TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19
Number 1
March 2025
DOI: 10.12716/1001.19.01.26

An Innovative Approach to the Problem of Transporting Spoil from Great Depths in Deep-Sea Mining

W. Filipek, K. Broda & B. Tora
AGH University of Science and Technology, Kraków, Poland

ABSTRACT: The article presents an innovative approach to one of the key challenges in offshore mining – transporting ore from the seabed to the surface. Traditional methods, such as CLB (with continuareline bucket), HP (hydraulic pumping), ALP (air-lift pumping) or hybrid techniques, are associated with high energy consumption and high operating and environmental costs. To adddress these limitations, the authors propose an alternative solution based on the use of physicochemical phenomena, which significantly reduces energy consumption.
The starting point is the analysis of basic physical principles, such as potential energy or the buoyancy principle, in the context of the aquatic environment and high pressure conditions at great depths. The authors consider the use of the natural properties of the working medium as a source of power for the ascent process, as well as the potential for energy recovery, which enhances the energy balance and the transport system's efficiency.
The article presents the results of theoretical and simulation studies, which have laid foundation for numerous patents and scientific publications. The authors emphasize the practical potential of the proposed solutions, indicating at the same time the need for further work on their implementation in real-world conditions.

1 INTRODUCTION

The biggest problem in offshore (open-pit) mining is transport from great depths to the surface. Despite many studies [1,8,21,25,26,27], the solutions used so far, based on the continuareline bucket (CLB) method, the hydraulic pumping (HP) method or the air-lift pumping (ALP) method, are far from ideal. First of all, they are energy-intensive and thus generate high costs, hence the search for less costly methods. It is also important that operation and transportation be done in an environmentally friendly manner.

In our research, we have addressed the problem of transporting dredged material from the seabed to the surface and decided to look at the problem from the perspective of a new energy source. The idea is based on the concept of using the phase transition of a solid or liquid into a gaseous state or a solid into a liquid as a source of energy for transportation from the seabed [3-6,9-20].

Such were the beginnings, but as our research work progressed, we began to look at the problem a little differently. Therefore, in this article, we will synthetically review our scientific achievements that do not necessarily follow a temporal research chronology. The problem is transport from great depths and it is cyclic, so we have adopted the concept of operation of the transport module as a separate area where, among other things, we can realize the idea based on the applications of phase transition of a solid or liquid into a gaseous state or a solid into a liquid as a source of energy for transport from the seabed.

The principle of the transport module is based on the change in the average density of the entire module, which is inextricably linked to the buoyancy force acting on the submerged body [23,24]. In the case where the average density of the module is greater than that of the surrounding medium, the buoyancy force is less than the weight of the body and sinking (sinking) occurs, while in the opposite case the buoyancy force is greater than the weight of the body and the body rises. A special case is when the average density of the module is equal to the density of the surrounding medium, then the buoyancy force is equal to the weight of the body, and the body remains in "motionlessness" floating in the fluid.

The change in the average density of an object immersed in a given medium is currently achieved in two ways. The first, used in submarines, is based on the use of so-called ballast tanks, which are filled with water or emptied with compressed air as needed. This method is used when the depth of submersion is not great and does not exceed several hundred meters. Below this depth, the second method is used for technical reasons. It consists in submerging with ballast, and then, in order to surface, the ballast must be dumped by which it is irretrievably lost settling on the bottom of the water body under study. A separate approach is unmanned underwater vehicles, whose average density of an object submerged in a given medium is almost equal to the density of the surrounding medium. However, these objects are mainly used for research and not for transporting dredged material from the seabed on an industrial scale.

2 CONCEPT OF THE TRANSPORT MODULE.

The idea of using phase transition as a source of energy for transport in an aquatic environment [12] is shown in Figure 1. It shows the two most important stages of the transport module's operation, namely: sinking to the bottom and rising to the surface. As mentioned earlier, the process of sinking to the bottom can be carried out only if the density ρ_m of the transport module - equal to the density ρ_s of the substance with volume V_s before the phase transition, assuming that we neglect the mass of the structure - is greater than the density ρ_{H2O} of the water surrounding the transport module. On the other hand, ascent can be realized only if the density ϱ_m will be less than the density ρ_{H2O}. It was assumed that the subscript "α" next to the density and volume symbol refers to the substance that has undergone a phase transition, which was previously, before the transition, marked with the subscript "s". At this stage of the presentation of the concept of using phase transformation as a source of energy for transport in the aquatic environment, we will not go into detail about what the substance or mixture of substances is and what physical and chemical processes it undergoes during the aforementioned phase transition.

It should be mentioned that the initial state of the processes taking place inside the transport module to change the average density ρ_m of the object under consideration is denoted by the subscript "s" and the final state is denoted by the subscript "α". The subscript "u" next to the symbol for density and volume refers to the excavated material (in the broad sense of the term) that the module transports from the seabed toward the surface. We can neglect the density of the transport module's structure because it is constant during both descent and ascent, so there is no problem in balancing it with selected floats of appropriate density so that its effect on the total density ρ_m of the transport module can be neglected.

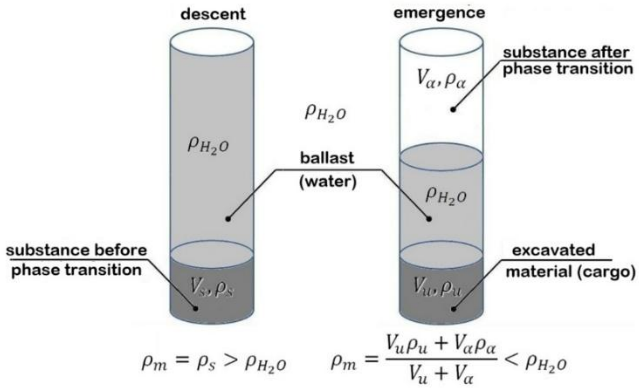

Figure 1. The concept of using phase transition as a source of energy for transport from the seabed [9].

An interesting concept we studied ex situ was an autonomous transport module [6,13-18,] using phase transition as an energy source for transport in an aquatic environment. The object was to submerge, wait a preset amount of time and automatically surface with the load. The control process of the module was carried out only by physical and chemical processes without the involvement of sensors or additional electrical or electronic control systems.

3 FACTORS DETERMINING THE OPERATION OF THE TRANSPORT MODULE.

In order for the proposed transport method to be competitive with current solutions, it must be characterized by lower energy intensity. The minimum energy required to move a mass between two points in a gravitational field is determined by the potential energy ΔE_p, or work $W_{1\text{-}2}$ (Figure 2). It is this quantity that we have taken as a reference point in our considerations. Taking the concept of free ascent of a body under the influence of a change in the average density ρ_m of the object under consideration (that is, the transport module), it is necessary to determine what work $W_{1\text{-}2}$ must be done by the working medium, for example, a gas (denoted by the subscript α), in order for the value of the buoyancy force to be greater than the weight of the device.

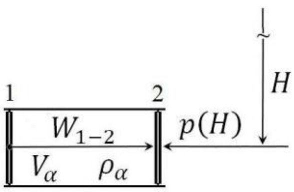

Figure 2, Diagram explaining how to determine the energy required for the free ascent of the transport module.

Equation (1)

$$\left.\begin{aligned}\gamma_\alpha &= \frac{\rho_\alpha}{\rho_{H_2O}}\\ \delta_{E\alpha} &= \frac{E}{\Delta E_p}\end{aligned}\right\}\delta_{E\alpha} = \frac{\rho_{H_2O}}{\rho_{H_2O}-\rho_\alpha} = \frac{1}{1-\gamma_\alpha} \qquad (1)$$

explains, among other things, that the work done in creating the volume V_α at depth H will always be greater than the hypothetical work we would have to do in pulling the considered object from depth H to the surface. It should be noted that in equation (1) there is no, any parameter that determines the physical properties of the transported excavated material like its density. However, in deriving this relation [10,11,12] we started from the formula for work $W_{1\text{-}2}$ taking into account the densities of the transported excavated material.

The coefficient $\delta_{E\alpha}$ is a dimensionless value and informs us about the energy demand in relation to the potential energy, but at the same time we have no information, for example, about the mass of the transported load. This can be interpreted as follows. Knowing the density ρ_α of the working medium, we know the value of energy demand. In addition, knowing the densities of the transported ore and the volume V_α, we can determine the mass of the ore we are able to transport. Nevertheless, it is the density ρ_α of the working medium that determines the energy demand.

Figure 3 shows the mutual correlation between γ_α and $\delta_{E\alpha}$.

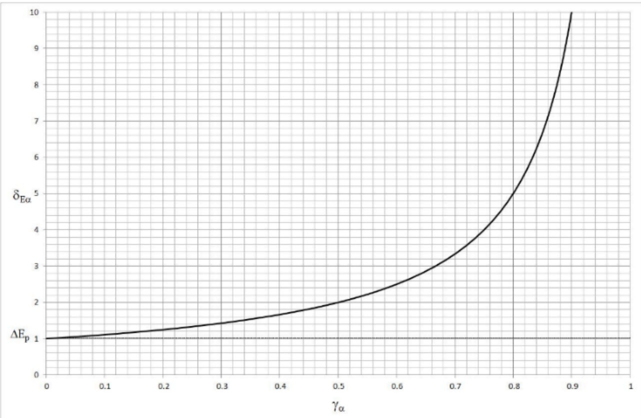

Figure 3. Graphical interpretation of the correlation of the δE_α coefficient with the γ_α coefficient [12].

We can see that in order for the work of creating an area V_α filled with a fluid of density ρ_α at depth H to be equal to the potential energy ΔE_p taken as a reference point, the density of ρ_α at depth H must be zero (vacuum). The more the density ρ_α approaches the value of ρ_{H2O}, the more work must be done by the working medium. This is as reasonable as possible, because the higher the value of density ρ_α is, the more work it must produce.

4 ENERGY COMPARISON OF THREE SEABED TRANSPORTATION CONCEPTS.

Let's now take a look, in terms of energy requirements, at three concepts for transporting excavated soil (cargo) from the seabed, shown in Figure 4. and discussed in more detail in the article [9,11]. In the first concept (I), we consider what energy is needed to pull the cargo from a certain depth to the surface. In the next one (II), based on hydraulic transport, we determine the minimum energy to guarantee the extraction of excavated material from the seabed. And in the third concept (III) based on changing the average density of the entire module as a source of energy for transport from the seabed, we focus on comparing this method of transport with the previous ones in terms of energy to determine its suitability.

In our considerations, the reference point is the potential energy Ep. In order to make the consideration of the first and second concepts more transparent, we assume that we can replace each transported load of mass m and volume V with a theoretical sphere of radius r with the same mass and volume and density ρ. Whereby, to simplify the notation of the relationship, we will assume that $\rho_{H2O}=\rho_p$ and it is the density of seawater at the considered depth.

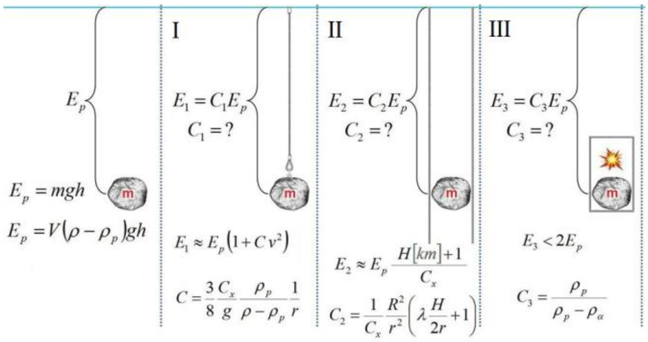

Figure 4. Graphical interpretation of comparison of energy demand for different methods of transport from the seabed.

In the first case considered (I), the energy E_1 required to transport the excavated material from the seabed to the surface is, as can be seen, the product of the potential energy E_p and the quadratic function $(1+C\cdot v^2)$ mainly dependent on the velocity of extraction of the cargo v. In the diagram shown, we ignore the effect of the lifting rope on the considered energy E_1 to relate it only to the cargo. In the analysis of energy E_2 (II) based on hydraulic transport, which currently seems to be the most popularized transport system, we can roughly estimate its value as directly proportional to the depth of immersion H, but as a parameter expressed in units of [km]. Whereby R is the inner diameter of the pipe in which the proces of transporting the cargo towards the Surface takes place. It should be noted that in the dependance on the energy E_2 there is no velocity of the cargo lift because it is taken as zero. There is also no value for the velocity of the medium, i.e. seawater, because it can be expressed in a different form, which is precisely derived in the article [11]. On the other hand, C_x in both cases considered is defined as the coefficient of drag force and depends on the geometry of the transported cargo.

Now let's look at our concept of transport III based on the change in the average density of the whole module. Note the much simpler expression of the dependence of E_3 on E_p with respect to the other two. However, the value of the coefficient C_3 less than twoi s due to the fact that the density of the working medium and, in particular, gas for a depth of 5 [km], which corresponds to a pressure of about 500 [bar], is for most of the fluids we analyze less than two (for example, for nitrogen it is 1.8). Comparing this with the two previous cases considered, it is easy to see that Concept III in the form as presented is energetically the most favorable for us with regard to the idea of transport from the seabed [5].

5 EFFECT OF COMPRESSION OF THE WORKING MEDIUM ON THE ENERGY BALANCE OF THE PROCESS

Concept III, presented above, in practice does not turn out to be as advantageous as it might seem, since it would probably have long since found application in the transport of dredged material from the seabed. It is worth noting that in Concept III we started our considerations with the assumption that the working medium already has a suitable pressure value. In reality, however, this is not the case, especially when the working medium is gas, which must first be compressed to the required pressure.

Let's analyze this problem in more detail, assuming that the working medium is nitrogen, and the starting point is located on the free surface of the sea, where the temperature is 20°C and the pressure is 1 bar. The end point, on the other hand, is located at a depth of about 5 km, where the temperature is 4°C and the pressure is 500 bar.

Using the online calculator available at [https://webbook.nist.gov/chemistry/fluid/], we can estimate the compression energy requirements of Ekom needed to achieve the pressure balancing hydrostatic pressure at a depth of 5 km. We will determine the work from equation:

$$W = \Delta H - \Delta U \quad (2)$$

Which is a fundamental relationship derived from the definition of enthalpy and the first law of thermodynamics [2,7,22].

Thus, for the assumed starting point, the value of internal energy U_1 is 217.08 kJ/kg and enthalpy H_1 = 304.06 kJ/kg.

At the end point, the value of internal energy U_2 is 127.83 kJ/kg and enthalpy H_2 = 241.10 kJ/kg. Meanwhile, the density of the medium at the end conditions is ρ_α=441.42 kg/m^3.

Based on the above values, according to relation (2), the work of compression W is 26.29 kJ/kg.

We can also estimate the potential energy E_p that is needed to move the excavated mass corresponding to 1 kg for a depth difference of 5 km. This value is $E_p \approx$ 49.05 kJ/kg. Note that in our considerations m=V·(ρ_u-ρ_p). Knowing the compression energy E_{kom}, we can determine the total energy requirement E_{3C} according to concept III.

$$E_{3C} = E_{kom} \cdot \delta_{E\alpha} \quad (3)$$

We can also, as in equation (1), define the dimensionless coefficient of

$$E_{3C} = E_{kom} \cdot \delta_{E\alpha} \quad (4)$$

and consequently the coefficient

$$E_{3C} = E_{kom} \cdot \delta_{E\alpha} \quad (5)$$

Finally, we can write the total energy demand E_{3C} in the form of

$$E_{3C} = E_{kom} \cdot \delta_{E\alpha} \quad (6)$$

Assuming δ_p = 1000 kg/m^3 and ρ_α as we defined earlier is the coefficient $\delta_{E\alpha}$ = 1.79. Since seawater is heavier than the assumed value of δ_p then consequently $\delta_{E\alpha}$ will be less than 1.79 but not significantly.

Returning to the determined energy of compression E_{kom}, we see that it is smaller than the estimated potential energy E_p. It also turns out that E_{3C} of 47.06 kJ/kg is smaller than the estimated potential energy Ep. The problem of the erroneous result is caused by our overzealousness in correctly assuming the end point for which t_2 is smaller than t_1 and determining the work of compression directly from equation (2). The compression process itself can be constrained by two extreme processes. One is a perfectly isothermal process and the other a perfectly isentropic process. In both cases considered, we assumed that the temperature of the initial point is t_1 = 20 °C. Let's look at the first process. In this case, the compression energy requirement E_{kom} is 32 kJ/kg. This is less than the estimated potential energy E_p but ultimately δ_η is greater than one and is 1.17. Consequently, the total energy demand E_{3C} is greater than the estimated potential energy E_p. In the second case, the compression energy demand E_{kom} is as high as 426.42 kJ/kg. The process temperature rises to a value of 1269 °C. The value of δ_η is 15.56 and the value of δ_{kom} is equal to 8.69.

6 CONCLUSIONS

In conclusion, in our research we actually took Newton's first law as a reference point: " if there are no external forces acting on a body, or the acting forces balance each other, then the body remains at rest, or moves in uniform rectilinear motion" which is a development of Galileo's ideas. He noted that if we remove the obstacles to motion, the need for any force to sustain motion disappears. Uniform rectilinear motion will go on by itself, without any external help; we sometimes refer to such motion as free motion, or translating free ascent to our research area.

In the context of our consideration of the total energy required for ascent with respect to E_p, two parameters are of key importance. The first is $\delta_{E\alpha}$, which is a dimensionless quantity that depends solely on the physical properties of the environment. We have no influence on the value of this parameter.

The second parameter, δ_{kom}, is also a dimensionless quantity, but its value is related to processes that we can already significantly influence. This raises the question of whether it is possible to eliminate this parameter. The analysis shows that the value of δ_{kom} depending on the compression process can take values from 0.65 to 8.89.

Aiming to eliminate the compression energy requirement, we proposed the concept of using the phase transformation - of a solid or liquid into a gas, or of a solid into a liquid - as an alternative energy source for transporting material from the seabed (Figure 1). This was the issue we tackled first which resulted in articles [3-6,9-20] and patents [6,18].

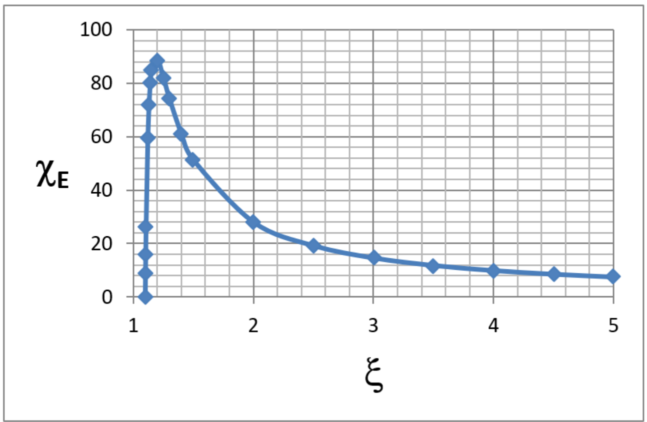

Figure 4. Dependence of the possibility of energy recovery χ_E [%] on the parameter ξ, which is the ratio of the density of the transported cargo ρ_u to the density of sea water ρ_p on the surface [9,11].

The concept of using the phase transformation of a solid or liquid into a gaseous state or a solid into a liquid has one characteristic property that distinguishes it from the systems currently in use. This characteristic is the possibility of using (in the next cycle) part of the energy (Figure 4) that has been generated or is necessary to initiate the ascent of the transport module. The method of transporting excavated material from the seabed using rope or hydraulic methods is associated with the property that the total energy that we had to use to perform the intended purpose is irretrievably lost [5].

Returning to the first case considered, in which the determined energy requirement E3C of 47.06 kJ/kg is less than the estimated potential energy Ep. was a stimulus for thought. The problem of the erroneous result, which earlier in this article we described as caused by our overzealousness in the correctness of the assumption of the endpoint, was actually the inspiration for a new look at the problem under consideration. This resulted in articles [5,15,17,19,20] and patents [6,18] dealing precisely with the recovery, storage and conversion of a portion of energy. The one that is not used at a given position of the transport module in the ascent and descent process in order to use it when it is needed to continue the set process.

ACKNOWLEDGEMENT

The research was financed from subsidies for the maintenance and development of the research potential of the AGH University of Science and Technology in Kraków, Poland.

REFERENCES

[1] Abramowski T, Kotliński R (2011) Współczesne wyzwania eksploatacji oceanicznych kopalin polimetalicznych. Górnictwo i geoinżynieria 35(5):41-61

[2] Atkins, P., de Paula, J. (2010). Physical Chemistry (9th ed.). Oxford University Press.

[3] Broda K., Filipek W., (2018). Sposób transportu i urządzenie transportujące ładunek w wodzie, zwłaszcza z dużych głębokości — [Method of transportation and the device transporting a load in water, preferably from large depths] / Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie; wynalazca: Krzysztof BRODA, Wiktor FILIPEK. — Int.Cl.: E21C 50/00(2006.01). — Polska. — Opis patentowy ; PL228529B1 ; Udziel. 2017-11-24 ; Opubl. 2018-04-30. — Zgłosz. nr P.414387 z dn. 2015-10-16

[4] Broda K., Filipek W., (2018). Sposób transportu i urządzenie transportujące ładunek w środowisku płynnym, zwłaszcza z dużych głębokości — [Method of transportation and the device transporting a load in fluid environment, preferably from large depths] / Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie ; wynalazca: Krzysztof BRODA, Wiktor FILIPEK. — Int.Cl.: E21C 50/00(2006.01). — Polska. — Opis patentowy ; PL228530B1 ; Udziel. 2017-11-24 ; Opubl. 2018-04-30. — Zgłosz. nr P.414388 z dn. 2015-10-16

[5] Broda K., Filipek W., Tora B. (2023). Polish Experience in Offshore Mining: The New Concept of Transport Deep-Sea Concretions and Processing; 4GEO, Springer, Springer Nature.

[6] Broda K., Filipek W., (2025). Sposób transportu i autonomiczne urządzenie do transportu ładunku w wodzie, zwłaszcza z dużych głębokości — [Method of transportation and an autonomous device for transportation of a load in water, preferably from large depths] / Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie ; wynalazca: Krzysztof BRODA, Wiktor FILIPEK. — Int.Cl.: E21C 50/00(2006.01). — Polska. — Opis patentowy ; PL246767B1 ; Udziel. 2024-12-12 ; Opubl. 2025-03-03. — Zgłosz. nr P.425482 z dn. 2018-05-09

[7] Çengel, Y.A., Boles, M.A. (2014). Thermodynamics: An Engineering Approach (8th ed.). McGraw-Hill Education.

[8] Depowski S, Kotliński R, Rühle E, Szamałek K (1998) Surowce mineralne mórz i oceanów, Wydawnictwo Naukowe Scholar, Warszawa

[9] 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) 2016, pg. 117-124

[10] 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, Scientific Journals of the Maritime University of Szczecin, 49 (121) 2017, 77-83.

[11] Filipek W., Broda K. (2017),The Theoretical Basis of the Concept of Using the Controlled Pyrotechnical Reaction Method as an Energy Source in Transportation from the Sea Bed, TransNav the International Journal on Marine Navigation and Safety of Sea Transportation, Vol.11, No. 4, 653-659.

[12] Filipek W., Broda K. (2017),Research on the Application of Controlled Pyrotechnic Reaction with the Use of Ammonium Nitrate for Transport from Seabed, TransNav the International Journal on Marine Navigation and Safety of Sea Transportation, Vol.11, No. 4, 647-652.

[13] Filipek W., Broda K. (2018) Theoretical research on the gas phase density change in processes occurring during work of the transport module intended for transport from the seabed / W: Proceedings of the international conference on Human safety in work environment : operating machinery and equipment : integrated

management systems: quality - environment - safety - technology : October 23–27, 2018, Gdańsk-Nynashamn-Stockholm-Tallinn-Stockholm-Nynashamn-Gdańsk. — Warszawa : STE Group Sp. z o. o., 2018. — (New Trends in Production Engineering ; ISSN 2545-2843 ; vol. 1 iss. 1). — ISBN: 978-83-952420-0-7. — S. 597–604. — Bibliogr. s. 603–604, Abstr.
[14] Filipek W., Broda K. (2018) Theoretical research on the stability of the transport module intended for transport from the seabed / W: Proceedings of the international conference on Human safety in work environment : operating machinery and equipment : integrated management systems: quality - environment - safety - technology : October 23–27, 2018, Gdańsk-Nynashamn-Stockholm-Tallinn-Stockholm-Nynashamn-Gdańsk. — Warszawa : STE Group Sp. z o. o., 2018. — (New Trends in Production Engineering ; ISSN 2545-2843 ; vol. 1 iss. 1). — ISBN: 978-83-952420-0-7. — S. 605–612. — Bibliogr. s. 611–612, Abstr.
[15] Filipek W., Broda K. (2018) Experimental research on the concept of using an autonomous transport module for transport from the seabed / // W: Proceedings of the international conference on Human safety in work environment : operating machinery and equipment : integrated management systems: quality - environment - safety - technology : October 23–27, 2018, Gdańsk-Nynashamn-Stockholm-Tallinn-Stockholm-Nynashamn-Gdańsk. — Warszawa : STE Group Sp. z o. o., 2018. — (New Trends in Production Engineering ; ISSN 2545-2843 ; vol. 1 iss. 1). — ISBN: 978-83-952420-0-7. — S. 267–275. — Bibliogr. s. 274–275, Abstr.
[16] Filipek W., Broda K. (2018) Research on the concept of using calcium carbide as a source of energy for transport from the seabed / W: Proceedings of the international conference on Human safety in work environment : operating machinery and equipment : integrated management systems: quality - environment - safety - technology : October 23–27, 2018, Gdańsk-Nynashamn-Stockholm-Tallinn-Stockholm-Nynashamn-Gdańsk. — Warszawa : STE Group Sp. z o. o., 2018. — (New Trends in Production Engineering ; ISSN 2545-2843 ; vol. 1 iss. 1). — ISBN: 978-83-952420-0-7. — S. 277–284. — Bibliogr. s. 284, Abstr.
[17] Filipek W., Broda K. (2019) Theoretical research on mass exchange between an autonomous transport module and the environment in the process of transport from the seabed / W: Advances in marine navigation and safety of sea transportation / eds. Adam Weintrit, Tomasz Neumann. — Boca Raton [etc.] : CRC Press/Balkema : Taylor & Francis Group, cop. 2019. — Publikacja zawiera materiały z: TransNav 2019 : 13th international conference on Marine navigation and safety of sea transportation : 12–14 June 2019, Gdynia, Poland. — ISBN: 978-0-367-35760-3 ; e-ISBN: 978-0-429-34193-9. — S. 143–149. — Bibliogr. s. 148–149, Abstr.. — Abstrakt w: TransNav 2019 : abstracts of papers presented during the 13th international conference on Marine navigation and safety of sea transportation : Gdynia, 12–14 June 2019 / eds. Adam Weintrit, Tomasz Neumann. — [Gdynia : s. n.], [2019]. — S. 71
[18] Filipek W., Sposób transportu i autonomiczne urządzenie do transportu ładunku w wodzie, zwłaszcza z głębin — [Method of transportation and an autonomous device for transportation of a load in water, preferably from deep waters] / Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie ; wynalazca: Wiktor FILIPEK. — Int.Cl.: B66F 19/00(2006.01). — Polska. — Opis patentowy ; PL237989B1 ; Udziel. 2021-03-15 ; Opubl. 2021-06-28. — Zgłosz. nr P.425483 z dn. 2018-05-09
[19] Filipek W., Broda K., (2024). Autokompresja jako sposób akumulacji energii odpadowej podczas wynurzania się autonomicznego modułu transportowego wykorzystującego zmianę wyporności — Autocompression as a method of accumulating waste energy during the emergence of an autonomous transport module using a change in buoyancy / Inżynieria Mineralna = Journal of the Polish Mineral Engineering Society ; ISSN 1640-4920. — 2024 — vol. 2 no. 1, s. 181–188. — Bibliogr. s. 187–188, Streszcz., Abstr. — Publikacja dostępna online od: 2024-07-25.
[20] Filipek W., Broda K., (2025). O możliwości zastosowania dwutlenku węgla jako nośnika energii do transportu z dna morskiego — On the possibility of using carbon dioxide as an energy carrier for transport from the seabed / Inżynieria Mineralna = Journal of the Polish Mineral Engineering Society ; ISSN 1640-4920. — 2024 — vol. 3 no. 2, s. 263–270. — Bibliogr. s. 269–270, Streszcz., Abstr. — Publikacja dostępna online od: 2025-03-03.
[21] Jones DO, Durden JM, Murphy K, Gjerde K, Gebicka A, Colaço A, Morato T, Cuvelier D, (2019) Existing environmental management approaches relevant to deep-sea mining. Mar Polic 103:172-181
[22] Moran, M.J., Shapiro, H.N., Boettner, D.D., Bailey, M.B. (2014). Fundamentals of Engineering Thermodynamics (8th ed.). Wiley.
[23] Roberson J.A., Crowe C.T., (1995) Engineering Fluid Mechanics, John Wiley & Sons, Inc.
[24] Roberson J.A., Cassidy J.J, Chaudhry M.H., (1995) Hydraulic Engineering John Wiley & Sons, Inc.
[25] Sharma R., (2017) Deep-sea mining: resource potential, technical and environmental considerations. Springer International Publishing AG,
[26] SPC (2013) Deep sea minerals: sea-floor massive sulphides. A physical, biological, environmental, and technical review. In: Baker E, Beaudoin Y (Eds.), Vol. 1A, Secretariat of the Pacific Community, Sydney
[27] The Royal Society (2017) Future ocean resources [https://royalsociety.org/~/media/policy/ projects/future-oceans-resources/future-of-oceans-evidence-pack.pdf]