TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 11
Number 4
December 2017

DOI: 10.12716/1001.11.04.12

The Theoretical Basis of the Concept of Using the Controlled Pyrotechnical Reaction Method as an Energy Source in Transportation from the Sea Bed

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ABSTRACT: In recent years we have observed the global growing interest in undersea exploitation of mineral deposits. Research on various concepts of operating systems on the seabed has been conducted, where different methods of transporting excavated material from the bottom to the surface are used. Great depths, where there are the most interesting resources (eg. IOM lot for the Clarion-Clipperton 4500 m) set very high technical and technological demands which results in intensive search for solutions. The authors of the paper want to explain the concept of the use of pyrotechnic materials for transportation in the aquatic environment. The presented method is designed for the cyclic transport from great depths (less than 200 m from the seabed). The principle of operation of the relay unit is based on the change in the average density of the entire module which is inseparably connected with the force of buoyancy acting on the submerged body. Changing the density of the whole module to the given depth of immersion is strictly dependent on the amount of energy supplied to the system by a power source in the form of a controlled pyrotechnic reaction. However, during the ascent energy demand decreases. The problem of transport of spoil from depth not only boils down to such considerations as initiation of the process of ascent. One should also consider how to use the excess energy occurring during the movement of the object toward the surface. The authors of the paper present the concept of making the transport of cyclic depths (less than 200 m from the seabed) taking into account the optimal use of energy from controlled pyrotechnic reaction.

1 INTRODUCTION

In recent years we have seen the growing interest in the exploitation of seabed deposits. This is due to the increase in demand for minerals. The use of areas of shelves in sea mining (Karlic 1984, Depowski et al. 1998) provides a number of raw materials, not only oil and gas but also metallic materials such as titanium, zirconium, tin, gold, platinum and ferruginous sands, diamonds, phosphate rock, gravel and sand. The increasing interest has been stirred in huge areas of polymetallic nodules and polymetallic massive sulphide (SMS) (Abramowski & Kotliński 2011, SPC 2013). However, their operation is associated with many problems in science and technology (Sobota 2005). Nautilus Minerals can boast about the biggest success to date leading exploitation at the depth of approx. 1600 meters on Solwara (www.nautilusminerals.com). Transport from the seabed at significant depths to the surface has posed the biggest problems for researchers and designers so far. The proposed solutions to date have their advantages and disadvantages (Sobota 2005, SPC 2013), the largest of which is their high energy intensity affecting the high cost. Therefore the search for less cost-intensive methods has been developing.

The authors proposed the implementation of a new method which involves the use of pyrotechnics as a source of energy in transport from the seabed at significant depths and presented its theoretical aspects and also carried out experiments (Filipek & Broda, 2016, 2017). Both the depth which can be used in this method and determination of the energy required for transport were shown, depending on the density of the transported material (output). Control methods for pyrotechnic reaction were also proposed. The results confirmed the possibility of the use of pyrotechnic materials for the transportation from significant depths.

In the article the authors compare three concepts for the transport of excavated material from the seabed in terms of energy demand.

Considering the first concept, we are estimating what amount of energy is needed to pull the load from a certain depth to the surface. In the next concept, based on hydraulic transport, we define minimum energy guaranteeing the output mining from the seabed. In discussing the third concept, based on the use of controlled pyrotechnic reaction as a source of energy for transport from the seabed, we focus on the comparison of the method of transportation with the previous energy conditions in order to determine its suitability.

In our deliberations, the benchmark is E_p potential energy. For greater transparency of considerations relating to the first and second concept, we assume that every transported load of *m* mass and *V* volume, can be replaced with the theoretical sphere of *r* radius of the same weight and volume and ρ density.

2 DETERMINATION OF THE MINIMUM ENERGY REQUIRED TO PULL THE LOAD FROM H DEPTH.

In our deliberations we skip rope impact on movement issues. We assume that the load (output and the container) has the shape of a sphere of *r* radius. The average density of the transported cargo is ρ, and the density of the surrounding fluid load is ρ_p. We are considering mining (transport) of cargo from *H* depth. The extracted load (emerging) out of this depth of *v* velocity is affected by F_v resistance force of movement in liquid and the *Q* power being the difference in the weight of Q_c load and buoyancy Q_w (1).

$$Q = Q_c - Q_w = mg - V\rho_p g = (\rho - \rho_p)gV \tag{1}$$

Since we have assumed the spherical shape of the load – $V = ¾\, \pi r^3$. Therefore:

$$Q = \frac{4}{3}\pi(\rho - \rho_p)gr^3 \tag{2}$$

As the load moves towards the surface in the liquid of significant density, we should take into account the resistance to motion which, for an object moving in a liquid *v* velocity, can be represented in general form (Roberson &Crowe 1995, Tuliszka 1980, Duckworth 1977) (3)

$$F_v = C_x \frac{\rho_p v^2}{2} S = C_x \frac{\rho_p v^2}{2} \pi r^2 \tag{3}$$

Where C_x means drag coefficient. The situation above is shown schematically in Figure 1.

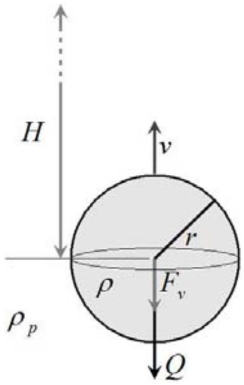

Figure 1. Distribution of forces acting on the extracted load from *H* depth

The amount of energy required for the ascent of the object at the given depth to the surface without the impact of the rope is marked for the first method with E_1. This energy is equal to the sum of the E_p potential energy and the energy associated with E_v movement:

$$E_1 = E_p + E_v \tag{4}$$

E_p potential energy in accordance with generally known equation is equal to the product of the force and the distance. According to this:

$$E_p = QH = \frac{4}{3}\pi(\rho - \rho_p)gHr^3 \tag{5}$$

And E_v – related energy amounts to

$$E_v = F_v H = C_x \frac{\rho_p v^2}{2} \pi H r^2 \tag{6}$$

In sum for E_1 (7)

$$E_1 = E_p + E_v = \frac{4}{3}\pi(\rho - \rho_p)gHr^3 + C_x \frac{\rho_p v^2}{2}\pi H r^2 = \\ = \pi H r^2 \left[\frac{4}{3}(\rho - \rho_p)gr + C_x \frac{\rho_p v^2}{2} \right] \tag{7}$$

An interesting finding, according to the authors, is what constitutes the ratio of the energy associated with E_v movement to E_p potential energy. It should be noted that the potential energy is always the same for the depth and density of the fluid, and the energy associated with the movement depends on the velocity and this is the only type of energy that we can control (velocity change), and it has an impact on transport costs. This ratio takes the following form:

$$\frac{E_v}{E_p}=\frac{C_x\frac{\rho_p v^2}{2}\pi Hr^2}{\frac{4}{3}\pi(\rho-\rho_p)gHr^3}=\frac{3}{8}\frac{C_x}{g}\frac{\rho_p}{\rho-\rho_p}\frac{v^2}{r}=Cv^2 \tag{8}$$

where: $C=\frac{3}{8}\frac{C_x}{g}\frac{\rho_p}{\rho-\rho_p}\frac{1}{r}$

After transformation of (8) we obtain:

$$E_v=CE_p v^2 \tag{9}$$

Substituting the above equation in (4) formula, we obtain:

$$E_1=E_p+CE_p v^2=E_p(1+Cv^2) \tag{10}$$

From the above equation it can be concluded that the total energy E_1 is the square function of v velocity of the transported load.

3 DETERMINATION OF MINIMUM ENERGY GUARANTEEING THAT THE LOAD WILL BE TRANSPORTED IN THE MOVING FLUID

The starting point for our consideration is to determine the minimum fluid v_p velocity at which you we can balance the transported weight adopted in line with the shape of a sphere.

In our discussion, we assume also that the sphere does not move or v = 0 (equilibrium). Under this assumption, F_v resistance movement in the fluid will be directed against Q force. This situation is presented in Figure 2.

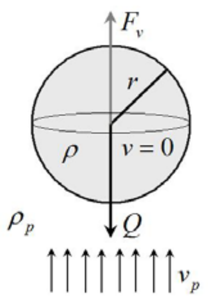

Figure 2. The distribution of forces acting on the stationary load in a moving fluid.

In the case in question when v = 0 forces Q and F_v must be equal. Thus:

$$Q=F_v \tag{11}$$

After substituting (2) and (3) values for v_p velocity we obtain:

$$\frac{4}{3}\pi(\rho-\rho_p)gr^3=C_x\frac{\rho_p v_p^2}{2}\pi r^2 \tag{12}$$

From this equations we determine the desired v_p velocity of the liquid:

$$v_p^2=\frac{8}{3}\frac{g}{C_x}\frac{\rho-\rho_p}{\rho_p}r \tag{13}$$

In order to check the accuracy of our considerations, we calculate E_v equations (for v_p velocity), which is marked as E_{vp} to E_p. For the case when $v = 0$ this equations should constitute 1. Therefore:

$$\frac{E_{v_p}}{E_p}=\frac{C_x\frac{\rho_p v_p^2}{2}\pi Hr^2}{\frac{4}{3}\pi(\rho-\rho_p)gHr^3}=\frac{3}{8}\frac{C_x}{g}\frac{\rho_p}{\rho-\rho_p}\frac{v_p^2}{r} \tag{14}$$

Substituting the following equation (13) into the formula below we obtain:

$$\frac{E_{v_p}}{E_p}=\frac{3}{8}\frac{C_x}{g}\frac{\rho_p}{\rho-\rho_p}\frac{1}{r}\frac{8}{3}\frac{g}{C_x}\frac{\rho-\rho_p}{\rho_p}r=\frac{1}{1}=1 \tag{15}$$

In this way we may conclude the correctness of our reasoning.

In the next step we will move the load inside the pipe of R radius and H length (height), wherein the load is transported to the surface. Velocity of the fluid in the pipeline is v_p and the density ρ_p. Figure 3 shows this case.

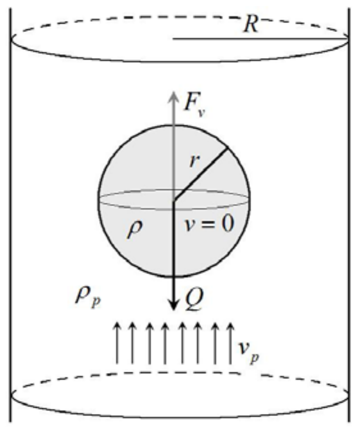

Figure 3. Spherical load within the pipeline, wherein the fluid is moving at a speed v_p in a state of equilibrium.

Let us consider the above case where the forces Q and F_v are equal, i.e., load is at rest (rate of load ascent v = 0). In our deliberations we have to take into account the energy needed to impart v_p velocity for the fluid in the pipeline and the energy loss line. We do not take into account the local loss, which actually occurs because we consider the simplest case of a simple pipeline. In fact, due to the omitted loss, local energy demand will be far greater. Starting from Hagen-Poisseuille equation (Roberson & Crowe 1995, Tuliszka 1980, Duckworth 1977), we determine the linear losses (in the form of pressure loss):

$$\Delta p_L=\lambda\frac{H}{2R}\frac{\rho_p v_p^2}{2} \tag{16}$$

Thus E_s loss energy equals:

$$E_s = \Delta p_L V \tag{17}$$

where V is the volume of liquid flowing at v_p through the perpendicular section of the pipeline of R radius and in t time. Thus

$$V = \pi R^2 v_p t \tag{18}$$

whereas flow time can be determined in a simple equation $t=H/v_p$. After substitution we obtain:

$$V = \pi R^2 v_p \frac{H}{v_p} = \pi R^2 H \tag{19}$$

Finally, loss energy will amount to

$$E_s = \lambda \frac{H}{2R} \frac{\rho_p v_p^2}{2} \pi R^2 H = \lambda \pi \frac{H^2}{4} \rho_p v_p^2 \tag{20}$$

Total energy E_2 required that the load is in a steady state (v = 0) is the sum of the energies E_s and loss of kinetic energy E_k liquid

$$E_2 = E_s + E_k \tag{21}$$

After substituting (20) equation to the formula above and the known equation for kinetic energy we obtain

$$E_2 = \Delta p_L V + \frac{\rho_p v_p^2}{2} V = \pi R^2 H \frac{\rho_p v_p^2}{2} \left(\lambda \frac{H}{2R} + 1 \right) \tag{22}$$

Substituting equation (13) to the formula above we obtain:

$$\begin{aligned} E_2 &= \pi R^2 H \frac{\rho_p}{2} \left(\lambda \frac{H}{2R} + 1 \right) \frac{8}{3} \frac{g}{C_x} \frac{\rho - \rho_p}{\rho_p} r = \\ &= \frac{4}{3} \frac{\pi R^2 H g}{C_x} (\rho - \rho_p) \left(\lambda \frac{H}{2R} + 1 \right) r \end{aligned} \tag{23}$$

Comparing the resultant energy dependence of the potential energy required to transport the load (5), we obtain the equation:

$$\frac{E_2}{E_p} = \frac{\frac{4}{3} \frac{\pi R^2 H g}{C_x} (\rho - \rho_p) \left(\lambda \frac{H}{2R} + 1 \right) r}{\frac{4}{3} \pi (\rho - \rho_p) g H r^3} = \frac{1}{C_x} \frac{R^2}{r^2} \left(\lambda \frac{H}{2R} + 1 \right) \tag{24}$$

Comparing the parameters appearing in the formula above, we conclude that this ratio will always assume the value greater than 1 and thus the total energy needed to maintain the load at steady state is always greater than the potential energy.

4 THE CONCEPT OF OPTIMIZING THE USE OF ENERGY FROM THE CONTROLLED PYROTECHNIC REACTION IN TRANSPORT FROM THE SEABED.

In our paper (Filipek & Broda 2016) we demonstrated that the description of the pressure distribution as a function of depth is virtually impossible without the knowledge of the local change of the density of liquids with the altitude and the local changes in the gravitational acceleration of depth. Therefore, we assumed that the pressure of 1 bar corresponds to the pressure of 10 m of water column (0.1 MPa). Or

$$\begin{aligned} 1\,[bar] &\approx 10\ mH_2O \approx 10^5 [\mathrm{Pa}] = 0{,}1 [\mathrm{MPa}] \\ 100\,[bar] &\approx 1\ kmH_2O \approx 10^7 [\mathrm{Pa}] = 10 [\mathrm{MPa}] \end{aligned} \tag{25}$$

From the considerations set out in the papers (Filipek & Broda, 2016, 2017) it turns out that in the case of using a controlled pyrotechnic reaction as a source of energy for transport from the seabed, two main reaction products emerge, namely carbon dioxide and nitrogen. Due to the low pressure of condensation (e.g. at as low pressure as 4 MPa at temperature of 4 °C (277 K), which corresponds to the pressure at depth of 400 m, carbon dioxide is transformed from a gas to liquid) we can therefore regard it as an adverse reaction product which should be eliminated. At pressures above 22 MPa (which corresponds to the depth of 2200 m), the density of the liquid CO_2 is greater than the density of water. Accordingly, the CO_2 as the reaction product became a negative ballast.

Let us assume that in further consideration the working medium will be pure nitrogen at a temperature equal to the temperature of the surrounding fluid. This does not mean that our concept of cyclic transport of CO_2 will not be included as a working medium. Works on the solution to this problem are underway and the results will be the subject of subsequent publications. In further discussion, in order to determine the hydrostatic pressure and medium density ρ_p, where the transport takes place we adopted clean water. Justification for the choice were presented in the paper (Filipek & Broda 2016). Graphs of the density of water, carbon dioxide and nitrogen pressure (hydrostatic pressure), temperature of 4 °C (277 K) are shown in Figure 4.

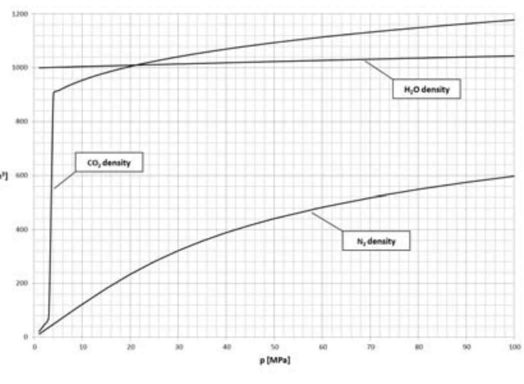

Figure 4. The dependence of H_2O, CO_2 and N_2 density on pressure (based on data from the http://www.peacesoftware.de/ einigewerte/einigewerte_e.html).

The article (Filipek & Broda, 2016) introduced the equation (26) determining the ratio of the total energy to potential energy in relation to the concept of using a controlled pyrotechnic reaction as a source of energy for transport from the seabed:

$$\delta = \frac{E_3}{E_p} = \frac{\rho_p}{\rho_p - \rho_\alpha} \tag{26}$$

wherein in our discussion ρ_α is the density of the controlled pyrotechnic reaction cooled to ambient fluid. In view of the above described assumptions, ρ_α is therefore density of nitrogen at a given pressure (hydrostatic pressure) and at a given temperature. The above relationship as function of pressure is shown in Figure 5.

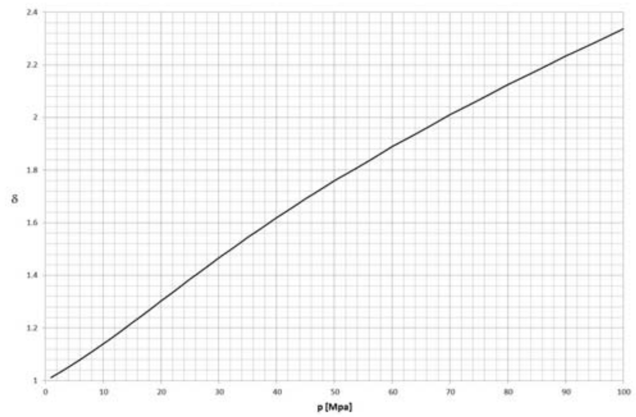

Figure 5. Relationship of total energy E_3 to the potential energy E_p to p pressure for nitrogen as the working medium.

In our concept, in order to retrieve the load of V volume and ρ density, we should generate Q_w buoyancy by creating V_α volume and ρ_α density as the result of the controlled pyrotechnic reaction. The desired $V\alpha$ volume can be derived from the equation (Filipek & Broda, 2016):

$$V_\alpha = V \frac{\rho - \rho_p}{\rho_p - \rho_\alpha} \tag{27}$$

In fact, V_α value is closely related to depth, and hence to the hydrostatic pressure. Due to this fact, more correct form of (27) equation is (28)

$$V_\alpha(p) = V \frac{\rho - \rho_p(p)}{\rho_p(p) - \rho_\alpha(p)} \tag{28}$$

During the ascent the difference between inner and outer pressure increases. In order to achieve these pressures to compensate, the excess nitrogen must be dissipated or we have to increase the volume occupied by nitrogen proportionately to the increase of hydrostatic pressure. Consequently, the density of nitrogen will change (decrease) resulting in an increase in Q_w buoyancy. Due to the increasing buoyancy, the load amount can be increased. Let us consider a case in which V_α generated at a given depth is not changed during the ascent. Assume that at a given depth from which we begin to consider the process of load transport the volume amounts to $V = V_0$. In addition, we assume that the volume $V_\alpha(p)$ generated at a given depth amounts to V_α and $\rho_p(p) = \rho_{po}$ and $\rho_\alpha(p) = \rho_{\alpha o}$. Rearranging (28) equation, we obtain the following:

$$V(p) = V_\alpha \frac{\rho_p(p) - \rho_\alpha(p)}{\rho - \rho_p(p)} \tag{29}$$

Therefore, the increase in buoyancy generates the possibility of increasing the amount of the transported load of ρ density by additional ΔV volume. Having included the above variables we obtain the following

$$\Delta V = V(p) - V_o = V_\alpha \frac{\rho_p(p) - \rho_\alpha(p)}{\rho - \rho_p(p)} - V_\alpha \frac{\rho_{po} - \rho_{\alpha o}}{\rho - \rho_{po}} \tag{30}$$

Calculating $\Delta V/V_o$ relationship, we obtain the following equation:

$$\frac{\Delta V}{V_o} = \frac{\rho_p(p) - \rho_\alpha(p)}{\rho - \rho_p(p)} \frac{\rho - \rho_{po}}{\rho_{po} - \rho_{\alpha o}} - 1 \tag{31}$$

Now imagine that the transport system consists of sequentially connected serial (vertical) equal transport elements. Let us consider what additional load our system can transport in relation to the adopted initial load of V_o volume. To do this, increases the volume of the individual elements of the transport system should be added, which we can express in the following equation:

$$\chi = \sum \frac{\Delta V}{V_o} = \sum_i \left(\frac{\rho_p(i) - \rho_\alpha(i)}{\rho - \rho_p(i)} \frac{\rho - \rho_{po}}{\rho_{po} - \rho_{\alpha o}} - 1 \right) = \int \left(\frac{\rho_p(i) - \rho_\alpha(i)}{\rho - \rho_p(i)} \frac{\rho - \rho_{po}}{\rho_{po} - \rho_{\alpha o}} - 1 \right) di \tag{32}$$

The analytical solution of the above equation exists. The authors worked it out but because of a complicated form authors used in this case, the iterative method is applied, assuming that the lowermost part of the system is at a depth corresponding to the pressure of 100 MPa at a depth corresponding to the final pressure of 1 MPa. The individual elements of the transport system are spaced (vertically) with a distance corresponding to the pressure of 1 MPa.

The results are shown in the graph (Figure 6), assuming that $\xi_o = \rho/\rho_{pp}$ where ρ_{pp} is the density of the fluid at the surface. From the graph it is clear that the system has a large reserve of energy as such for example for ξ_o= 2 system it can also transport the 36-times the volume of transported load in one V_o segment, of course, with the established intervals between the segments.

In the next step we will try to determine how much energy we are able to recover with the previously made assumptions.

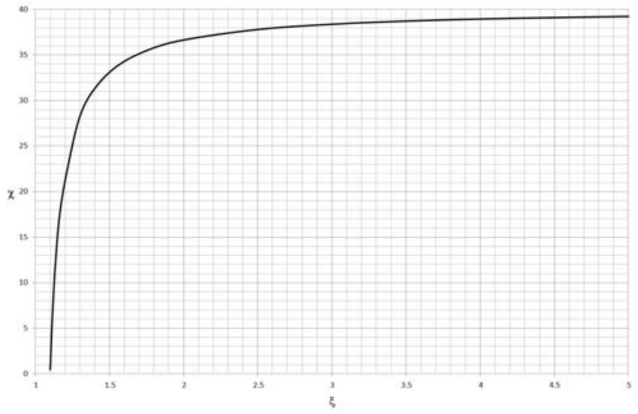

Figure 6. The relationship of the growth times of the transported V_o volume to density of transported ρ load in relation to ρ_{pp} fluid density at the surface.

Let us convert (26) into the following form:

$$E_3 = E_p \frac{\rho_p}{\rho_p - \rho_\alpha} \tag{33}$$

Where E_p potential Energy can be expressed with the following equation

$$E_p = pV \frac{\rho - \rho_p}{\rho_p} \tag{34}$$

which was derived in Filipek & Broda (2016). Substituting (34) into (33) we obtain

$$E_3 = \frac{\rho - \rho_p}{\rho_p - \rho_\alpha} pV \tag{35}$$

ΔE energy increase resulting from ΔV volume increase amounts to:

$$\Delta E = p\Delta V \tag{36}$$

Considering relation $\Delta E/E_3$ we obtain

$$\frac{\Delta E}{E_3} = \left(\frac{\rho_p - \rho_\alpha}{\rho - \rho_p} \frac{\rho - \rho_{po}}{\rho_{po} - \rho_{\alpha o}} - 1 \right) \frac{\rho_p - \rho_\alpha}{\rho - \rho_p} \tag{37}$$

For the whole transport system with the previous assumptions (37) equation takes the following form:

$$\chi_E = \sum_i \frac{\Delta E(i)}{E_3(i)} = \\ = \left(\frac{\rho_p(i) - \rho_\alpha(i)}{\rho - \rho_p(i)} \frac{\rho - \rho_{po}}{\rho_{po} - \rho_{\alpha o}} - 1 \right) \frac{\rho_p(i) - \rho_\alpha(i)}{\rho - \rho_p(i)} \tag{38}$$

On the basis of the equation we can compile a graph (Fig.7)

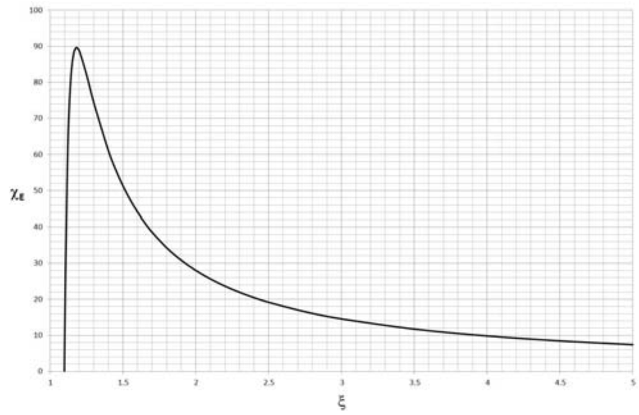

Figure 7. Relation of multiplicity factor to the related density of the ρ transported load to ρ_{pp} fluid density at the surface.

In the graph we can clearly observe the extremum. The optimal energetic status of the system corresponds to this extremum.

5 CONCLUSION

In this paper, considering energy demand in the three concepts of output transport from the seabed, the authors adopted in fact Newton's first law as a point of reference: "if the body does not act affected by external forces, or the forces are balanced, the body remains at rest or moves with rectilinear uniform motion " which is the development of the Galileo's ideas (Halliday &Resnick 1978, Feynman 1963). He noted that if we remove the obstacles to the movement, it will no longer be necessary to support the movement by any force. Rectilinear uniform motion will be performed by itself, without any external help. Such movement is sometimes referred to as free movement. Such adoption of the reference point allows to determine energy demand, but from the physical point of view we have to take into consideration three different cases in fact although in each case operating forces are balanced. In the first case, considered transported load to be taken to the surface is held at a constant v velocity, therefore, according to Newton's first law of motion the motion is rectilinear and uniform. In the second and third case the v velocity of the objects equals zero. As a result, theoretically considered object will never reach the surface. However, both these cases also substantially differ from each other physically. In the second case we have from the physical point of view the so called system of stable equilibrium (Halliday &Resnick 1978, Feynman 1963) and unless deliberately intended otherwise, the body is at rest.

In order to retrieve the transported object to the surface we must provide additional energy which will be greater than the value determined from the equation (23). While in the third case under consideration we have, from the physical point of view, the system of the so called unstable balance (Halliday &Resnick 1978, Feynman 1963). Slight deflection of the object in question from the point of equilibrium results in the freedom of movement without the need to provide additional energy. In order to compare these three concepts unambiguously for the transport of load from the seabed to the surface, we must clearly align the method based on which will base the comparison. Assume that the reference is the minimum energy E_o necessary for a considered object to remain at rest v = 0, that is, a steady state and providing a higher energy $E_o = E + dE$ allowed to start the process of its ascent. In the first considered case for $v = 0$, we obtain, in accordance with equation (10), $E_1 = E_p = E_o$.

In the latter case of converting the equations (24) we obtain:

$$E_2 = \frac{1}{C_x}\frac{R^2}{r^2}\left(\lambda\frac{H}{2R}+1\right)E_p = \frac{1}{C_x}\frac{R^2}{r^2}\left(\lambda\frac{H}{2R}+1\right)E_o \qquad (39)$$

In this equation C_x is unknown, the value of which in a general way, we are not able to determine without knowing the geometry of the load being transported by pipeline of R radius. Assumption adopted earlier to replace this load with a sphere is of course correct when it comes to such a size as V, r and ρ. It does not concern C_x parameter.

A rough value of this parameter can be estimated as $C_x < 1$. The ratio R/r can be replaced by the value of volume concentration C_v (Sobota 2005) which has a value within a range of from 0.1 to 0.16. Linear Drag coefficient λ falls between 0.0076 to 0.0101 (Sobota 2005). R value, however, is generally less than 1 [m]. From these considerations emerges a picture of a very energy-intensive methods of transporting excavated material from the seabed to the surface.

More preferred approach is to use the method of controlled pyrotechnic reaction as a source of energy in transport from the seabed. In the case, when the working fluid is nitrogen ratio of E_3 to E_o is shown in Figure 5, which shows that this ratio does not exceed 2.4. This method, however, is more energy-intensive than the method analyzed as first. However, there is one very positive aspect of this method. In the first method, there is an additional demand for energy, which is directly proportional to the square of the speed of ascent object on the surface. In the case of the third method, once initiated, the process of ascent is theoretically self-supported. Additionally, it generates excess energy that can be exploited.

In Figure 6 and the equation (31, 32) it is evident that the application of controlled pyrotechnic reaction as a source of energy for transport from the seabed is much more advantageous in the case of using a serial connection than the conveying elements for the transport of a single load.

ACKNOWLEDGMENTS

This article was written within Statutes Research AGH, No. 11.11.100.005

REFERENCES

Abramowski, T. & Kotliński, R. 2011. Współczesne wyzwania eksploatacji oceanicznych kopalin polimetalicznych. Górnictwo i geoinżynieria. Rok 35, zeszyt 5, pp.41-61.
Depowski, S. & Kotliński, R. & Rühle, E. & Szamałek, K. 1998. Surowce mineralne mórz i oceanów, Wydawnictwo Naukowe Scholar, Warszawa
Duckworth, R.A. 1977. Mechanics of Fluids. London: Longman Group Limited
Feynman, R.P. & Leighton, R.B. & Sands, M. 1977. The Feynman Lectures on Physics, vol.1. Addison Wesley
Filipek, W. & Broda, K. 2016. Theoretical foundation of the implementation of controlled pyrotechnical reactions as an energy source for transportation from the sea bed. Scientific Journals of the Maritime University of Szczecin 48 (120): 117-124
Filipek, W. & Broda, K. 2017. Experimental verification of the concept of the use of controlled pyrotechnic reaction as a source of energy as a part of the transport system from the seabed. In press
Halliday, D. & Resnick, R. 1978. Physics, Part I. New York: John Wiley & Sons, Inc.
http://www.nautilusminerals.com [12 March 2016]
http://www.peacesoftware.de/einigewerte/einigewerte_e.html
Karlic, S. 1984. Zarys górnictwa morskiego, Wydawnictwo „Śląsk", Katowice
Roberson, J.A. & Crowe, C.T. 1995. Engineering Fluid Mechanics. John Wiley & Sons, Inc.
Sobota, J. et. al. 2005. Systemy i technologie wydobycia konkrecji z dna oceanów. Zeszyty Naukowe Akademii Rolniczej we Wrocławiu nr 521, Monografie XLIII, Seria: Współczesne problemy inżynierii środowiska. Wrocław
SPC, 2013 Deep Sea Minerals: Sea-Floor Massive Sulphides, a physical, biological, environmental, and technical review. Baker, E., and Beaudoin, Y. (Eds.) Vol. 1A, Secretariat of the Pacific Community, ISBN 978-82-7701-119-6, Available from: http://gsd.spc.int/dsm/public/files/meetings/TrainingWorkshop4/UNEP_vol1A.pdf [12 July 2015]
Tuliszka, E. 1980. Mechanika płynów. Warszawa: Państwowe Wydawnictwo Naukowe