the device for lifting the IMC collected on the bottom are calculated. With the use of Kevlar ropes of serial production up to 0.06 meters in diameter, with a cycle time of up to 2 hours and a lifting speed of up to 3 meters per second, a productivity of about 400,000 tons per year can be realized for IMC. The development of machines based on the calculated parameters and approbation of their designs will create a unique complex for the extraction of minerals at oceanic deposits.

1. Introduction

Many countries experience a shortage of metals, so mining of minerals from the bottom of the world's ocean will soon become an urgent task. At depths from one and a half to five kilometers, on the world ocean floor, millions tons of minerals are located. The bottom of the ocean containing unique deposits of polymetallic ores makes up 40 percent of the total area of the world's ocean, that is, more than half of the entire surface of the ocean [1-3]. With the help of modern geophysical studies, methods of selection of near-bottom samples, geologists today have made geological maps of 30 thousand square kilometers of near-bottom territories.

As a result of geological studies of the ocean floor, it has been proved that three types of minerals are more interesting [4-6].
1) Iron-manganese concretions (IMC) are unique formations; they are the source of the most important metals, whose deposits on the earth's surface ended. Manganese is a part of many alloyed steels, which are very in demand in industry.

2) Cobalt-manganese crusts (CMC) that formed as a result of spills in the bottom part of the sea of deep-sea lava contain a high percentage of metals. In some parts of the ocean, cobalt-manganese crusts are an ore with such a high content of metals that it does not require multi-stage ore processing, since the ore can be considered almost the "feinstein".

3) Sulphides are usually located near the operating fountains of magma intrusion from volcanoes in the near-bottom region. These unique deposits are vertical pipes a few meters in diameter and a height of tens of meters.

In terms of mining, the IMC is of greatest interest. These are spherical formations, with a diameter of 5 to 15 centimeters. They are located on the surface of bottom, can be immersed in silt; the density of IMC is 20-70 kg / m\(^2\).

The extraction of IMC is possible in various ways [7-9]:

1) The method of mechanical raking, the paws and scraper conveyors can be used.

2) The method of hydraulic gripping. The pumps in the device create a flow of water and through the nozzle, they create the effect of gripping IMC in the pipe.

3) The Nautilus-Minerals consortium offers the extraction of iron-manganese nodules and cobalt-manganese crusts by transferring to bottom development the open pit quarries technology. That is, machines similar to machines that work in quarries are used. In this case, the machine cuts IMC or CMC, the pieces of material fall into the conveyor and into the bunker. These machines require solving the problems of high-power supply for engines.

4) At the department of mechanical engineering of the St. Petersburg National University of mineral resources "Mining", the method of vacuum capture of IMC is developed. The greatest difficulty is the lifting of material from the bottom of the world's oceans. The analysis of patents shows that there are following ways of transportation:

1) The Nautilus-Minerals consortium offers hydro-transport as a lifting device. In this case, it is required to ensure the highest strength of the pipes. It is also necessary to provide bottom-crushing IMC up to the size of no more than 5 cm. The pipeline must consist of separate parts that are connected by hinges that contain sealed capsules for reducing the weight of the pipe section.

2) Air-lift systems. Compressed air is supplied to the pipe at a certain depth. They are used at a depth of less than 1.5 km.

3) The underwater descent vehicle, which descends to the bottom, is loaded with IMC and rises from the bottom to the surface. The underwater descent vehicle is applicable at depths of up to 1 km.

4) Lifting in a special container. A winch installed on the ship is used as the equipment for lifting a special container on a rope with IMC.

The calculations show that if ropes made of Kevlar, manufactured in Germany or China, are used, the maximum pulling force, which can be realized with a rope of 6 centimeters in diameter, is 1500 kN. For a lifting speed of up to 3 m/s and a cycle time of up to 2 hours, the vessel's productivity can be 400,000 tons of IMC per year.

Unfortunately, today there are no methods of mining from the bottom of the world ocean and transporting IMC meeting the ecological requirements. Also today, there is no complete technology for extracting metals from IMC and CMC.

2. The calculation of technological equipment for deep-sea mining
The work of mechanisms in the near-bottom regions of the world ocean has a number of fundamental difficulties: at a depth of 5 km - the pressure of 50 MPa and the temperature of 2-3 degrees; local underwater currents and areas of water with increased salt content; devices must meet international environmental requirements.

In accordance with such requirements, the device for the vacuum gripping of IMC of the drum or lamellar type was developed at the department of mechanical engineering of the St. Petersburg National University of mineral resources "Mining" (Fig. 1) [10]. The device allows the collection of IMC by means of plates in which a vacuum is created, and the IMC are pressed against the plates by a
pressure drop. Creation of technical equipment for transshipment of IMC in the tank and then to lift containers will allow one to solve the problem of efficient extraction of IMC. For these purposes, a descent deep-water machine has been developed that collects and loads IMC into a container that is lowered to the bottom.

As shown in Figure 1, the machine extraction of IMC has a handle - 3 and a plate - 2 with cavities. After lowering the machine to the bottom, handles 3 are successively lowered to the bottom, capture IMC and transfer them to machine's capacity 1. The capacity loading cycle includes 10-12 overloads of plates from the position of capture of IMC to the unloading position and can be 1-5 minutes. The capacity is loaded up to 2 tons of IMC. Thus, for 1 hour, 10-20 tons of IMC can be produced. To produce 80 tons IMC, 4-5 machines will be needed to extract IMC and special means for transferring IMC to the container.

![Image of the machine for mining of IMC](image.png)

**Figure 1.** The machine for mining of IMC

For create the technological process of lifting the container, it is necessary to perform calculation of all parameters of the process equipment. All the main parameters of the technological equipment for lifting are determined on the basis of the condition that the lifting rope does not break. The authors have considered the use of Kevlar ropes with a tensile strength of 3620 MPa.

As initial data, let us take the characteristics of the commercially available twelve strand braided ropes of 100% Dyneema fiber: LIROS (Germany) and HY PRO (China). These ropes are very resistant to tension (less than 1%), very light, simple to plexus, and do not absorb water and are resistant to ultraviolet radiation. Also these ropes have high wear resistance.

Figure 2 shows the dependence of the diameter of the rope on the maximum lifted weight and on the weight of the kilometer rope. The dash-dotted line shows the dependence for the HY PRO rope; the dashed-dotted line shows the dependence for the LIROS rope; the solid line shows the theoretical calculation.
To calculate the parameters of the technological equipment for lifting, let us apply a rope with a diameter of 48 millimeters. For deep-sea applications, let us take the rope length equal to five kilometers. The weight of such rope will be 6250 kilograms. 

\[ l = 5000 m, m_r = 6250 kg, d = 0.048 m, F_r = 0.00087 m^2 \]

For the rope in question, the allowable tension with a safety factor of 2.2 is 1431 kN

\[ N = \frac{3620 \times 10^6}{2.2} F_r = 1431511.7 N \]

The maximum lifting weight is 145 tons

\[ M_{\text{max}} = 145924 kg \]

The weight of the lifted container with the necessary equipment is 10 tons.

The resistance force when lifting a cylindrical container with a spherical fairing is calculated by the formula:

\[ F_c = c_f \frac{\rho v^2 S}{2} = 0.47 \frac{1025 \times 3^2}{2} \times 3.14 \times 1.8^2 = 22055 N \]

The resistance force of the rope when lifting is calculated by the formula:

\[ F_k = c_k \frac{\rho v^2}{2} V^{2/3} = 0.05 \frac{1025 \times 3^2}{2} \times (l \pi d^2 / 4)^{2/3} = 1844 N \]

The maximum value of the dynamic component of the tensile force at the initial jerk speed is determined in accordance with the technique described in the handbook - Ship devices.

\[ k_f = 0.656, k_h = 1.808, \]

\[ E = 1.3 \times 10^{11}, l = 5000, a = \frac{EF_r l}{m_r} \]

\[ T_d = EF_r v_0 (k_h + k_f \sqrt{m_r}) / a = \]

\[ 1.3 \times 10^{11} \times 0.00087 v_0 \left( 1.808 + 0.656 \sqrt{\frac{145924}{6250}} \right) / \left( \frac{1.3 \times 10^{11} \times 0.00087}{1.25} \right) = \]

\[ = 59186.244 v_0 = 177559 N \]

The maximum useful mass of the ore to be lifted into a container at a speed of 3 m / s from a five kilometer bottom using a Kevlar rope with a diameter of 48 millimeters with a safety factor of 2.2 is 109 tons.
The time of lifting the container with ore includes the time of acceleration to a speed of 3 m/s, the travel time at this speed, the deceleration time and is equal to 28 minutes.

\[ t_{up} = 60 + \frac{4800}{3} + 30 = 1690 \text{sec} \]

The extraction time of 100 tons of ore by specialized deep-water machines is 60 minutes.

The full cycle time is 2 hours. Theoretical productivity is 50 tons per hour.

With full automation of works (365x24), the annual turnover is 438 thousand tons.

At manual works (260x8), the annual turn makes 104 thousand tons.

3. Conclusion

Thus, to solve the transport problem for IMC from a depth of more than three kilometers, the special container on the rope can be used as a lifting device. The container is lifted using the winch, which is mounted on the ship. At the same time, steel ropes cannot be widely used. The container is loaded by means of devices moving along the bottom, equipped with vacuum grippers for IMC. The calculations show that if ropes made of Kevlar, manufactured in Germany or China are used, the maximum pulling force, which can be realized with a rope of 6 centimeters in diameter, taking into account the safety factor of 2.2, is 1500 kN. The calculations show that the weight of the rope will not be more than 100 kN. The dynamic component of the tensile strength of the rope at the initial moment of lifting the container from the bottom is no more than 200 kN. With an area of the lifted container up to 10 square meters and at a lifting speed of up to 3 m/s, the weight of the lifted IMC can be up to 800 kN. For the above-mentioned parameters, the productivity of a single vessel can be about 400 thousand tons of IMC per year, which makes it possible to talk about the profitability of the method. In the practical implementation of the above-mentioned methods for the extraction of iron-manganese concretions, it is necessary to completely determine the technology for the isolation of metals from iron-manganese concretions.
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