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Preliminary Design Considerations for a Ship to Mine Polymetallic Nodules in the Clarion-Clipperton Zone

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ABSTRACT

In this paper we present some initial considerations which can be used in developing the design of a polymetallic nodules mining ship. The requirements for cargo volume and deadweight are studied on the basis of assumed production output. A novel concept for cargo discharging to a shuttle transport ship by self-unloading is proposed. The presented analysis of cargo characteristics showed that there are several issues which affect the subdivision of the ship and the approach to the problem of arranging its structure. The first proposal of a general ship layout is given, including ship subdivision, hull shape, hydrostatics calculations and a functional study.

KEY WORDS: polymetallic nodules; deep; ocean; mining; ship; design;

INTRODUCTION

Up so far, mining ships for polymetallic nodules extraction in commercial scale have neither been in operation nor even their design was seriously analysed. Any comparison between an initial analysis of the economic feasibility of nodules mining (e.g. Yamazaki, 2008) and FPSO ship building costs (Cotty, Selhorts, 2003), (Abramowski, Kaup, 2006) which might be considered as the type of a ship most similar to a future nodule mining ship, reveals that its design concept has tremendous impact on economic effects of the undertaking. The overall CAPEX for an FPSO to build may vary from 200 to 1200 mUSD, depending on the water depth, production region, outfitting, type of positioning system etc. Although an FPSO is designed for different cargo and the nodule cargo imposes some problems discussed later in the paper, it seems similar as far as its function is concerned.

Some proposals regarding the nodule mining ship's main particulars have been published and some tests have been carried out. None of them however can be viewed as data ready for use in commercial scale. The most notable has been the design and ocean trials of *The Hughes Glomar Explorer* (Chung, 2009 a,b). The ship was intended to be used in exploration phase rather than full-scale mining. This is due to insufficient cargo storage space reserved for the extracted nodules and the lack of at-sea unloading systems having a capacity sufficient for the effective transfer of nodule slurry to transportation ships. Other proposals concerning the mining ship particulars were put forward (Brink, Chung, 1981) regarding the size of the ship – 300,000 tons of displacement. Authors clearly stated that they treated this size more as an input parameter for a DP system simulations. Some of the ship particulars were presented for ship's weight of 350,000 tons. This parameter is obviously important for dynamics simulations but it does not correspond with the steel and outfitting weight of an empty ship – so called lightship condition, which is in turn critical for ship CAPEX analysis. Moreover, what is showed further in the paper, the proposal for a 300,000 tons displacement mining vessel seems to be somewhat oversized.

Any proper estimation of the ratio of mining ship displacement (fully loaded) to lightship or weight of cargo values (displacement efficiency coefficient) should be based on initial considerations regarding the transshipment timing cycle and the nodules production rate, as well as, what is often forgotten, the nodules density (changing much depending on the grade of their crushing). The nodules mining ship is most likely supposed to spend all its technical life at the field. Due to extremely long distances from an ore field in the Clarion-Clipperton Zone to any shore stations under consideration, it will have to assume the role of a large storage terminal following the mining machine on the seabed.

BASIC CONSIDERATIONS

Any ship design should firstly fulfil the equilibrium condition which requires the weight of the ship and buoyancy being the same. In notation used in ship's design practice this can be written as follows:

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot k = W + DWT \quad (1)$$

where: L – ship length, B – breadth, T – draught, C_B – block coefficient, ρ – the density of water, k – appendage coefficient, W – the overall weight of ship structure (including outfitting), DWT – deadweight in tons.

In the initial design phase the above equation contains five essential unknowns (L, B, T, C_B, W) with DWT being a goal to attain, given by a shipowner. Usual practice in the design is to build additional regression relations with the above variables, based on a so-called similar ships database. It is possible after several iterations to reach a satisfactory solution, making the use of design process constraints like e.g. restrictions on water depth or transit canals breadth, or operational requirements concerning speed, manoeuvrability or sea keeping qualities. Nonetheless, for a mining ship there is no similar ships database and an open question regarding the deadweight parameter should still be discussed. There are no clear premises for the determination of deadweight, but it must assumed that it represents a maximum cargo load that the ship can store in the holds, fulfilling the requirements of the Loading Line Convention. The cargo is then trans-shipped in a certain cycle to the shuttle transport ship. This cycle depends on the assumed output of the mining ship and yearly nodules production. Several ISA contractors have analysed this problem and proposed that yearly production of wet nodules should be in the range of 1,000,000 – 5,000,000 tons. For the development stage of mining ship design it seems to be reasonable just to adopt a mean value of this range and then work out several design concepts. For this purpose it was assumed as a starting point that the yearly production is 3,000,000 tons of wet nodules. Adopting the achievable loading rate range from 5,000 to 8,000 t/h and a transshipment cycle period of 5–10 days, the deadweight range for the mining ship may be assumed to be 60,000–120,000 tons, with its discharging operation lasting 12–18 hours.

CARGO TYPE IMPACT ON MINING SHIP STRUCTURE AND SUBDIVISION

Polymetallic nodules are bulk cargo so their stowage factor should be carefully studied. Stowage factor states how many cubic meters are taken by one cargo tonne. This is critical for the calculation of cargo holds space. Run of mine (ROM) in nodule production is not homogenous cargo. Some authors proposed to crush the nodules in the mining machine and pump them as slurry, although there were proposals to transport them vertically without crushing as well. The density of nodules is changing from abt. 2 t/m^3 non-crushed, to 3.5 t/m^3 in slurry. This results in stowage factor of 0.28 - 0.5 m^3/t and this is a typical range for iron ore.

According to the SOLAS (Safety of Life at Sea Convention) chapter XII *Additional Safety Measures for Bulk Carriers* by the IMO (International Maritime Organization), now in force since 1999, all new bulkers 150 metres in length or more, carrying cargoes with a density of 1 t/m^3 and above, should have sufficient damage stability to survive flooding of any one cargo hold, taking into account dynamic effects resulting from the presence of water in the hold and taking into account the recommendations adopted by IMO. This requires special scenario-based damage stability simulations for any initial mining ship concept.

Cargoes with a density of 1.78 t/m^3 and above (heavy cargoes) include e.g. iron ore, pig iron, steel, bauxite. Therefore, polymetallic nodules in any state of ROM will be treated by regulations as heavy cargo. IMO requested a study into bulk carrier damage conditions to be carried out by the IACS (International Association of Classification Societies). IACS concluded that if a foremost hold of a ship is flooded, the bulkhead between the two foremost holds may not be able to resist the pressure forces exerted by the sloshing of cargo and water mixture. If the bulkhead between hold one and the next hold collapses, flooding could rapidly occur throughout the whole cargo length of the ship and the vessel is likely to sink in a matter of minutes. IACS concluded that the weakest areas are the bulkhead between the two foremost holds at the fore end of the vessel, and the double bottom at this location. Particular attention should be paid to these areas of such ships' structural design and, where necessary, additional reinforcements should be provided.

Another important issue arising from the density of cargo and concerning storage of heavy cargo in holds is a very low position of the centre of mass when a ship is fully loaded. Whereas this results in very favourable initial stability (large value of metacentric height), at the same time it causes a very short period of rolling and high accelerations bringing about inertial forces acting on ship structures, outfitting and its cargo. It is then suggested to design an elevated double bottom to keep the centre of gravity higher. The above considerations are reflected in typical arrangements used for an ore carrier, Fig. 1, which are different than those applied for a standard bulk cargo vessel.

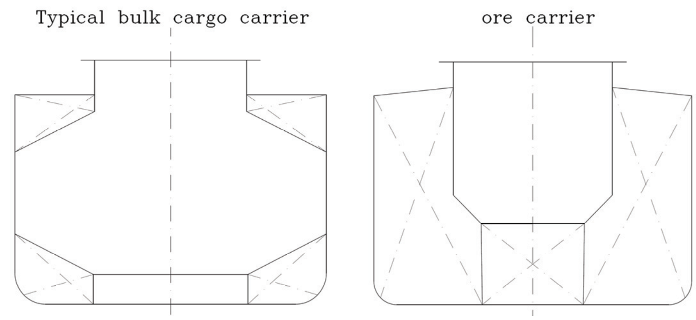

Fig. 1. Heavy cargo (such as polymetallic nodules or ore) influence on the midship section structure of a bulk cargo vessel.

Any proposal for a mining ship will be required to fulfil construction rules prescribed by a classification society and it is definitely expected that due to the nature of the cargo a society is likely to apply their rules for bulk cargo vessels, even if the ship is expected to be used more as a terminal than for ore transport.

MINING EQUIPEMENT AND UNLOADING DEVICES

Essentially, apart from its terminal and storage function, a mining ship must follow the mining collector and store the mined nodules received via a connected riser. It is not the purpose of this paper to analyse that equipment and proposals in any detail, but some considerations must be made from the point of view of preliminary ship design.

Riser deployment system. The issue to be discussed early in the design phase is whether the mining ship needs a tower for deploying the riser by itself. Present technologies for oil and gas extraction and the related development of riser technology (Di Silvestro, Casola, Fatica, Mameli, Prandi, 2006), allow for the installation and deployment of the riser built in a shipyard as a whole, which takes place by means of a towing operation and positioning the riser in deep water with the use of buoyancy elements. Risers are towed to the field and several methods for this type of riser erection have been worked out. The towing operation may take place on sea surface, or the riser may be towed submerged, also in horizontal position.
Such an approach provides even more space on a mining ship, which can be used for additional cargo or other equipment. In case of a design where a mining ship should deploy riser by itself, a lot of space is needed for riser sections and an installation tower must be erected on a ship. The design concept presented here assumes that the ship will not deploy the riser by itself.

Ship motion compensation. Vertical ship movement (heave) causes vertical force acting on the riser, which can be transferred down and results in unwanted stresses in the structure. Heave compensators reduce the effect of vertical ship heave on the vertical transport system. Without heave compensation, mining operations would require calm seas, with large amounts of time spent waiting for good weather. Several design solutions used in oil and gas extraction technology can be directly applied, as this technology is widely used. Final design can be selected in more advanced design phases, and the result depends also on the deformation characteristics of a riser. Some authors proposed a so-called flexible riser which may likely reduce the problem of heave compensation. However, no detailed study has been presented so far for the application of this proposal within the nodules mining system.

Cargo unloading system and its influence on ship subdivision. The devices for cargo trans-shipment are a crucial part of the mining ship design. They should be able to transfer the accumulated nodules at a sufficient loading rate, shortening the time of this operation to a minimum. Several options are available in this regard, starting from standard grab cranes installed above the cargo holds, as well as systems installed onboard the so-called self-unloading bulk cargo vessels. The latter are a particularly tempting option - due to a consistent structure of such a design, there is a single system of conveyor belt(s) placed along the whole length of the ship, gathering nodules from all cargo holds. Such a system can easily be designed to include a dewatering or drying mechanism. Dewatering conveyor belt devices are commonly used in mines and on ships as well. Self-unloaders have a capital cost which is 20-35 per cent higher than conventional bulkers and also provide less space for cargo than conventional ships of the same size do. However, these disadvantages are balanced by a facilitation of cargo discharging, which is a crucial function of a nodule mining ship. The use of such a system for a mining ship brings about another advantage - as there is no need to unload the vessel in ports, in consequence it is unnecessary to provide full-size hatch covers which simplifies the design and improves longitudinal strength of the hull. The drawback of such a system is that there is no watertight subdivision along the length of the cargo part. This complicates the design process and a solution can either be to use additional watertight compartments or to arrange various function areas of the ship in such a way as to allow shorter floodable compartments. For the sake of prototype design suitable for further investigations, it was assumed that the discharging boom will be located in the aft part of the ship - see general arrangement of the designed ship presented in appendices.

Eight holds are planned, four on each board with a “V” shaped cross-section, with trimming tops fulfilling also the wing tanks function. The gates for the discharge of nodules are situated at the base point of each hold. Upper and lower wing tanks for ballast and fuel occupy the spaces created by the shape of the holds, and double bottom ballast tanks are also included. During the discharging operation, the nodules are driven by gravity from the holds through hydraulically operated hopper gates to two dewatering conveyor belts which run aft beneath the holds. They are then raised from hold level to boom height by a vertical conveyor, from where it joins the boom conveyor belt to be discharged. The boom unloads nodules at any point up to 35 m from the ship's sides, which makes possible to transfer the cargo to the most typical large bulk cargo ships. Floatation of the ship during unloading is corrected by ballasting. The operation takes place concurrently with unloading.

The reason for fitting eight holds, four on each ship’s board is to shorten the breadth of a single hold and decrease the risk of stability loss due to cargo free surface effects. This solution improves damage stability characteristics in longitudinal direction, due to the presence of watertight longitudinal bulkhead. Whereas the density of the nodules makes them a type of bulk cargo, they may be prone to fluidization, especially when they are crushed to finer sizes by a mining machine. Free surface effect affects the stability of a ship due to a shift of its centre of gravity. The shift of the centre of gravity occurs due to a change in mass distribution caused by ship motions, especially rolling. Such motions may be due to sharp turns (operational), or due to natural reasons such as wind or wave forces acting on a ship. The changes of ship mass distribution may be due to liquid or otherwise easily occurring cargo shifts in a cargo hold. Since the head of liquid keeps it level parallel to waterline, thus the centre of liquid mass moves with the movement of liquid head in the ship. This typically happens when a ship has partially filled fuel tanks or water tanks and causes instability which may lead to ship capsizing. Decreasing the breadth of a hold reduces the risk of stability loss. The metacentric height reduces proportionally to the third power of breadth dimension of a hold, the effect is proportional to the moment of inertia of free surface.

INITIAL PROPOSAL FOR MINING SHIP DESIGN

The design proposal has been prepared for the purposes of presentation of the above considerations, while the presented results can serve as a starting point for further, more detailed analysis. The assumptions for the design are as follows:

Yearly production of wet nodules, YPO = 3,000,000 t/y
Working days, WD = 320
Daily production, DP = 9375 t/d
Nodules stowage factor, NSF = 0.4 m^3/t
Cargo hold volume coefficient, CVC = 0.7
Self-discharging rate, SR = 6000 t/h
Unloading cycle, UC = 7–8 days
Duration of unloading cycle, DUC = 12-15h

The above assumptions lead to the following deadweight and cargo volume requirements:

Deadweight of the designed ship, DWT = 72,000 t
Overall cargo volume, OCV = 41,000 m^3

Considerations regarding the unloading system and the requirements given above are a starting point for ship subdivision design. Additionally, they may be used as an indication for an assessment of mining collector(-s) production rate. The result of the design process is presented in appendices. It was assumed that the ship’s superstructure is best located in the fore part of the vessel. It is obvious that the ship has to be equipped with a dynamic positioning system, powered by a diesel-electric plant. Consequently, the superstructure can be placed in the fore part of the ship as it is unnecessary to install a shaft line. This is the most favourable location for the good visibility of all operations and, even more important in the case under consideration, it reduces the risk of first hold bulkhead collapsing which is an operational problem for bulkers discussed earlier in the paper. The area for deploying and hoisting a mining collector is located in the very aft of the ship, together with a crane used for that purpose. Full scale hatch covers are not used in the design.

The ratios of designed ship main dimensions were adopted using the FPSO design experience, except for the ratio of length to height (depth), L/H, which was increased due to envisaged heavy cargo and possible problems with longitudinal strength as well as more demanding requirements of the Loading Line Convention (ship will be classified as type B). The following ranges of main dimension ratios were adopted:

L/B = 5 – 5.3;   L/H = 9.5 – 10.5;   B/H = 1.8 – 2.0

The ship should fit the limits of new Panama Canal locks, but as these are increased so significantly (L = 366 m, B = 48 m, T = 15.2 m), this does not present a problem for deadweight values under consideration. Starting from the adopted ratios and the requirements regarding minimum cargo volume a subdivision of the ship has been prepared. The results are presented as a general arrangement drawing and pictures of the shape of the hull. Definition of hull shape allowed for calculating the principal hydrostatic characteristics which are given in Table 1.

Table 1. Hydrostatic characteristics of the mining ship.

Parameter	Value	Unit
Displacement, D	110840	[tonne]
Draft, T	12.9	[m]
Length of waterline, L_{WL}	227	[m]
Breadth, B	43.2	[m]
Midship area, A_M	554	[m^2]
Waterplane area, A_W	9352	[m^2]
Block coeff. C_B	0.845	[–]
Midship coeff. C_M	0.996	[–]
Waterplane area coeff. C_{WP}	0.950	[–]
Long. center of buoyancy, LCB from AP	115.8	[m]
Center of floatation, LCF from AP	109.6	[m]
Height of buoyancy center, KB	6.8	[m]
Trans. metacentric radius, r_T	12.7	[m]
Long. metacentric radius, r_L	344.2	[m]
Trans. metacenter, KM_T	19.5	[m]
Long. metacenter, KM_L	351	[m]
Immersion (tons per cm draft)	95.9	tonne/cm
Wetted surface area	14349	[m^2]

According to the hydrostatic calculations and the criteria for deadweight, the weight of steel and the outfitting should not exceed W=38,840 tons. There is a large margin for a reduction of this value in the design iterations to follow. Dividing the deadweight by the displacement we can obtain a value of displacement efficiency - 0.65. From the cargo efficiency point of view this value is far from extreme, as standard designs of transport ships can achieve this ratio falling in 0.75–0.85 range. It should however be remembered that much additional weight is required for mining equipment and self-unloading machinery, and that hull structures will need to be additionally strengthened due to the nature of cargo and the planned location of ship operations, remote from ship repair services.

CONCLUSIONS

The analysis of problems involved in the design of a mining ship reveals several issues which should be carefully studied during more detailed design phases. One of the most important systems of such a ship, strongly affecting the adopted design solutions, is the unloading system. The presented initial design (see appendix) was prepared assuming constant yearly production of nodules. Whether the self-unloading system proposed here is feasible for operation at the assumed unloading rate in the environment of Clarion Clipperton Zone should be further studied in detail. It is also necessary to analyze the accelerations and inertia forces acting on the loading boom as a result of ship motions, and perhaps to apply a stabilization device or a different approach. The obtained results can be used as a starting point for the design iterations to follow. Further research and development works will be devoted to the estimation of the power required for a dynamic positioning system, seakeeping calculations, stability and damage stability analysis, stress criteria and the layout of stiffeners, as well as capital and operation costs. On the basis of the achieved results it can be concluded at present time that the capital cost for a mining ship might be comparable (excluding costs of riser and mining collector) with the cost of a complex bulk cargo carrier, equipped with a dynamic positioning system and additional outfitting necessary to meet the operational prerequisites. However, the cost of outfitting and design development in such projects usually are very high and exceed the initial estimates.

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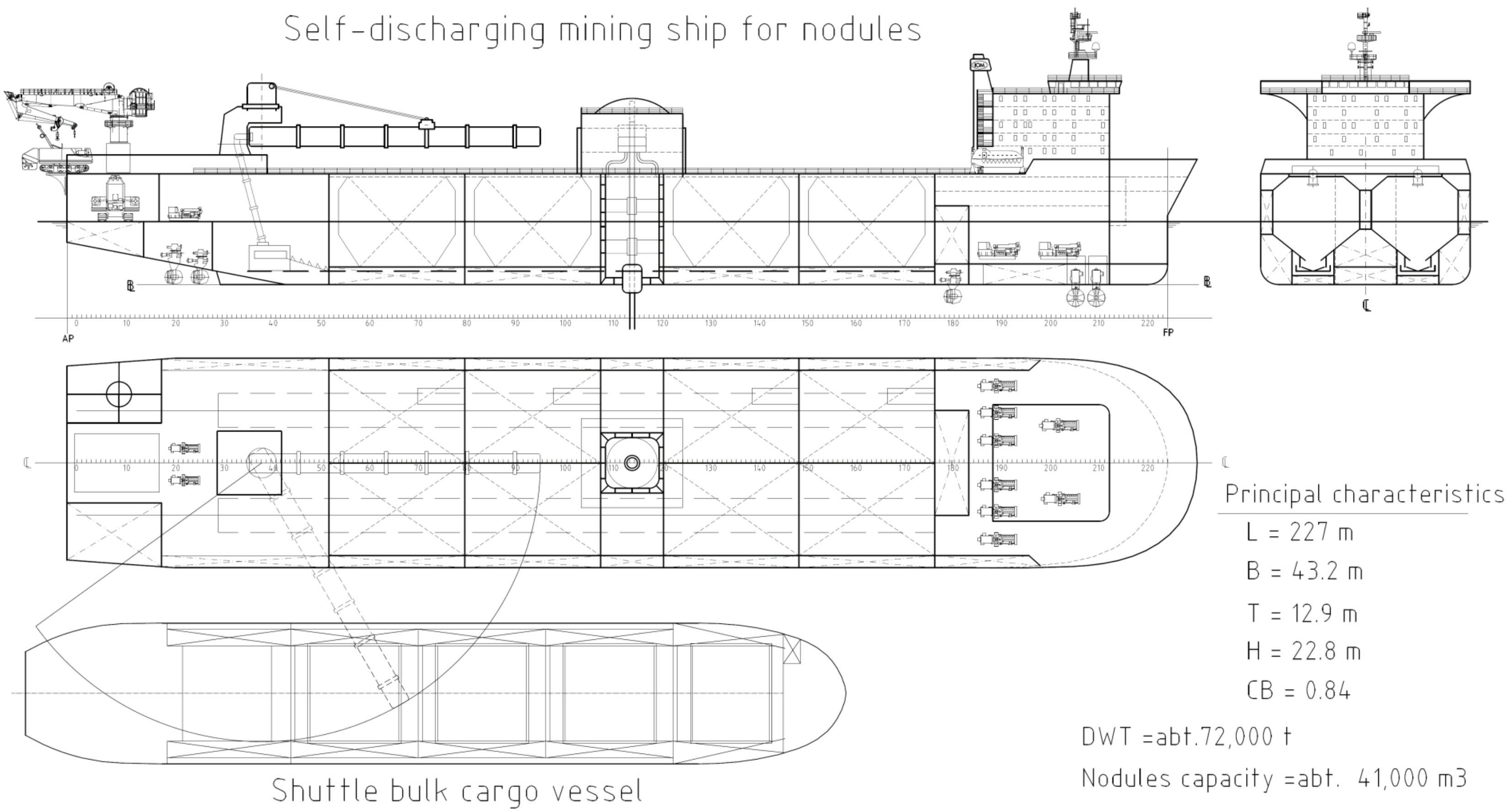
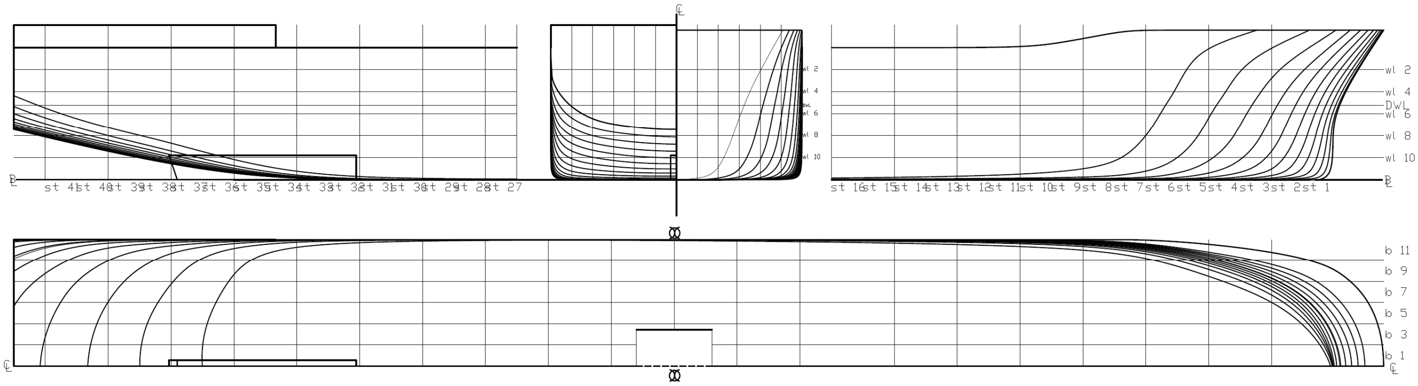
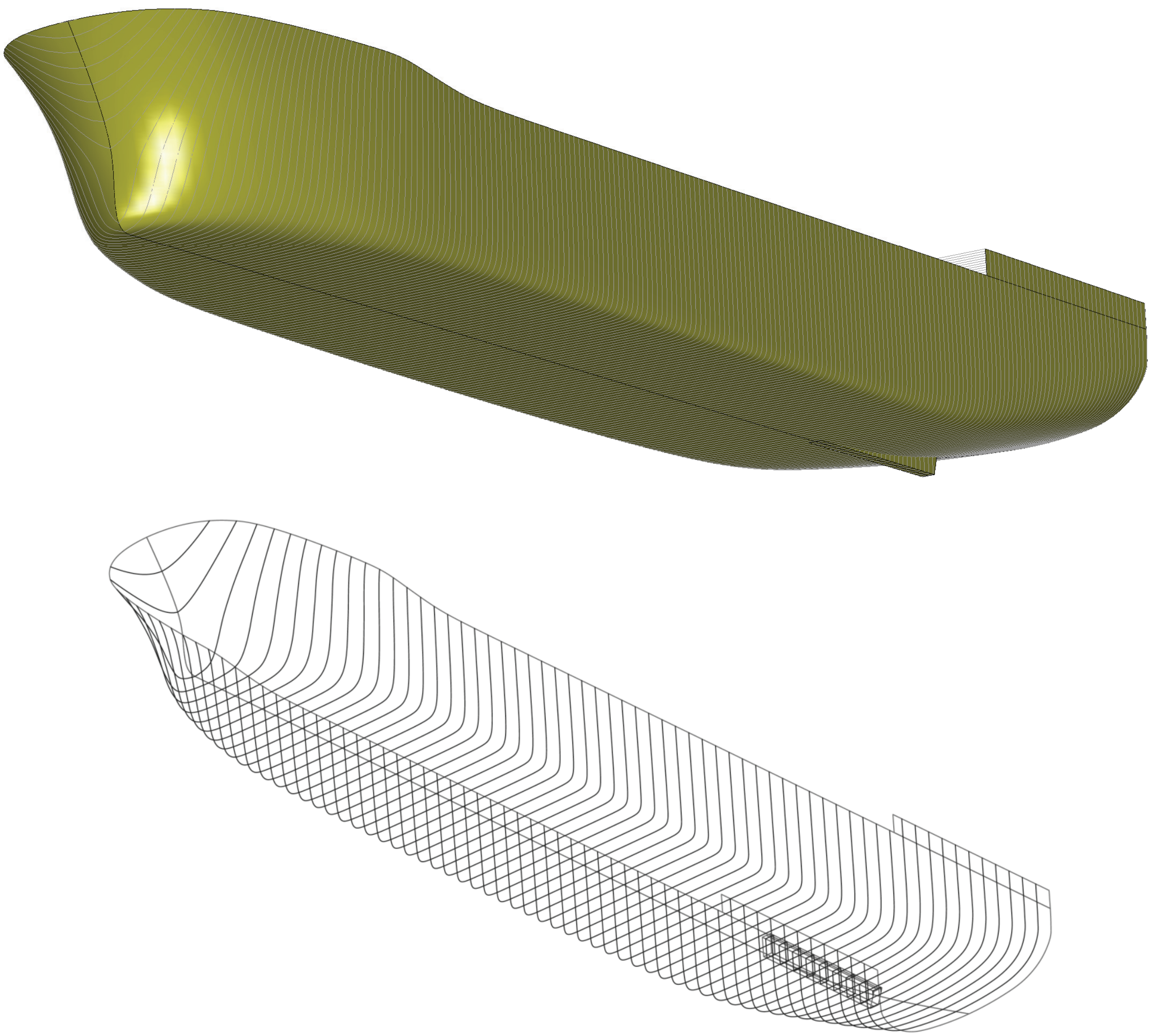


Initial proposal for general arrangement of the polymetallic nodules mining ship for CCZ



The designed hull shape of the mining ship



3D view of hull shape