Substantiation of the technology of mineral extraction from the bottom of the continental shelf with an autonomous underwater vehicle

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Abstract
The extraction of mineral resources from the bottom of the continental shelf is presently becoming very promising in terms of their current depletion on the continents. However, the development of the mineral resource base of the world ocean requires the creation of specialized equipment and technological schemes for its use. Such equipment should ensure safe, environmentally friendly, trouble-free operation in difficult hydrosphere conditions. One of the innovative ways of such development is the use of autonomous mining vehicles. The most energy-consuming part of the work of these vehicles is the process of lifting the loaded vehicle to the surface. This article discusses the optimization of energy costs for lifting an autonomous mining vehicle from the bottom of the continental shelf with the use of gases formed during the detonation of explosives.

Keywords: minerals, underwater mining, autonomous vehicle, lift force

Introduction
Non-traditional sources of mineral raw materials (NMR), which include deposits of strategic metals on the shelf and the ocean floor, are of particular relevance as one of the factors in solving the global problem of mineral resource supply for current and future generations. In this regard, the effective and environmentally safe development of the mineral resources of the World Ocean is becoming one of the main strategic tasks for humanity in the 21st century (Volkov, 2022).

The ocean covers more than 70% of the earth's surface. Huge mineral resources are concentrated on the shelf and bottom of the deep-water regions of the World Ocean (Geology of the Future, 2019). Sands, gravel, phosphorites, as well as coastal placer deposits of diamonds, cassiterite (Sn), ilmenite, rutile (Ti), gold, rare earth elements (REE) and other metals are of particular commercial interest.

The exploration of deposits on the shelf and the bottom of the deep-sea regions of the World Ocean is stimulated by the exhaustion of sources of raw materials on the continent. The share of production of "traditional" solid minerals in offshore fields in the world today is 10-15%. It is predicted that by 2050 this share may increase to 20-25% due to the involvement in the development of areas located from the coastline at a distance of 25-50 km or more and at depths of up to 30-50 m (Geology of the Future, 2019).

It should be noted that high technical and economic performance can be achieved in underwater mining. As a rule, stripping works, construction of access roads, dumps, tailings are not required here, and preparatory work is sharply reduced. Thus, offshore deposits are being developed much faster than on land with significantly lower specific capital investments (Kostin and Nurok, 1968).

Currently, there is a large number of technological equipment for the extraction of minerals from the bottom of the water area (Birney, 2006; Bashir et al., 2012; Boschen et al., 2013; Wynn et al., 2014; Petersen et al., 2016). The review of this
equipment allowed the creation of the systematization of underwater production facilities according to the principle of mineral recovery from an underwater mine face to a warehouse (Figure 1) (Kislyakov et al., 2021).

The article proposes a technical solution for the application of an autonomous production vehicle that uses emitted gases during the detonation of explosives for floating to the surface.

Figure 1. Systematization of underwater mining facilities based on the principle of mineral recovery.

Methods

The device works as follows. The vehicle is lowered into the aquatic environment with an open grab bucket. When the device is lowered to the bottom of the continental shelf, the process of penetration of the bucket teeth into the rock begins due to the weight of the device. After the penetration of the teeth to a certain level sufficient for the necessary stability of the equipment, a sensor is activated. That gives a signal to detonate the explosive located inside the teeth. Simultaneously with the detonation of the explosive, the bucket closing mechanism is activated, capturing and filling the container with loosened mineral rock. When detonated, the explosive releases a large amount of gas filling the container of flexible material. As a result, the lift force arises, which causes the device to float to the surface. After surfacing, the vehicle is removed from the water area by hooking the loop for lifting onto the carrier vessel (Kislyakov et al., 2017).

The main advantage of this device is that the grab bucket itself is made of flexible material to reduce the metal consumption of the equipment and possible gas filling of the upper part of the grab bucket. The inserts of steel spokes located along the perimeter are used to strengthen the grab bucket made of flexible material. The penetration of the tooth tips made in the form of hooks into the rock of the mineral deposit occurs to prevent the device from being thrown back during the detonation of the explosive. The sensor allows the detection of the bucket position signal. Simultaneous activation of the extraction process and gas extraction reduces the total cycle time of the equipment. The teeth are ellipsoidal so that the impact force is directed to the bottom of the water area, thereby reducing the load on the equipment and loosening the rock. When the explosive is detonated, gas is released filling the upper part of the bucket. As a result, the lift force arises, thereby reducing the cost of additional devices and substances for gas release. The upper part of the grab bucket is made of flexible material, which allows for keeping the emitted gases directly in the bucket without using an additional container.

The principles of the installation are presented in Figure 2 (Kislyakov et al., 2017).

Results and Discussion

A feature of the technological process in the use of this vehicle is the complete absence of steel or composite cables, as well as all kinds of flexible pipelines used in classical deep-sea mining technologies. These vehicles make it possible to extract minerals from the bottom of the continental shelf without any connection with the carrier vessel. The principle of operation of autonomous vehicles is illustrated in the following Figures 3 and 4.
Figure 2. Autonomous underwater vehicle in the form of a grab bucket:
(a) the general view of the device, b) bucket tooth, c) device when embedded in the rock:
1 – flexible material; 2 – steel spokes; 3 – teeth; 4 – spring mechanism; 5 – mechanical sensor; 6 – bucket closing mechanism; 7 – flexible rods; 8 – electric detonator; 9 – explosive; 10 – waterproof case; 11 – loop for lifting the device to the ship; 12 – electrical wires; 13 – hook

Figure 3. Technological scheme of operation of an autonomous device in the summer:
1 – carrier vessel for delivery of an autonomous device; 2 – the mining autonomous device; 3 – flexible cavity for surfacing; 4 – a grab bucket; 5 – rock; Pa – the buoyant force (Archimedes’ principle); Rc – resistance force; Gt – gravity force; HB – water depth; Hn – deposit thickness

The vehicle is lowered into the aquatic environment with the open grab bucket. When the device is lowered to the bottom of the continental shelf, the process of penetration of the bucket teeth into the rock begins due to the weight of the device. After the penetration of the teeth to a certain level sufficient for the necessary stability of the equipment, the sensor is activated. The sensor then gives a signal to detonate the explosive
located inside the teeth. The released gases fill the container made of flexible material. This process creates the lift force that causes the device to float to the surface. After surfacing, the device is found using a beacon on the device. Next, it is loaded onto the carrier vessel. The use of an autonomous mining vehicle is possible both in summer with the help of carrier vessels and in winter from the surface of a frozen water area with the help of cranes operating in places of prepared openings in the ice. The device floats into the supported openings in the ice, where it is removed from the water by means of a crane and unloaded into a vehicle that transports the minerals to the processing site.

Upon completion of the considered process, the technical preparation for a new submersion cycle takes place. A technical inspection is carried out, the teeth of the device are brought into working position with an open grab bucket, the explosive is reloaded, and the integrity of the flexible container is checked. Next, the device is transported to the opening in the ice from where it is launched. Using a crane, the vehicle is lowered into the water, where the submersion begins under its own weight. Preparatory operations during the summer period are similar, except for the use of a separate vehicle for transporting the mineral and the vehicle itself to the submersion site. In that case the carrier vessel performs all of the listed functions.

![Figure 4. The technological scheme of operation of an autonomous device in winter:](image)

1 – crawler crane for delivery of an autonomous device; 2 – the mining autonomous device; 3 – flexible cavity for surfacing; 4 – a grab bucket; 5 – rock; \( P_a \) – the buoyant force (Archimedes’ principle); \( R_c \) – resistance force; \( G_t \) – gravity force; \( H_B \) – water depth; \( H_n \) – placer deposit thickness.

However, there is a problem of uncertainty in the calculations of the location of the autonomous vehicle during surfacing. This uncertainty is due to undercurrents that carry the device to an unknown distance.

To determine the distance between the point of lowering a solid body into the aquatic environment and the point of sampling, we consider the forces influencing the solid body with mass \( m_m \) and volume \( V_m \) descending in an unlimited volume of fluid at rest. Its movement is caused by gravity force \( G_t \), opposite to which the buoyant force (Archimedes’ principle) \( P_a \) and the resistance force \( R_c \) are directed. We determine it according to Newton’s second law:

\[
m_m \frac{dv}{dt} = G_t - P_a - R_c,
\]

where \( v \) is the speed of the body, m/s; \( t \) is the time of the body movement, s; \( dt \) is the time change, s; \( dv \) is the speed change, m/s; \( dv/dt \) is the acceleration m/s\(^2\).

The resistance force of a fluid to the body movement depends on its size, shape, surface roughness, orientation with respect to the flow and speed of movement. Its value is determined by the formula:

\[
R_c = \eta_1 \cdot S \cdot \frac{\rho \cdot v^2}{2},
\]

where \( S \) is the midsection area of the body, m\(^2\); \( \rho \) is the liquid density, kg/m\(^3\); \( \eta_1 \) is the correction factor, which depends on the shape of the body, roughness.

Having solved equation (1) with respect to acceleration and taking into account equation (2), we find:
\[
\frac{dv}{dt} = \left[ g \cdot \left( \frac{\rho_m - 1}{\rho} \right) - \frac{\eta \cdot S \cdot v^2}{V_m} \right] \cdot \frac{\rho}{\rho_m},
\]
(3)

where \( \rho_m \) is the body density, kg/m\(^3\); \( g \) is the free fall acceleration, m/s\(^2\).

Equation (3) shows that the acceleration of the body movement in a liquid takes place until the resistance force \( R_c \), which increases with the increasing speed, balances the difference in forces \( G - P_a \). From this moment on, the body begins to descend uniformly in the liquid with the acceleration equal to 0. The speed of uniform movement of the submerged body is called hydraulic fineness. Its value at zero acceleration can be determined from the formula (3).

The rate of lowering the body to the bottom of the reservoir is equal to:

\[
V_y = \sqrt{\frac{2 \cdot g \cdot V_m \cdot \left( \frac{\rho_m - 1}{\rho} \right)}{\eta \cdot S}}.
\]
(4)

The speed of uniform movement of the body along the Y-axis is determined according to this formula. However, the movement of the body is influenced by the lateral fluid flow directed along the X-axis, Figure 5.

![Figure 5. Deviation of a solid body from rectilinear motion taking into account the factor of lateral velocity of fluid flow.](image)

Based on the fact that the fluid flow influences lateral pressure, as a result of which the body deviates from rectilinear motion, the resistance will be calculated using the Stokes formula:

\[
k = \frac{\pi \cdot \eta \cdot l}{\rho},
\]
(5)

where \( \rho \) is the liquid density, kg/m\(^3\); \( l \) is the installation length, m; \( \eta \) is the coefficient of dynamic viscosity of the liquid, Pa s.

To determine the distance from the place of descent of the installation to the place of sampling, we use Newton's second law in the projection on the X-axis. Taking into account the factor of the force influencing the body in the direction of the flow vector and the force opposing the flow vector, we obtain the following dependence:

\[
\rho \cdot v^2 \cdot S - k \cdot v = m \cdot \frac{dv}{dt},
\]
(6)

where \( m \) is the mass of the installation and the equipment contained in it, kg; \( t \) is the time during
which the device floats from the surface to the bottom of the water area, \( s \); \( v_{cs} \) is the medium flow velocity, m/s.

At the moment when the force of lateral pressure is balanced by the resistance force, where the acceleration of the body becomes equal to zero, we transform the expression and obtain the speed of the lateral movement of the body equal to:

\[
V_x = \frac{\rho \cdot v_{cs}^2 \cdot S}{k}.
\]

(7)

Having transformed the obtained dependence in view of the resistance in the medium calculated by the Stokes formula, and solving the resulting equation, we obtain the following expression:

\[
V_x = \frac{V_0 \left(2 \cdot A - 2 \cdot \sqrt{A^2 + 4 \cdot A - 4}\right)}{2 \cdot (A - 1)},
\]

(8)

where \( A \) is a constant variable.

\[
A = \frac{S \cdot \rho^2}{\pi \cdot \eta \cdot l}.
\]

(9)

Knowing the flow velocity and the time of lowering the vehicle to the bottom, we determine the deviation distance (m):

\[
S_x = v_x \cdot t
\]

(10)

The velocity of the body floating to the surface of the reservoir is considered taking into account Newton's second law. After analyzing the forces influencing the body during the floating to the surface, the following expression is obtained:

\[
V_{ui} = \sqrt{\frac{2 \left[\rho \cdot g \cdot (V - V_0) - m \cdot g\right]}{\eta \cdot S \cdot \rho}},
\]

(11)

where \( V \) is the volume of the entire installation, m\(^3\); \( V_0 \) is the required volume of gas for the surfacing of this installation, m\(^3\); \( \eta \) is the coefficient of dynamic viscosity of the liquid, Pa s; \( s \) is the midsection area of the body, m\(^2\).

The required volume of gas for the surfacing of this installation in m\(^3\), we determined according to the formula:

\[
V_0 = \frac{m \cdot g + \eta \cdot \rho \cdot v_{cs}^2 \cdot S}{2 \cdot \rho \cdot g} = \frac{m}{\rho} + \eta \cdot \frac{v_{cs}^2 \cdot S}{2 \cdot g} \cdot V,
\]

(12)

To calculate the deviation of the installation from the place of sampling to the surface, we use the formula (6). Based on the presented methodology for calculating the distance of deviation under the influence of the flow, the calculation is made for water area conditions with a depth of up to 500 m and a flow velocity of up to 6 m/s. The results of the calculation when lowering are presented in Table 1 when surfacing – in Table 2.

Table 1. Deviation of the installation from rectilinear motion when lowering the tank to the bottom, depending on the depth of the reservoir.

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Deviation of the installation from rectilinear motion at different flow velocities, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 m/s</td>
</tr>
<tr>
<td>100</td>
<td>3.1</td>
</tr>
<tr>
<td>200</td>
<td>6.2</td>
</tr>
<tr>
<td>300</td>
<td>9.3</td>
</tr>
<tr>
<td>400</td>
<td>12.5</td>
</tr>
<tr>
<td>500</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Table 2. Deviation of the installation from rectilinear motion when surfacing, depending on the depth of the reservoir.

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Deviation of the installation from rectilinear motion at different flow velocities when surfacing, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 m/s</td>
</tr>
<tr>
<td>100</td>
<td>2.857</td>
</tr>
<tr>
<td>200</td>
<td>5.714</td>
</tr>
<tr>
<td>300</td>
<td>8.571</td>
</tr>
<tr>
<td>400</td>
<td>11.427</td>
</tr>
<tr>
<td>500</td>
<td>14.284</td>
</tr>
</tbody>
</table>

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Figure 6. The graph of the deviation of the installation from rectilinear motion, taking into account the lateral flow when lowering to the bottom.

Figure 7. The graph of the deviation of the installation from rectilinear motion, taking into account the lateral flow when surfacing.

Table 3. The influence of depth and flow velocity on the distance of transportation of the installation.

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>The distance between the launch point of the installation and the point of its surfacing, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>6.0 23.9 53.8 95.7 149.6 215.4</td>
</tr>
<tr>
<td>200</td>
<td>12.0 47.9 107.7 191.5 299.2 430.8</td>
</tr>
<tr>
<td>300</td>
<td>17.9 71.8 161.5 287.2 448.7 646.2</td>
</tr>
<tr>
<td>400</td>
<td>23.9 95.7 215.4 382.9 598.3 861.6</td>
</tr>
<tr>
<td>500</td>
<td>29.9 119.7 269.2 478.7 747.9 1077.0</td>
</tr>
</tbody>
</table>
Conclusion

As a result of the study, a new method of autonomous mining of minerals from the bottom of the continental shelf is substantiated. The increased efficiency of the device is directly related to the reduction of metal consumption, simplification of mining processes, and reduction of time for the extraction of minerals by combining the processes of loosening, excavation and transportation of the mineral to the surface of the reservoir without any connection of the vehicle with the carrier vessel. The calculations of the deviation of the installation from rectilinear movement are made taking into account the speed of the lateral flow when the vehicle is immersed to the bottom and surfaced.

References


