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ON THE USE OF SELECTED 4TH GENERATION NUCLEAR REACTORS IN MARINE POWER PLANTS

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ABSTRACT

This article provides a review of the possibility of using different types of reactors to power ships. The analyses were carried out for three different large vessels: a container ship, a liquid gas carrier and a bulk carrier. A novelty of this work is the analysis of the proposal to adapt marine power plants to ecological requirements in shipping by replacing the conventional propulsion system based on internal combustion engines with nuclear propulsion. The subjects of comparison are primarily the dimensions of the most important devices of the nuclear power plant and the preliminary fitness analysis. It was assumed for this purpose that the nuclear power plant fits in the engine room compartment and uses the space left after the removal of the combustion engines. At the same time, this propulsion provides at all times sufficient energy for port, technological and shipping operations at an economically justifiable speed. For deep-sea vessels, which are supposed to reach null emissions of CO, CO2, NOx, SOx and H2O, this is one of the most reasonable solutions. Finally the paper proves that all the above-mentioned marine functions could be effectively applied in power plants equipped with 4th generation nuclear reactors.

Keywords: nuclear reactor, ship propulsion, nuclear power plants

INTRODUCTION

The growth of international trade is increasing the demand for the transportation of goods between different regions of the world. Currently, 80% of the volume and 70% of the value of all cargo is transported by ships. With an increased number of ship journeys, the amount of fuel burned is growing, which increases the production of CO_2, NO_x and SO_x, having an adverse impact on the environment [1], [2]. A reduction of the harmful impact on the environment can be achieved, among others, by modernizing existing systems and improving their parameters [3], [4] and by additionally introducing and developing new solutions, such as fuel cells [5] or nuclear propulsion. Nuclear fuel has the advantage of negligible life-cycle CO_2 emissions and a relatively low price compared to other fuels [6].

Currently, nuclear fuel is used in Russian warships and icebreakers (Taimyr and Arctica) [7]. The list of active Russian navy ships consists of 64 units [8], 14 of which have nuclear propulsion, as described in Table 1. There are plans to launch the construction of new nuclear submarines. In the near future two nuclear submarines armed with intercontinental ballistic missiles are to be built, along with two diesel-powered submarines.

Examples of other nuclear-powered ships include NS Savannah, Otto Hahn, Mutsu, and NS Sevmorput [9]. The future of water transport is in the use of small nuclear reactors on commercial ships, e.g. container ships, bulk carriers or liquid gas carriers. For reasons of operational safety, it is proposed to use reactors of the 4th generation such as the HTGR reactors (High Temperature Gas Reactors), where nuclear fuel in the form of TRISO fuel can be used. In order to cool the reactor, helium should be used, the leakage of which, in the event of damage, will not cause a threat to the ship's crew or to the environment.

Tab. 1 Russian nuclear attack submarines

Class	Project	Boat	Commissioned
Sierra II	945A	Nizhny Novgorod	1990
	945A	Pskov	1993
Victor III	671RTMK	Obninsk	1990
	671RTMK	Tambov	1992
Akula	971	Bratsk	1989
	971	Pantera	1990
	971	Narval	1990
	971I	Kuzbass	1992
	971I	Volk	1992
	971I	Leopard	1993
	971I	Tigr	1994
	971I	Samara	1995
	971U	Vepr	1996
	971M	Gepard	2000

This article also presents the existing concepts of the use of nuclear propulsion, currently most often occurring in submarines. This work presents the possibility of using reactors to propel ships in order to improve their energy performance by replacing the combustion engines of some existing types of ships with nuclear reactors. The potential realisation of this advantageous idea proves that the use of a VHTR reactor plant does not change significantly the machinery room dimensions and even offers the possibility to enlarge the cargo space. This is particularly important for the forecasted new ship types.

The main novelty, to the best of the authors' knowledge, is the proposal to replace traditional internal combustion engines with a drive using nuclear reactors. Numerous advantages of VHTR marine applications are also quoted and discussed. They mainly concern environmental, technical and economic features. This paper also compares the dimensions of the most important devices. The research goal is to analyse the feasibility of replacing internal combustion engines powered by fossil fuels with turbines using nuclear reactors. The technical goal is to determine the change in the dimensions of the essential components for deep-sea vessels which, in the long run, will strive for zero emissions of CO, CO_2, NO_x and SO_x. A novelty is the analysis presenting the possibility of replacing the combustion engine with nuclear propulsion to make ships more environment-friendly. The dimensions of the essential components of the nuclear power plant have been compared and a preliminary efficiency analysis has been carried out.

A BRIEF OVERVIEW OF REACTORS SELECTED FOR MARINE PROPULSION

Ishida and Yoritsune have presented a low-power Pressurised-Water Reactor (PWR) called the "DRX deep-sea reactor" [10]. It is used in a research bathyscaphe capable of diving to a depth of 6.5 m. This reactor has a power of 750 kWt, or 150 kWe. It was studied at the Japan Atomic Energy Research Institute in terms of its suitability for submarine use. Fig. 1 shows a diagram of the location of the reactor in the submarine. This boat has a total length of 24.5 m and a width of 4.5 m. The reactor has an operating pressure of 8.4 MPa, and temperatures at the inlet and outlet of 282 and 298 °C, respectively., The steam temperature is 243 °C and the pressure is 3 MPa. The core is cooled by a natural coolant circulation system. The upper space inside the reactor is filled with water. Only control rods are used to adjust the power of the reactor. In this reactor, the values of the negative reactivity coefficients of the moderator density are greater than those in a conventional onshore PWR reactor [11].

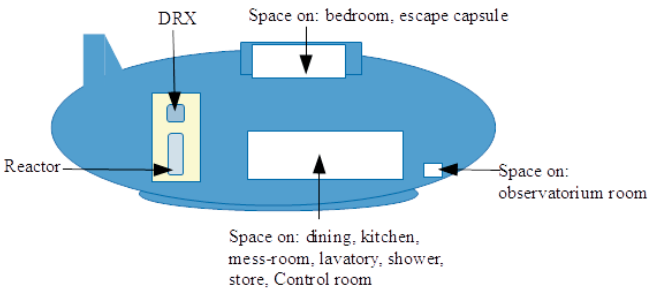

Fig. 1. The location of the reactor and other compartments in the bathyscaphe based on [10]

A Small Modular Reactor (SMR) for offshore drilling platforms (fixed and floating) has been presented by Yan [12]. This concept was also explored by Lee et al. [13], who improved the safety features of the reactor by providing passive cooling and a reactor-vessel emergency cooling system. Sea water is used for this purpose (the reactor is submerged). Floating reactors have also been presented by Isshiki [14] and by Tanigaki et al. [15], whose papers focused on the safety aspects of designing a ship. The research on the safety and use of reactors in watercraft has been ongoing since that time.

The small reactor with a sodium-based Direct Reactor Auxiliary Cooling System (DRACS) (Fig. 2) [16] has apower of 50 MWe, and the device can be used on land. The advantages of this reactor are the lack of the requirement for continuous fuel supply and the service life of its core without refuelling, assumed to be 30 years. Due to its dimensions and power, the reactor can be used for ship propulsion. This system equipped with 50 MWe can achieve a power of 120 MWt. The reactor has just one cooling system and uses fuel in the form of ternary metal. The temperature of the primary system is at a level of 550/395 °C. Flow diodes (Tesla valves) are used for protection and allow the occurrence of natural convective flow for the removal of decay heat.

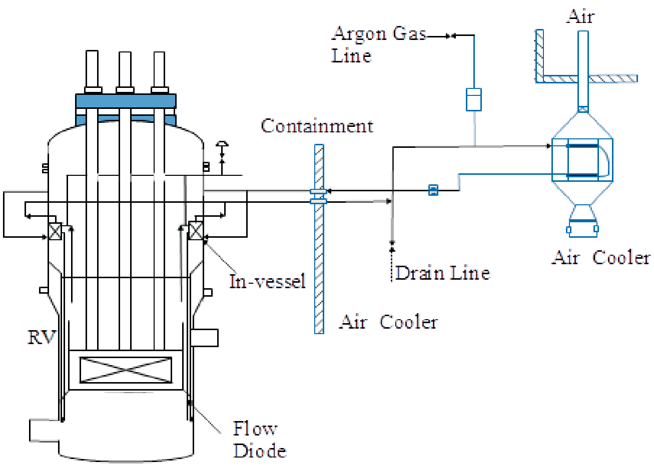

Fig. 2. The DRACS system based on [16]

The NEREUS project acronym stands for: "A Naturally safe, Efficient, pebble-bed Reactor graphite moderated easy to operate, Ultimately Simple and small" [17]. The project includes ideas on the possibilities of nuclear energy and aims to implement modular HTR installations cooled by helium with a moderator in the form of graphite. The designed system is to be used to propel ships. The installation will be designed in such a way that the construction, repairs and general logistical support will be carried out through a proven management system. The gas turbine (Brayton) cycle has a higher efficiency, so it produces less pollution than existing nuclear power plants that use the steam (Rankin) cycle. In the reactor core, during the fuel cycle, the reaction chain should be maintained. Due to the fission process, the amount of fuel decreases gradually. Fresh fuel is constantly added and spent fuel is removed. The NEREUS system is based on the use of combustible wastes. It is envisaged that the ship will be refuelled once every three years. The combination of enriched fuel and combustible wastes will make it possible to reach 20 MW in the reactor, of which 8 MW will be transferred to the generator. The control of energy production is strongly dependent on the temperature of the fuel. The control of the self-regulation power makes the fuel very safe and suitable for unmanned power plants. The project mainly concerns the market for the propulsion of ships, and enables efficient functioning of the unmanned engine room. The output controlling the power of the installation is supplied by the generator and implemented by means of mass flow control in the closed cycle system.

SELECTED PROPOSALS FOR THE USE OF HIGH-TEMPERATURE REACTORS IN SHIP POWER PLANTS

The technology and the current issues are summarised in the report by Arostegui and Holt [18]. The types of advanced nuclear reactors are categorised in various ways. The categorisation presented here is from the Congressional Research Service, which identifies three primary categories: advanced water-cooled reactors, non-water-cooled reactors, and fusion reactors. Descriptions of these reactors are given based on the website: Resources of the future.

Nuclear energy is generated by splitting uranium atoms in a controlled operation called fission. Traditionally, nuclear power is generated using light-water nuclear reactors to heat water and create steam to drive a turbine; however, several new reactor technologies are in development. These advanced nuclear reactors extend beyond traditional reactors, offering the opportunity of safer, cheaper, and more efficient generation of emissions-free electricity, as well as heat for industrial processes. Currently, almost all nuclear energy across the globe is generated by non-advanced reactors (Table 2), with few advanced reactors in active use for energy generation.

Three ship types (the bulk carrier, the container ship and the liquid gas carrier) were selected for this study to assess the possibility of using a VHTR to power the main propulsion engine. For each of them, a location for the nuclear reactor and the main propulsion was proposed. The possibilities of solving each of these power plants are illustrated based on the example of the currently existing combustion power plant shown in the scaled cross-section of the ship. An attempt has been made to propose a location for the reactor as far away from the crew cabins as possible. It should also be taken into account that ships that could use high-temperature reactors

Tab. 2 Operable nuclear power plants [19]

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	304	288.7	enriched UO_2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	61	61.8	enriched UO_2	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	48	24.5	natural UO_2	heavy water	heavy water
Advanced gas-cooled reactor (AGR)	UK	11	6.1	natural U (metal), enriched UO_2	CO_2	graphite
Light water graphite reactor (LWGR)	Russia	11	7.4	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	2	1.4	PuO_2 and UO_2	liquid sodium	none
High-temperature gas-cooled reactor (HTGR)	China	1	0.2	enriched UO_2	helium	graphite

should be redesigned to provide for the power plant specially designed for this novel propulsion. This will allow the ship to better adapt to the power and geometry characteristics of the power plant containing the VHTR.

The selected ships [20] belong to the category of watercraft with large carrying capacities, significant hull dimensions (up to approx. 400 m in length and approx. 60 m in width) and high demand for propulsive power (from 24 to 67 MW). In the original design, they are propelled by low-speed (70 to 80 rpm) diesel engines driving the screw propellers directly.

A PROPOSAL FOR A TURBO STEAM POWER PLANT USING THE VHTR REACTOR

Only one power plant type with a high-temperature reactor was considered. It is similar to the PWR-type double-contour nuclear power plant (Fig. 3) pebble-bed, and the use of TRISO balls was adopted. In test reactors these now allow hot helium with a temperature of up to 950 °C to be obtained [21]. The helium is cooled in a spiral exchanger with an option for separation into the steam generator and the superheater sections, producing steam for the secondary turbine circuit. In onshore power plants supercritical steam parameters are currently used to achieve a net efficiency of the turbine circuit of up to 46%. It can be expected that such high steam parameters will meet with resistance in the shipbuilding industry, but even these conventional steam parameters allow a 42% net efficiency to be reached. At the same time, it should be noted that spiral exchangers and steam generators are devices with relatively small dimensions. The results of the earlier work [22] on the problems of helium-steam heat exchange, illustrated in Fig. 4, show this feature by comparing the dimensions of an onshore steam boiler for a 300 MW power plant to a corresponding helium exchanger. The difference is spectacular: the helium steam generator is only about 33 m tall and has a diameter of about 4 m. This also proves that helium exchangers do not pose a serious problem in marine applications in terms of the exchanger dimensions or weight. Given the thermal power of a 70 MW power plant, the environmental advantages and the reduction of the fuel tanks provide an additional stimulus for the research on such power plants. One such major advantage is the fact that the only emission to the environment is heat from the condenser cooling system. In contrast, helium itself, as an inert gas, does not ionise [23]; only trace amounts of cinder, dust, etc. that are possible in the helium system can pose a small (many times lower than the current 3rd generation power plants) radioactive hazard in the event of a leak. Thus, such a power plant clearly stands out favourably against the background of the conventional and nuclear power plants in current use.

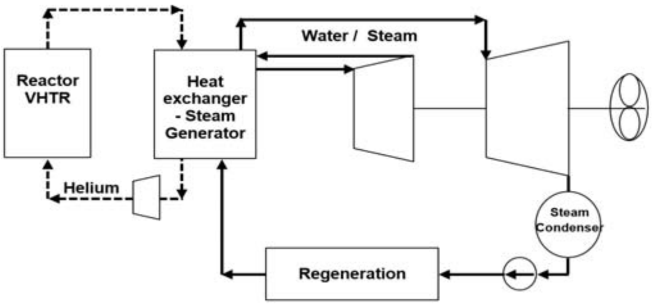

Fig. 3. A simplified diagram of a double-contour 4th generation power plant based on the use of a high-temperature reactor in the primary circuit

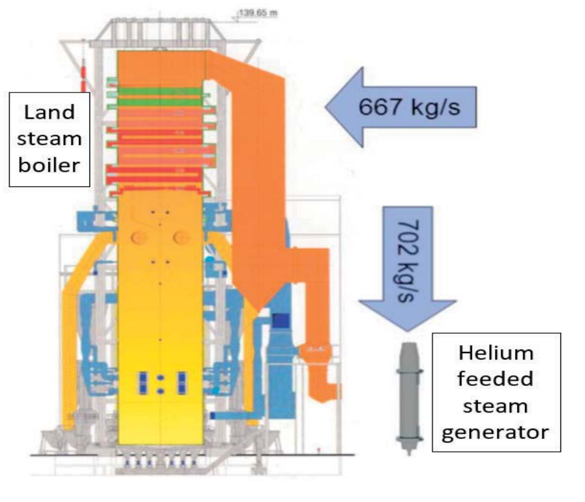

Fig. 4. A comparison of the dimensions of an onshore boiler for a 300 MW power plant (approx. 750 MW of the boiler thermal power) with the corresponding helium-based superheated steam generator based on [22]. Dimensions of the helium steam generator: height about 33 m, diameter about 4 m

A BRIEF DIMENSIONAL ANALYSIS OF THE ESSENTIAL POWER PLANT EQUIPMENT

The steam generator

The next part of the paper will consider proposals for the modernisation of power plants in the selected large ships, aimed at the use of HTGR. The highest power necessary to propel one of them is about 70 MW. Assuming that it will be possible to achieve a net efficiency of 40%, the heat output of the steam generator will be approx. 175 MW (4 times less than for the case in Fig. 4 [22]). This will also lead to a reduction of the heat transfer area in the steam generator by approx. 4 times. This, in turn, can lead to a reduction in the height of the steam generator to approx. 10 m. In the following part of the paper, such dimensions of the steam generator will be adopted, at the appropriate scale, for the geometric analysis of the basic devices on the longitudinal cross-sections of the example ships in Fig. 5 and Fig. 6.

The reactor

The reactor itself, the most important component of the presented idea for a modern drive, is also small in size. Based on [24], it is possible to quote the dimensions of the tested 4th generation reactors with a pebble-type bed for a thermal power of 250 MW: core height 10 m, diameter 3.5 m, pressure vessel height 16 m and diameter 5.6 m. Taking into account for the heat transfer, in a simplified way, only the Peclet relationship for the required thermal power of a marine power plant of 175 MW, it can be estimated that it is possible to reduce these dimensions by at least 20%. On this basis, it can be estimated that, with this thermal power of the ship's VHTR reactor with pebble-bed, the size of the space needed for its installation, together with the necessary devices, at the helium inlet and outlet will be: height about 20 m, width about 10 m and depth about 15 m. As with the characteristics of the steam generator, these sizes, at the appropriate scale, will be used for the geometric analysis on the longitudinal cross-sections of the ships considered in Fig. 5 and Fig. 6.

The turbine

The dimensions of the space for the drive depend on its power, thermodynamic parameters and the working medium [25]. It is also important from the operational point of view to ensure trouble-free operating conditions, i.e., among others, protection against propulsion vibrations [26], [27], and to ensure appropriate controls [28]. For the ships considered below, with the prospect of using the VHTR reactors, as in Fig. 4 it is possible to use at least three solutions:

- one steam turbine drives one screw propeller through the gearbox;
- two steam turbines drive two screw propellers through the gearbox;
- one steam turbine provides propulsion for a high-power electric generator while the screw propeller is driven by electric motors (turbo-electric drive).

A ship's steam turbine with the gearbox and condenser with a capacity of up to 35 MW requires space for assembly: height approx. 10 m, length approx. 10 m and width approx. 8–10 m [29]. The largest ship turbines have so far had up to 50 MW of power, so the 70 MW power plant should be replaced (without the use of unusual special solutions) by two units with a capacity of 35 MW each. However, in the case of turbo-electric propulsion, one steam turbine can be installed to drive a generator up to 80 MW. The dimensions of the space for such a turbine are height about 8–10 m, length about 15–20 m and width about 8 m [29]. It can be noted that for the ships in question, 60 m wide, there is a possibility of not only longitudinal but also transverse placement of the turbine. This allows for better use of the power plant's space. See the diagrams in Fig. 5 and Fig. 6.

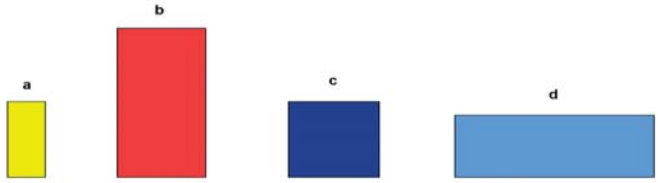

Fig. 5. A comparative diagram of the spaces needed for the installation of the essential equipment of the power plant with a VHTR reactor with a thermal power of 175 MW on the same scale in the longitudinal projection: a – the steam generator, b – the pebble-bed-type VHTR reactor, c – the 35 MW steam turbine with the gearbox and condenser, d – the 80 MW steam turbine of the ship's power plant with the generator and condenser

It is worth noting that the second largest device in Fig. 5 is the turbine, which can also be compacted by introducing another working medium, especially in the last flow stages. Such an analysis was carried out in [30], where a thermodynamic analysis of the circuit, which consisted of a closed Joule–Brayton cycle with helium as the working medium, was shown. The nuclear reactor was studied in several configurations of thermodynamic cycles, namely with heat recuperation, compressor intercoolers, simple circulation and a combined system where 3 Rankine cycles working on ammonia, ethanol and steam were compared. Low boiling point liquids were also analysed under supercritical conditions, achieving in some configurations higher energy efficiency than a typical gas–steam circuit. The volume flow rates in the last stages of the turbine were reduced, compared to the steam turbine, to 38% and 80%, respectively, using ethanol and ammonia. However, this solution was intended for powers of the order of 180 MWe and higher and can therefore be applied to the commercial power industry. This work [30] also did not take into account the possibility of arranging individual devices in order to make the optimum use of the space in which they are located. Another solution combining the reduction of the turbine dimensions through the introduction of the ORC factor, but additionally ensuring proper management of waste heat, is presented in the article [31]. Here, the dimensions of the turbine are divided into the high-temperature part (with steam as the working medium) and the low-temperature part (with a low boiling point medium). In total, both parts generate similar power to that of a large-size unsplit steam turbine and, after using waste heat, there is even an increase in power along with a decrease in the dimensions of the low-pressure turbine up to several dozen percent, depending on the ORC factor. However, in this solution, the operation of the cycle is based on the steam generator, which is a boiler, and the power of the entire system goes beyond the standards of ships, so it would be necessary to design a dedicated ORC turbine for the ship power plant. However, details about the power, emissivity of the system, cycles efficiency, thermodynamic parameters, as well as individual dimensions affecting the overall dimensions, should be analysed using tools such as Computational Flow Mechanics [32] or comprehensive approach taking into account both Computational Fluid Dynamics and Computational Flow Mechanics [33].

PROPOSALS FOR THE MODERNISATION OF SELECTED MARINE POWER PLANTS THROUGH THE USE OF VHTR REACTORS

The first part of this section presents data on the selected ship types. The following subsections will describe the most important solutions allowing the introduction of nuclear reactors to ships powered so far in a traditional way.

The container ship (Fig. 6a) acc. to [20]

The container ship is represented by the CMA CGM ANTOINE DE SAINT EXUPERY. It was built in 2018 and has the following parameters: overall length 400 m, moulded breadth 59 m, gross tonnage 217,673, deadweight capacity 172,400 DWT, nominal capacity 20,600 TEU. The ship is powered by one WinGD W11x92 two-stroke engine with a power of 67,430 kW at the MCR, and for the CSR it is 57,315 – for the single propeller with a diameter of 10.2 m and the maximum speed of 80 rpm. The captain's bridge and crew quarters are located in the front part of the ship and the engines in the aft part.

It was initially assumed that the introduction of the VHTR reactor and the steam turbine assembly into the power plant would be made for the existing hull. The current location of the power plant in the aft part, away from the superstructure, fully meets the condition of distancing the nuclear reactor from the crew premises. The spaces necessary for the main equipment of the power plant are very roughly marked in Fig. 6a. Of course, the proposals for their placement can change and should be a subject of detailed analyses. Besides, it can be expected that the 4th generation nuclear power plants will rather be installed on new ships. On the other hand, in the case of the largest ships, modernisation of the power plant can happen when the advantages of the drive described here are confirmed in practice. There is enough space in the power plant to use a turbo-electric drive with a VHTR reactor.

The bulk carrier (Fig. 6b) acc. to [20]

SAO DIANA is one of the largest bulk carriers used to transport ore. It was built in 2018 and has seven holds, each with a capacity of 26,000 cubic meters. The parameters of the ship are as follows: overall length 333 m, moulded breadth 59 m, deadweight capacity 326,107 DWT, nominal capacity 180,000 m^3.

The operating speed of the ship is 14.5 knots and it is powered by the MAN B&W 7G80ME-C9.5 engine, achieving a power of 23,390 kW.

As in the previous case, the introduction of the VHTR reactor and the steam turbine assembly into the power plant will be made for the existing hull. The current power plant is at the stern. The existing vessel has a dual-fuel engine and a separate LNG tank. This prompts the proposal of two modernisation solutions for the VHTR power plant. One is to set up the VHTR reactor in the current power plant and the other is to set it up in the rebuilt space of the LNG tank. The latter meets the requirement for moving the reactor away from the superstructure. In the first case, better radiation protection will be needed. The spaces necessary for the main power plant equipment are pre-marked in Fig. 6b. Their distribution should depend on detailed analyses, as in the previous case. It can be noted that, for such a bulk carrier configuration as the one analysed, the possibility of using turbo-electric propulsion is very beneficial. The power plant together with the reactor can be placed in the space after the LNG tank, and the remaining equipment in the power plant under the superstructure. With the use of such a modern power plant on new ships of this type, designers will be able to better optimise the propulsion with the VHTR reactor.

The tanker (Fig. 6c) acc. to [20]

The next vessel selected to analyse the possibility of using a nuclear reactor is the DHT Bronco tanker, which was built in 2018, and has a double bottom. It is designed to save as much energy as possible. It has five central cargo tanks and ten side tanks, one on each side of the central tank, as well as two residual tanks. The rated power of the main engine is 32,970 kW at 72 rpm and it is the Hyundai MAN B&W 7G80ME-C9.5-HPSCR engine equipped with high-pressure selective catalyst reduction. The parameters of the ship are as follows: overall length 333 m, moulded breadth 60 m, cargo capacity, liquid volume 353,900 m^3, maximum loading capacity 25,500 m^3/hour, discharge rate 15,000 m^3/hour.

The proposal to use the VHTR reactor and steam turbine assembly in the power plant is also based on the configuration of the existing hull. The power plant is located at the stern. One way of locating the VHTR reactor is possible: in the space of the current power plant. Steam can also be used to drive the cargo pumps. Good radiation protection will be needed. The spaces necessary for the main power plant equipment are pre-marked in Fig. 6c. Their distribution should depend on detailed analyses, as in the previous cases. The use of a turbo-electric drive with a VHTR reactor in this case is also possible.

Other ships

Advances in the miniaturisation of reactors will soon allow the use of different types of power plants with different VHTR reactors of the 4th generation. One example of the study of such concepts, in this case for a helium turbogas power plant, is the NEREUS project [17]. The energy and geometry analysis of the possibility of using one of the types of the 4th generation reactors on the three large ships presented in the previous subsections is also an example of such research. The considerations are illustrated on the currently existing ship structures. Most likely, however, power plants with the 4th generation reactors will be used primarily on new ships of various sizes. This will allow for a more flexible design of the power plant than in the case analysed above. But this will also ensure all the energy and environmental benefits for seagoing shipping.

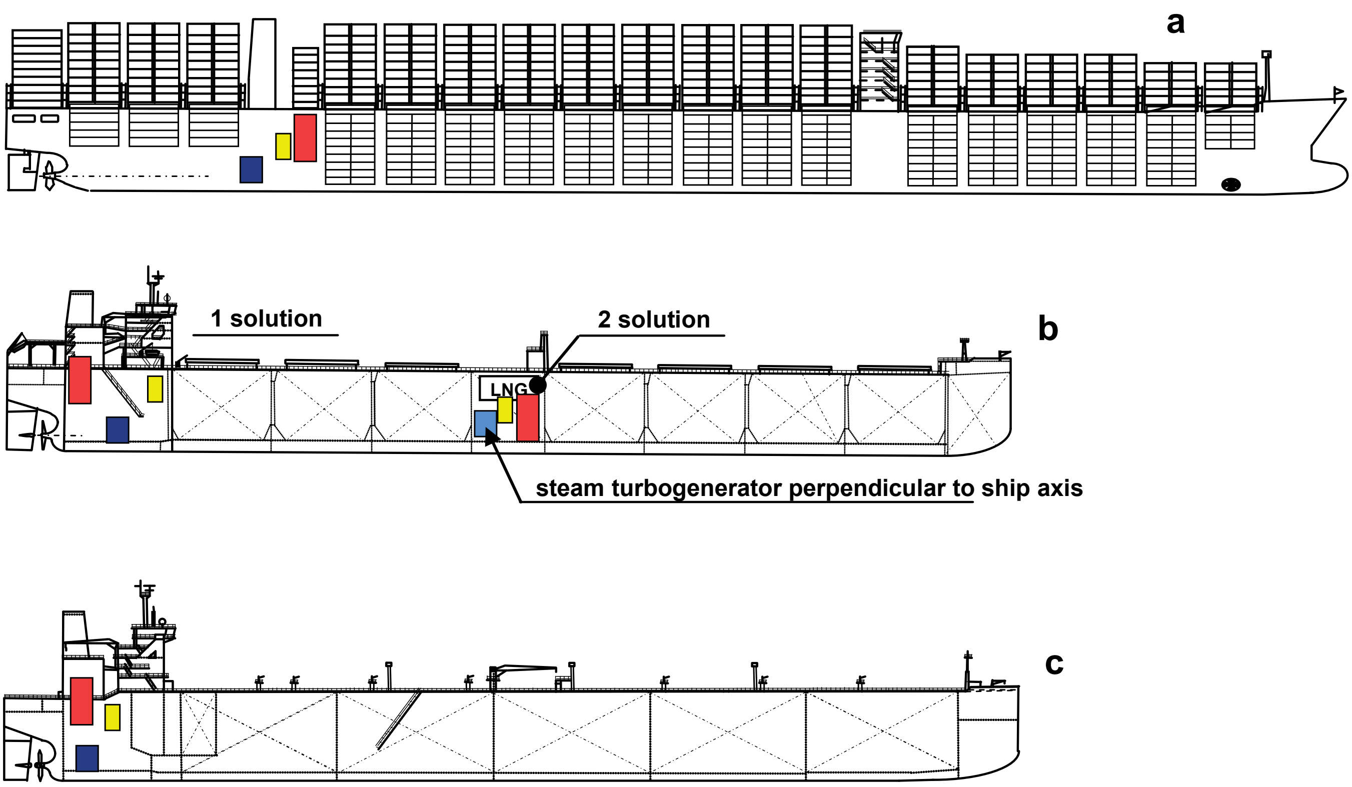

Fig. 6. Initial proposals for installing a power plant with a 4th generation VHTR reactor for the selected large-size ships with structures according to [20]. All the ships are on the same scale. a – The container ship (ANTOINE DE SAINT EXUPERY), b – the bulk carrier (SAO DIANA), c – the tanker (BRONCO). Red – the VHTR reactor, yellow – the steam generator, dark blue – the main turbine (35 MW), light blue – the steam turbogenerator (80 MW)

CONCLUSION

This paper discusses the possibility of applying nuclear propulsion to civilian ships. The potential locations of the reactor in the three types of ships have been presented. The proposal to place nuclear reactors in place of conventional fuel engines is a major novelty of the work. The paper proves that all marine functions could be effectively applied in power plants equipped with 4th generation nuclear reactors. The potential realisation of this advantageous idea proves that the use of a VHTR reactor plant does not change significantly the machinery room dimensions and even gives the possibility to enlarge the cargo space. This is particularly important for the forecasted new ship types. Numerous advantages of VHTR marine applications are also quoted and discussed. They concern mainly environmental, technical and economic features. The proposed procedure of such propulsion design tested in the paper is shown in Fig. 7.

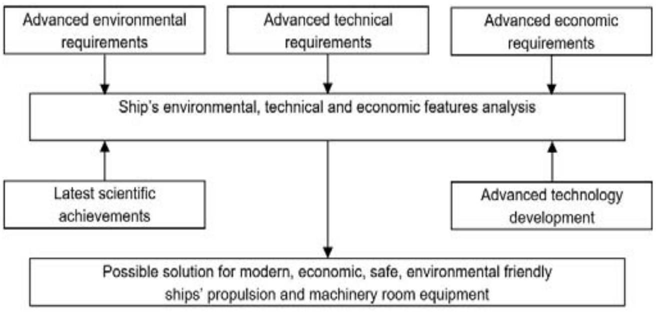

Fig. 7. Simplified general system of design analysis presented in the paper. A similar procedure can be applied for the design of modern ships' plants based on VHTR nuclear reactors adoption

Nuclear propulsion, due to the currently lowest environmental burden (lower than other alternative energy methods including renewable energy), can in the future be successfully installed also on vessels that already sail using conventional fossil fuels. At the same time, this propulsion provides at all times sufficient energy for port, technological and shipping operations at an economically justifiable speed.

The use of helium as a reactor coolant provides much greater anti-radioactive safety than the currently existing nuclear energy technologies. This is very important for civilian marine applications. According to the authors, the reactor with the pebble-bed in the two-contour cycle of the turbo steam power plant stands out here. In addition to good environmental features, it provides high efficiency for ocean-going ships and frees the ship's structure from huge conventional fuel tanks.

The paper has analysed the possibility of placing a power plant with the 4th generation nuclear reactors on three selected, currently existing, large-size ships. Most likely, however, power plants based on the 4th generation reactors will be used primarily on new ships of various sizes. This will allow for more flexible design of the power plant than in the cases analysed in the paper.

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