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The Potential of Next Generation Nuclear Power for Marine Propulsion of Commercial Vessels

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ABSTRACT

Nuclear energy has the potential to become one of the main alternatives to achieve sustainable marine shipping and reduce its greenhouse gas emissions. This study defines a power generation arrangement and evaluates design speed for nuclear powered vessels. Higher design speeds show promising economic results. This includes higher revenue and trade while maintaining a relatively low operational expenditures when compared with conventional powered ships. This study is carried out for a large container vessel and a large bulk carrier to support the implementation of nuclear energy technology. This study reviews reactors designed to a 25- to 75-year service life, using a fully electric power generation and propulsion layout.

KEY WORDS

Nuclear energy, commercial shipping, marine design, molten salt reactor, comparative study.

NOMENCLATURE

B	Breadth
CapEx	Capital expenditures
Cb	Block coefficient
DWT	Deadweight
EIRP	Energy Innovation Reform Project
FEU	Forty-foot equivalent unit
Fn	Froude Number ($Fn = v / \sqrt{g \cdot L}$)
GT	Gross tonnage
IAEA	International Atomic Energy Agency
Lbp	Length between perpendiculars
LSW	Lightship Weight
VLSFO	Very low sulphur fuel oil (0.5% Sulphur)
MSR	Molten salt reactor
NEA	Nuclear Energy Agency
O&M	Operation and maintenance
OpEx	Operational expenses
Pb	Brake power
Pd	Propulsion power
Pne	Nuclear electrical power
PWR	Pressurized water reactor
sfc	Specific fuel consumption
SMR	Small modular reactor
T	Draft
TEU	Twenty-foot equivalent unit
v	Ship speed
VHTR	Very high temperature reactor
WNA	World Nuclear Association

INTRODUCTION

With the need for shipping to become more sustainable and reduce its harmful emissions, nuclear marine propulsion has potential to be one of the solutions. Earlier research (Houtkoop, 2022) has shown the initial potential of next generation nuclear technology for shipping with replacement of conventional power generation. However, the full potential of nuclear on marine applications, especially for new builds, is not fully known yet. Therefore, the goal of this study is to develop new build cases and explore their potential focusing on design speed, propulsion and power generation, and ship design.

This paper is built up as follows. The first section studies parts of nuclear power generation and propulsion and establishes a technically feasible basis for the propulsion configuration and arrangement. This is followed by a section introducing the case studies with their own background for further economic analysis in the second section. The third and fourth section elaborate on the speed-dependent total cost of ownership and shipping income respectively that serve as input for the analysis of the cases. The fifth section clarifies the overall calculation method to determine the most economic speed for the complete range investigated in this research. The sixth section presents the results with initial review followed by the seventh section discussing the results further. This final sections of this paper cover the conclusion and recommendations.

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POWER GENERATION AND PROPULSION

This section describes the considered and selected options to convert and distribute nuclear power to propulsion and other electrical consumers. It does so by reviewing the main topics covering reactor, shielding, heat exchangers, turbines, propulsion configuration, and arrangement.

System Design

The system design of a nuclear power plant can be made in various ways. This study is not exclusive for one reactor type or one system design. Instead this study aims to be representative for a range of designs. For a better understanding of the principles of a nuclear power plant a basic system design is shown in Figure 1. It is based on primary loop going through the reactor, an intermediate loop and an open air loop. Two hypothetical options for the reactor and mediums for the respective loops are shown in Table 1. The reasoning for the respective design options are provided in subsections *Heat Exchangers* and *Turbines*. Alternative nuclear power plant designs with a different number of loops are also possible. Furthermore, different types of mediums with respective open or closed cycles are also possible. However, both are not further reviewed in this study.

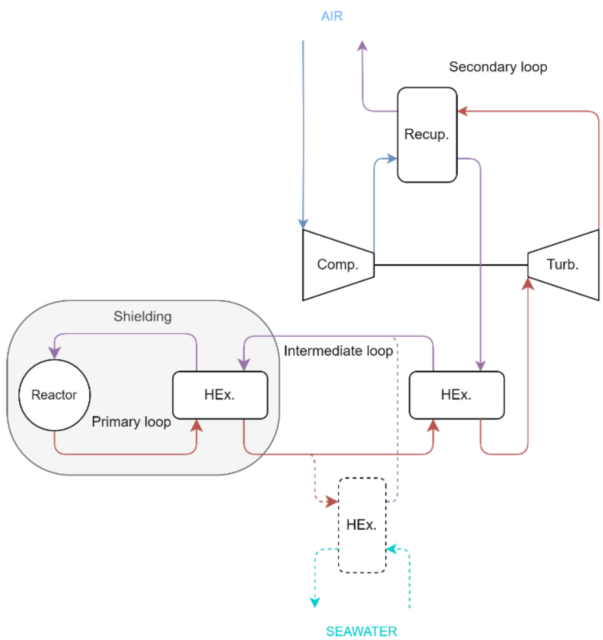

Figure 1: Basic system design of a nuclear power plant

Table 1: Hypothetical options for (V)HTR and MSR and heat transfer loop mediums

Hypothetical option	Reactor	Primary loop	Intermediate loop	Secondary loop
1	(V)HTR	Helium	Salt	Open Air
2	MSR	Salt	Helium	Open Air

Reactor

This study is not exclusive to one reactor type, and researches a bandwidth of reactor capital expenditures (CapEx). As examples of reactor types, earlier research (Houtkoop, 2022) has indicated that for a number of reasons, (Very) High Temperature Reactors ((V)HTRs) and Molten Salt Reactors (MSRs) have a lot of potential for the maritime industry. An important reason is the passive safety properties which prevent issues with stability and thus ensures reactor safety without outside intervention. Another reason is the high burn-up of these reactor types. Burn-up is an effectivity measure indicating how much thermal energy the reactor can extract from a given quantity of nuclear fuel. A higher burn-up is favorable as it reduces the amount of required nuclear fuel and produced waste per power produced (Houtkoop, 2022). Furthermore, both these reactor types have the potential to (partially) use the thorium fuel cycle. In addition to thorium being three times more abundant than uranium, the thorium fuel cycle has a higher proliferation resistance, meaning it is a very unattractive route to create nuclear weapons with it. This eliminates (or greatly reduces) the potential of weaponization. With thorium, the high-level nuclear waste longevity can be reduced from more than 10,000 years to approximately 300 years (Hargraves, 2010).

Shielding

The shielding around the reactor, to contain the respective forms of radiation, has a substantial mass and volume primarily consisting of water or concrete and additionally lead (Houtkoop, 2022). This partially clarifies why nuclear power generation onboard vessels is primarily interesting for large ocean-going vessels, as the shielding could become disproportionally large in terms of mass and volume for smaller vessels. This is further reflected upon in sub-section Background of section Case Studies. Future developments of making (reactors and) shielding more compact could change this. An example of this development for both reactors and shielding is Westinghouse and other parties developing SMR of the range of 5000kWe. This is believed to be ideal for the smaller size of ocean-going vessels (Petrakakos, 2024).

Heat Exchangers

Heat exchangers are essential to transfer the heat from the nuclear reactor to the turbines as shown in Figure 1. In the earlier research (Houtkoop, 2022) three heat exchanger types were compared as shown in Table 2.

Table 2: Summary of heat exchanger evaluation *(Houtkoop, 2022)*

Heat exchanger → Property ↓	**Shell and tube**	**Helical coil**	**Printed circuit**
Heat transfer coefficient [$W/m^2 \cdot K$]	500	1000	2000
Surface density [m^2/m^3]	75	80	1100

Printed circuit heat exchangers have the best volumetric power density. However, it has a low technical readiness level at the size under consideration. Therefore, helical coil heat exchangers are selected as the most suitable as these are more developed and proven.

The hypothetical option 1, as shown in Table 1, with (V)HTR, uses an intermediate salt loop. Hypothetical option 2, as shown in Table 1, with MSR, uses an intermediate helium loop. The main reason for this is the containment of radiation. In alternative designs supercritical CO2 could also be considered.

Turbines

In earlier research (Houtkoop, 2022) multiple turbine concepts have been investigated for marine nuclear power generation, namely:

- Rankine cycle (Steam)
  - Superheat
  - Superheat and reheat
  - Superheat and feedwater heating
- Closed Brayton cycle
  - Simple cycle
  - Recuperation
  - Intercooling and/or recuperation
- Open Brayton cycle
  - Simple cycle
  - Recuperation
  - Intercooling and/or recuperation

To evaluate these options, multiple performance indicators, being weight, volume, system complexity, and load response were used. The open Brayton cycle was found to be the most suitable as shown in Table 3.

Table 3: Summary of turbine evaluation *(Houtkoop, 2022)*

Turbine → Property ↓	**Rankine (steam)**	**Closed Brayton**	**Open Brayton**
Efficiency	++	+	+
Volume (system)	-	+	0
Weight (system)	-	+	0
Complexity (system)	--	-	+
Load response	+	+	++

The open Brayton cycle turbine is, in terms of its development close to the current marine gas turbine, operating with air as the medium. The main difference with the conventional marine gas turbine is the use of a heat exchanger to supply heat instead of using a combustion process. One of the benefits of open cycle is that it does not require a condenser or heat exchanger for cooling, as the used air is simply rejected (Houtkoop, 2022). This however comes at the expense of having inlet and outlet ducting that are associated with performance and pressure losses and a space requirement (Stapersma, 2019).

For load response the open Brayton cycle turbine is again limited by the reactor and its heat exchanger. The aeroderivative open Brayton turbine can operate on far greater load responses than gas turbines operating on the combustion process. A greater load response similar to this can be achieved when considering load rejection strategies (Houtkoop, 2022). The resulting concept applying heat rejection to improve load response is shown in Figure 2. This configuration also shows the separation of compressor turbine and the load turbine. The benefit of this is that the compressor operation upon load change is not disturbed resulting in a larger load envelope (Stapersma, 2019). In alternative designs supercritical CO2 could also be considered.

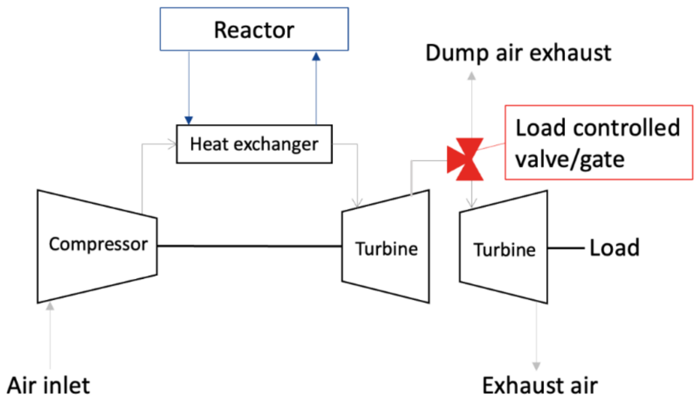

Figure 2: Open Brayton, heat rejection and load turbine (Houtkoop, 2022)

Propulsion Configuration

To convert the power generated by turbine to propulsion multiple propulsion configurations can be considered. In principle this comes down to three options namely, turbine-direct, turbine-electric, or a hybrid form of both. For this study a complete electric propulsion is selected. By doing so, a conservative approach in terms of efficiency for the nuclear option is established, assuring that the results are not overly optimistic. Additionally, full electric propulsion offers flexibility in arrangement and options for easy integration of peak shaving with batteries for improved load response. Furthermore, it also offers options for reverse cold ironing while in port and easy integration of back-up power by means of diesel generators. Nevertheless, future studies are encouraged to review options to further optimize the nuclear option with, for example, turbine-direct propulsion or hybrid propulsion.

Arrangement

Combining the found options discussed in each subsection, an initial overall arrangement is formed and shown in Figure 3. It has the reactor, shielding, and intermediate heat exchangers in the middle. There are two power generation rooms each with a primary heat exchanger, turbine, and generator. Furthermore, it has a redundant electrical propulsion system. This is supplemented with batteries and emergency diesel generators.

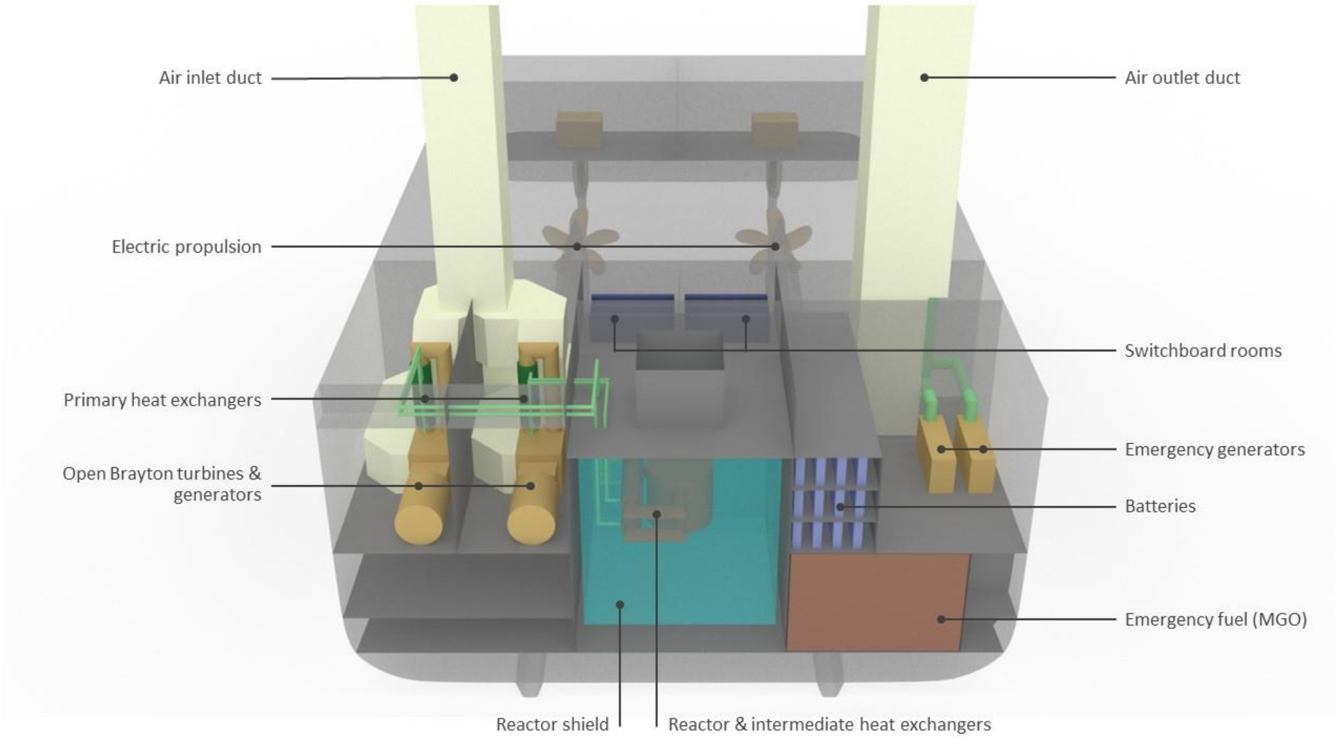

Figure 3: Nuclear power generation and propulsion arrangement

CASE STUDIES

In this section the case studies to evaluate design speed are defined. In order to explain the selection of these case studies more background on nuclear energy and marine propulsion is reflected upon first.

Background

Earlier research has shown that Generation IV (Gen-IV) nuclear reactors have a lot of potential to decarbonize the power sector effectively (Buongiorno, 2018). Furthermore, specifically Gen-IV Molten Salt Reactors (MSR) designs, which enable use of the thorium fuel cycle, are expected to be cost-competitive with other energy sources (Mignacca, 2020). In addition to onshore nuclear power plants other concepts are also being developed for floating nuclear power plants (Lobner, 2021). Additionally, studies have reviewed MSR application on vessels and have shown it to be economically competitive with other alternatives (Emblemsvåg, 2021) (Gennaro, 2020).

Furthermore, research work of (Houtkoop, 2022) *Nuclear reactors for marine propulsion and power generation systems* has shown that nuclear marine propulsion has a lot of potential for large ocean-going vessels to reduce harmful emissions. The completion of the study (Houtkoop, 2022) inspired to explore the potential of higher design speeds with nuclear marine propulsion. It could potentially make the ship more profitable. This is because fuel cost, as part of operational expenditures (OpEx), only grows marginally with higher speeds for nuclear powered vessels. Ultimately the main limiting factor would be the CapEx of the installation with more power. Additionally, the reactor can be used for a longer period of time by either reusing it in a new ship or by extending the service life of the initial ship. This would allow to depreciate the CapEx of the reactor over more years thus improving the economic model of the investment and enabling considerations for higher speeds further. Of the high potential ship types covered in (Houtkoop, 2022), two are selected for this study as new build cases, a container vessel and a bulk carrier. As shown in Figure 4, the weight of reactor and shielding is smaller than the conventional fuel weight, plotted as dots, for a ship set containting built vessels from the last decades, it would replace in like-for-like replacement. The blue and red lines represent the lower and upper weight estimates of the nuclear reactor and shielding. The dashed black line is a trend line of the respective data point. Therefore, the integration is considered to be managable with limited design impact for large ocean going container and bulk vessels.

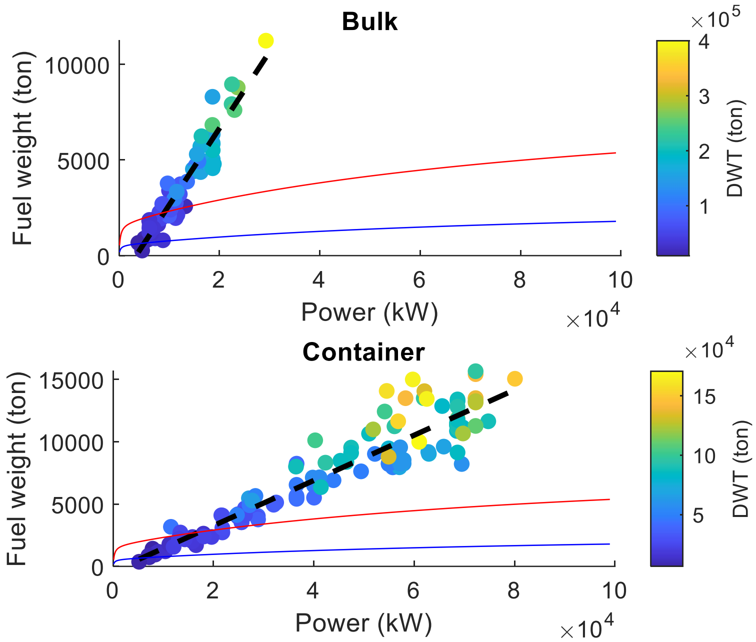

Figure 4: Plots of vessels fuel weights vs reactor and shielding weight estimates *(Houtkoop, 2022)*
Blue and red lines: Lower and upper bound of weight estimates of the nuclear reactor and shielding
Black dashed line: trend line of data points

Container

To study container cases a market representative selection of ship size and route is made. For this study this results in the selection of a ship size of 20,000 TEU with two routes as described below in Table 4.

Table 4: Container cases

Case	Route (Baltic Exchange, 2023)	Distance [nm] (Ports.com, 2010-2023)	Port duration* [day]	Suez canal duration* [day]
I	North Europe – China/East Asia (FBX11 & 12)	11,999 (Rotterdam – Shanghai)	3	1
II	Europe – North America East Coast (FBX21 & 22)	3,918 (Rotterdam – New York)	3	Not applicable

*No additional considerations are made with respect to port congestion that could result in waiting times. (C-Job Naval Architects, 2024)

Bulker

To study bulk carriers cases a market representative selection of ship size and route is made. For this study this results in the selection of a ship size of 300,000-ton DWT with the vessel transporting iron ore along two routes, as described below in Table 5.

Table 5: Bulker cases

Case	Route (Baltic Exchange, 2023)	Distance [nm] (Ports.com, 2010-2023)	Port duration* [day]	Suez canal duration [day]
III	Tubarao, Brazil to Qingdao, China (C3)	13,555 (Tubarao to Qingdao)	5	Not applicable
IV	West Australia to Qingdao China (C5)	4,059 (Hedland to Qingdao)	5	Not applicable

*No additional considerations are made with respect to port congestion that could result in waiting times. (C-Job Naval Architects, 2024)

SPEED-DEPENDENT TOTAL COST OF OWNERSHIP

To determine the most economical speed, the speed-dependent costs need to be identified which then can be deducted from the shipping income. As a result, it will show where the optimal speed lies. The speed-dependent total cost of ownership is divided into capital expenditures and operational expenditures. In this calculation, only main contributors are considered. Cost components that are not (substantially) influenced by speed are not included in this analysis, as this is an initial evaluation for optimum design speed and its design implementation.

Capital Expenditures

Speed-dependent capital expenditures (CapEx) are identified in two main components. The first is the nuclear reactor, which not only includes the reactor, but also its shielding, the heat exchangers, turbines, generators, and other respective auxiliaries. The second component includes electrical system elements, the electric motor, gearbox, propeller shaft and the propeller. Other components are not included in this study.

Nuclear Reactor

Small Modular Reactors (SMR), which are defined as nuclear reactors with 300,000 kWe or less, are the most suitable to establish a cost reference. Based on literature research, the estimated costs of SMRs are as presented in Table 6. Most references include estimated costs of Pressurized Water Reactors (PWRs) and only a few cover multiple reactor types. This study is not exclusive to one reactor type, as stated earlier, and instead it researches a bandwidth of reactor CapEx.

To estimate the nuclear reactor cost, the reactor size, in terms of power, needs to be defined. Referring to the range of installed brake power of large ocean-going vessels fitted with diesel engines, generally directly connected to the propeller shaft, as presented in Figure 4, the installed brake power ranges from 5,000 to 80,000 kW.

Table 6: Nuclear reactor CapEx *(Leurs, 2023)*

Source	Cost [$/kWe]	Power [MWe]	Type
(Abdulla A., 2013)	*2,000-9,200	45	PWR
(Abdulla A., 2013)	**9,200-25,500	45	PWR
(Stewart W.R., 2022)	5,230	160	PWR
(Vegel Benjamin, 2017)	4,790	225	PWR
(EIRP, 2016)	2,053-5,855	<300	Various
(Lloyd, 2018)	5,720	300	PWR
(Lloyd, 2018)	5,000	400	PWR
(Lloyd, 2018)	4,500	500	PWR
(Lloyd, 2018)	4,225	600	PWR
(Stewart W.R., 2022)	4,059	685	PWR
(Black Geoffrey A., 2019)	3,611	720	PWR

*11 experts
**5 experts

As can be seen in Table 6 there is a relative cost decrease with higher power generated. Furthermore, there are still quite some deviations between the calculated cost estimates. Based on these results a bandwidth of 3,000-9,000 $/kWe is selected for the analysis in this study. Respective decommissioning cost estimates show similar deviations as shown Table 7. For this analysis, since a large bandwidth of CapEx is investigated, the decommissioning cost is assumed to be included in the CapEx.

Table 7: Nuclear reactor decommissioning cost *(Leurs, 2023)*

Source	Cost [$/kWe]
(NEA, 2016)	1,070-1,220
(The World Bank, 1990)	144-254
(Sayres and Associates Corporation, 2008)	3,153
(United States General Accounting Office, 1992)	242-432

Other
For the other CapEx items, design guidelines and estimations of C-Job are used. The resulting costs are shown in Table 8.

Table 8: Other CapEx *(C-Job Naval Architects, 2024)*

Item	Cost
Electrical System	500 $/kW
Electric Motor	250 $/kW
Gearbox	75 $/kW
Propeller and Shaft	75 $/kW

Operational expenditures

Yearly speed-dependent operational expenditures (OpEx) are identified in three parts. The first is fuel cost. The second is the operations and maintenance cost. The third cost aspect is the voyage cost including port, canal, pilot, and tug fees. Whereas the fuel and operation and maintenance cost are evidently speed dependent, the voyage cost is also directly proportional to the vessels speed, because with higher speeds, ports and canals are visited more frequently, resulting in a higher yearly costs.

Fuel Cost
To determine the fuel cost per kWh ($/kWh), the respective specific fuel consumption (sfc) in g/kWh and cost of fuel $/kg of the respective fuel needs to be established. The efficiency g/kWh can be defined by assuming a burnup (IAEA, 2020) of 45 GWd/tHM (Gigawatt per day per ton of heavy metal) and a reactor efficiency of 33% (Shultis, 2002), resulting in 0.0028 g/kWh. To put this in perspective, marine diesel engines are generally in the order of 170 g/kWh (MAN Energy Solutions, 2024) using Very Low Sulphur Fuel Oil (VLSFO).

The World Nuclear Association (WNA) divides the front-end fuel cycle costs into four categories. The natural uranium mining cost, the conversion cost, the enrichment cost, and the fuel fabrication cost. These account for 51%, 7%, 24% and 18% of the cost respectively (Leurs, 2023). In summary, an average of 2,500 $/kg Uranium 5% enrichment was found (Leurs, 2023). Alternatively, in future work Uranium 20% enrichment or Thorium could also be investigated.

Combining 0.0028 g/kWh and 2500 $/kg one can find 0.0070 $/kWh as fuel cost for nuclear. To put this in perspective, for marine diesel engines this would be 0.102 $/kWh, based on 600 $/ton VLSFO (Ship and Bunker, 2024) and the earlier defined 170 g/kWh. With these prices, in terms of fuel cost, based on energy output, nuclear is roughly a factor of 15 cheaper than VLSFO.

Operations & Maintenance Cost
The operation and maintenance (O&M) cost of a nuclear power plant are the costs to maintain and operate a nuclear power plant. They consist of all non-fuel costs which are, for example, plant staffing, purchased services, replaceable materials, and equipment. Further, these can be divided into fixed and variable costs where fixed (plant staffing) are considered the biggest, which for a marine application will be assumed as nuclear power plant crew cost (Mignacca, 2020). The fixed costs are based on the installed electrical power and expressed in $/kW per year. Furthermore, the variable costs are based on MWh output expressed in $/MWh. An overview of O&M cost estimates is shown in Table 9. For this study, a round average is taken resulting in 130 $/kW per year and 4.0 $/MWh are used.

Table 9: Nuclear O&M cost *(Leurs, 2023)*

Source	O&M Fixed [$/kW per year]	O&M Variable [$/MWh]
(EIRP 2016)	96	3.0
(EIRP 2016)	158	5.0
(EIRP 2016)	206	6.5
(US Energy Information Administration 2022)	99	3.1
(US Energy Information Administration 2022)	114	2.8
(Vegel Benjamin 2017)	123	3.9
Round average	**130**	**4.0**

Voyage Cost
In this analysis the voyage cost consist of fees for ports, canals, pilots, and tugs. Based on reviews of the ports an average estimate has been established to be used in this analysis. An overview of the defined cost is shown in Table 10.

Table 10: Voyage cost *(Leurs, 2023)***

Item	Cost
Port Case I & II (Rotterdam, Shanghai, New York)	0.50 $/GT + *6.00 $/TEU
Port Case III & IV (Tubarao, Qingdao, Hedland)	0.80 $/GT
Pilotage Case I & II (Rotterdam, Shanghai, New York)	7,500 $/per visit
Pilotage Case III & IV (Tubarao, Qingdao, Hedland)	20,000 $/per visit
Tugs Case I & II (Rotterdam, Shanghai, New York)	6,000 $/tug 3 tugs per visit
Tugs Case III & IV (Tubarao, Qingdao, Hedland)	15,000 $/tug 3 tugs per visit
Suez Canal Case I	4.50 $/GT

*Based on 0.50 $/ton per TEU and 12 ton per TEU
**Rounded estimates from respective sources

SHIPPING INCOME
In this study, a range of freight rates is investigated to determine their influence on design speed. To obtain a realistic and market representative range of freight rates, historical data of the past 5 years from the Baltic Exchange (Baltic Exchange, 2023) has been studied.

Container Case I & II
Case I, with FBX11 and FBX12, and Case II, with FBX21 and FBX22, generally has an average freight rate between $1,000-$3,000 per FEU (Baltic Exchange, 2023). There are certain periods above and below this average range, but these are excluded from this study as they do not occur very often. Because container vessels do not always sail fully loaded, a utilization factor of 0.85 (Leurs, 2023) is used in this study.

Bulker Case III & IV
Case III, with C3 and Case IV, with C5, generally have an average freight rate between $5-$30 per ton of ore (Baltic Exchange, 2023). Similar to container freight rates, ore freight rates have certain periods above and below this average range. However, these are not included in this study. For utilization of the DWT for cargo 0.98 has been defined. 1.3% (0.013) of the DWT, being 4000 ton, is deducted to compensate for additional lightship weight (LSW) of the nuclear power plant as derived from earlier work (Houtkoop, 2022). The remaining 0.7% (0.007) of the DWT, being 2000 ton, is available for the consumables. The reference conventional base case Brasil Maru (Royal Institution of Naval Architects, 2008) has approximately 7500 ton of its DWT allocated for VLSFO. VLSFO is no longer present on the nuclear option and other consumables are only a fraction of fuel DWT. Therefore, the 2000 ton is deemed more than sufficient for other consumables. It is recommended to study the consequences of the integration of reactor and shield on LSW. The reason for this is that the longitudinal strength for bending and shear is different than with VLSFO storage.

DESIGN SPEED CALCULATION METHOD

In this section the design speed calculation method is clarified by defining the specifications of the ships. Furthermore, the economic speed determination is elaborated upon and illustrated showing how the cost are deducted from the shipping income resulting in a profit line.

Nuclear Options

With the income and speed-dependent costs identified, various scenarios can be calculated for different freight rates, reactor CapEx, and speeds. To do this, the vessel's total resistance is calculated for various speeds. Because relative high speeds are the area of interest, with large ocean going vessels, wave making resistance is a substantial part of the total resistance. To calculate it in a preliminary design stage a smaller vessel (Maersk-B Class (Leurs, 2023)) of the same type with a high Froude number is scaled up to the size and capacity of interest. Keeping the Froude number constant the total resistance is calculated. By doing so, for speeds up to the respective Froude number, it can be stated that the wave making resistance is not underestimated, which is considered a conservative approach for the initial designs. These estimates are then compared to Holtrop & Mennen (Leurs, 2023) to validate the order size of the respective resistance for the actual calculations. The initial estimates for the container cases are shown in Table 11.

Table 11: Initial design estimates container *(Leurs, 2023)***

Container	**Model**	**Ship**
Name	Maersk-B Class	Nuclear Container
Lbp x B x T [m]	278.20 x 32.18 x 12.20	475.72 x 55.03 x 20.86
Cb [-]	0.59	
Displacement [ton]	66,051	330,255
Froude number [-]	0.29	
Speed [kts]	29.2	38.2
Capacity [TEU]	4,000	20,000
Scale factor [-]	1.71	
Pd [MW]	68.0	444.3
Pb [MW]	68.6	457.9
Pne [MWe]	-	512.6

*Further clarified with power figures.

The power listed is brake power (Pb) for the existing vessels, listed under Model. Pb is the power provided by the engine on the shaft. The listed power for the nuclear option, listed under Ship, is the installed nuclear electrical power (Pne). This is calculated by correcting the translated Pb with 0.89 which is clarified in Figure 5.

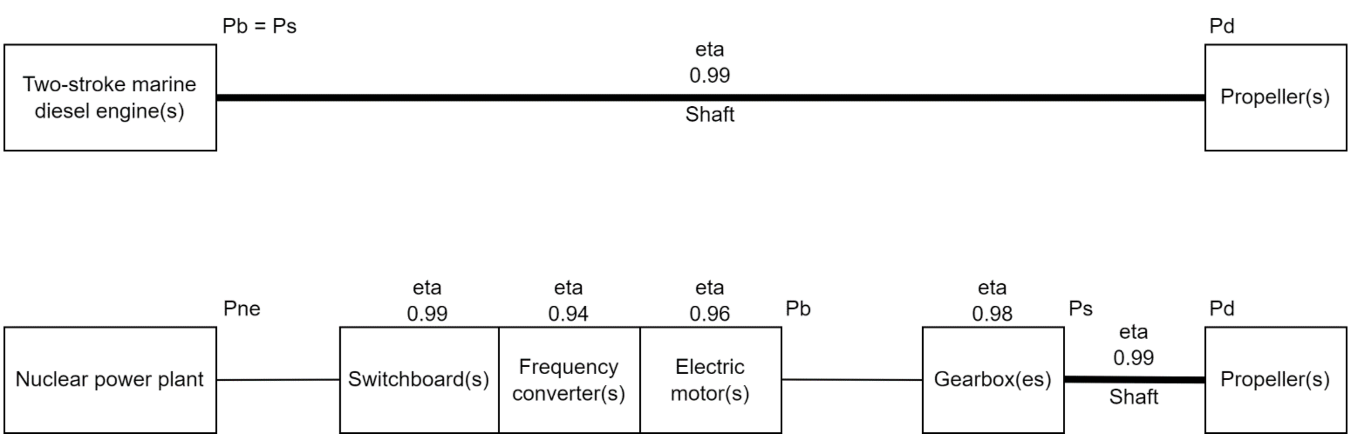

Figure 5: Conventional and nuclear power train (applied in this study) *(C-Job Naval Architects, 2024)*

The gearbox is included as a conservative approach but it might not be needed. This study aims to represent a broad range of designs. To make this tangible with a hypothetical speed of 30 knots it would result in roughly 249 MWe Pne. For a hypothetical vessel that uses two electric motors, this would translate into a power output of roughly 111 MWe per electric motor. The impact of the size of such electric motors without gearbox is not fully known. Additionally, similar to the selection of full electrical propulsion, adding the gearbox, with efficiency loss, contributes to a conservative approach in terms of efficiency. By doing so there is additional margin that assures that the results are not overly optimistic for the nuclear option. Therefore, the gearboxes are included in this study, in addition to making sure that the size of the electric motors are manageable. Nevertheless, future studies are also encouraged to review options to further optimize the nuclear option with (full) electrical propulsion without gearbox in addition to other propulsion configurations.

The same method used for scaling the container vessel has been used for the bulk carrier using Golden Wealth bulk carrier as reference vessel which has Fn 0.25 with 18,842 ton DWT (Ship Spotting, 2011). However, it was found that the resulting economic speeds were not in the high speed region (Fn>0.2) but clearly in the lower speed region (Fn<0.2). Therefore, using this reference vessel and method was not found suitable as the results were reasonably accurate on the high speeds but too conservative for the lower speeds. Therefore, a different reference vessel was selected, Brasil Maru, with a lower Froude number and larger deadweight resulting in a smaller scale factor. Here it should be noted that any potential results above this Froude number could be considered too optimistic. The initial estimates for the bulker cases are shown in Table 12.

Table 12: Initial design estimates bulker

Bulker	**Model**	**Ship**
Name	Brasil Maru*	Nuclear Bulker
Lbp x B x T [m]	325.00 x 60.00 x 18.10	336.31 x 62.09 x 18.73
Cb [-]	0.85**	
Displacement [ton]	307,508	330,255
Froude number [-]	0.15	
Speed [kts]	16.0	16.3
DWT [ton]	270,728	300,000
Scale factor [-]	1.03	
Pd [MW]	23.4	26.4
Pb [MW]	23.6	27.2
Pne [MWe]	-	30.4

*Data Brasil Maru: (Royal Institution of Naval Architects, 2008) & (Class NK, 2023)
**Estimate based on trend line derived from (C-Job Naval Architects, 2024)

As discussed in the background section of this study, the service life of nuclear reactors, approximately 75 years, are substantially longer than the service life of a conventional vessels, approximately 25 years. A first consideration would be to extend the service life of the vessel to make the use of nuclear reactor more attractive economically. However, an alternative form of economic use of the nuclear reactor is to decommission the ship, at its service of life of 25 years, and preserve the nuclear reactor which can then be used for a new vessel. Reviewing the options, this study views that the selection of either option on how to extend the use of the nuclear reactor, is independent on the design speed analysis. Therefore, in this study only the potential of extended use of the nuclear reactor is investigated with 50 and 75 years in addition to the conventional 25 years of service life of a vessel as illustrated in Figure 6. This study does not include evaluation of either option on how to extend the service life of the ship with nuclear reactor as illustrated in Figure 7. Future studies are encouraged to review these options, including all aspects of the ship and nuclear reactor, in order to determine the most attractive strategy.

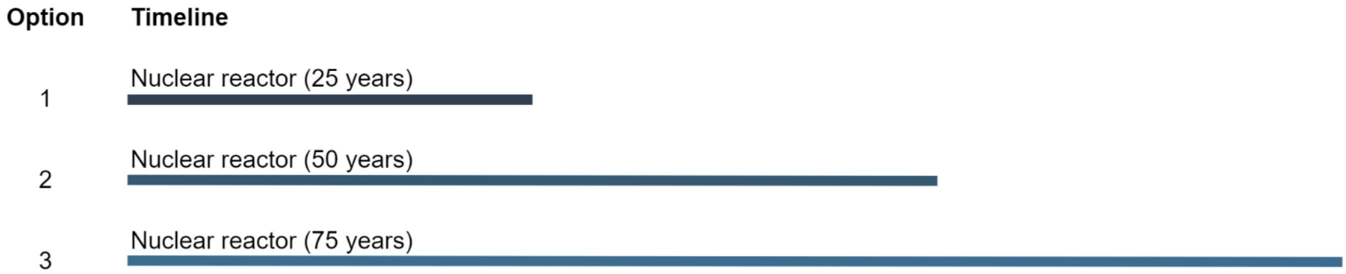

Figure 6: Service life options nuclear reactor (investigated in this study)

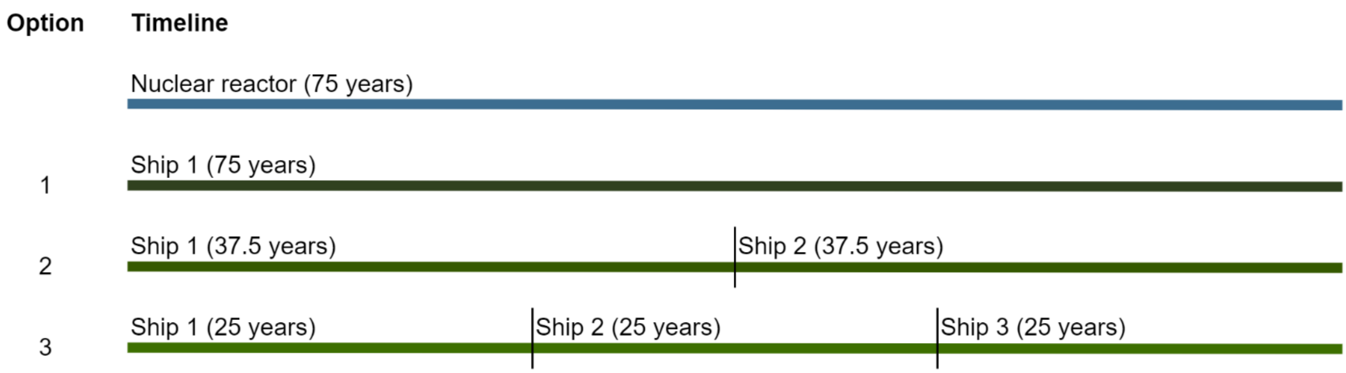

Figure 7: Service life options ship with nuclear reactor 75 years (not investigated in this study)

Conventional Option

To determine whether the resulting speeds of the nuclear options are actually higher compared to conventional configurations, as anticipated, a conventional option as reference is established. This conventional option will use the parameters as per Table 13 based on established design guidelines.

Table 13: Conventional option parameters

Item	Parameters	Source
Income	Same as Nuclear	-
CapEx: Marine diesel engine (2-stroke)	350 $/kW	(C-Job Naval Architects, 2024)
OpEx: Fuel cost (VLSFO) Specific fuel consumption	300-800 $/ton 170 g/kWh	(Ship and Bunker, 2024) (MAN Energy Solutions, 2024)
OpEx: O&M Fixed per year	35 $/kW	(Leurs, 2023)
OpEx: O&M Variable	10 $/MWh	(Leurs, 2023)
OpEx: Voyage	Same as Nuclear	-

Case Calculations

With the shipping income, and all cost components defined each case can be evaluated accordingly to determine the maximum profit and thus the optimum speed. An example of an individual scenario calculation is shown in Figure 8 which regards Case I, Nuclear, service life 75 years, freight rate $2000 per FEU, reactor CapEx $6,000 per kW. By combining all maximum profit scenario results an overview can be made with most economic speeds. These results are presented in the next section for all 4 cases with 3D graphs.

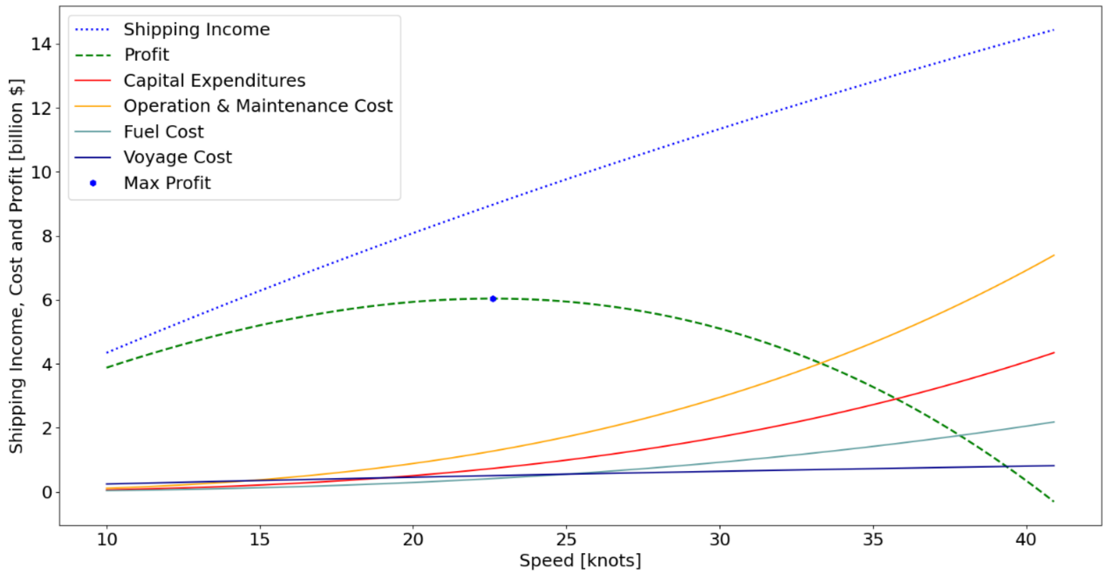

Figure 8: Example of individual scenario calculation
(Case I, Option Nuclear service life 75 years, scenario freight rate $2000 per FEU, reactor CapEx $6,000 per kW)

DESIGN SPEED RESULTS

Results covering the entire range of scenarios are presented in 3D graphs per case. Additionally, three specific scenarios are listed in tables for further considerations as shown in Table 14. For the conventional option, three specific scenarios are defined as per Table 15, similarly as with the nuclear options.

Table 14: Specific nuclear scenarios

Scenario	Freight rate	Nuclear reactor CapEx
A	High	Low
B	Average	Average
C	Low	High

Table 15: Specific conventional scenarios

Scenario	Freight rate	Fuel cost
A	High	Low
B	Average	Average
C	Low	High

Container

In this subsection the results of the container cases are presented and initially reflected upon. More extensive evaluation is covered in the section *Discussion*.

Case I

Using the figures of shipping income and speed-dependent cost with the described calculation method, Case I can be calculated with the results shown in Figure 9 (where the color gradient covers the resulting speed levels). The principal coding to generate these figures is sourced from (Leurs, 2023) and is adjusted with refined assumptions for this study. Furthermore, the results of the specific scenarios of nuclear with both 25, 50, and 75 years of service life, and the conventional VLSFO reference with 25 years are shown in Table 15.

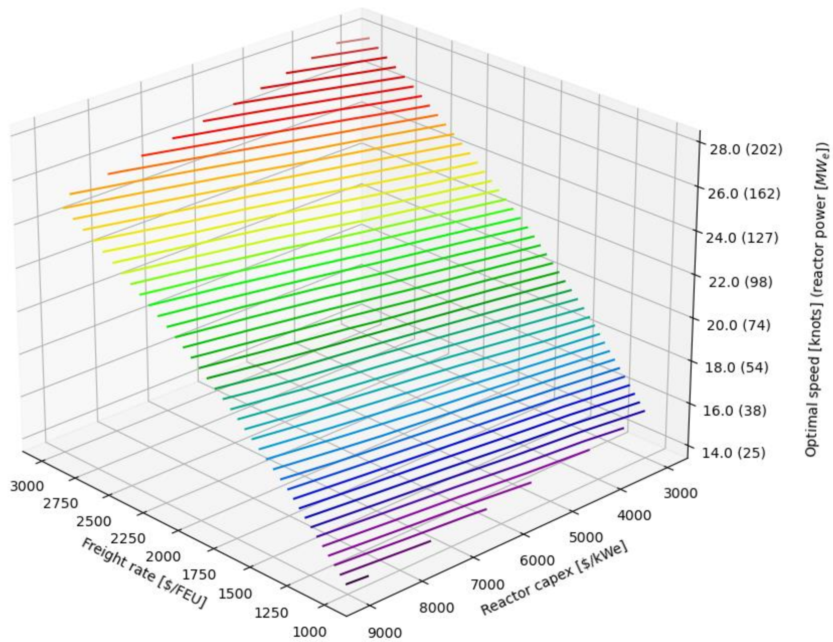

Figure 9: Case I, Nuclear, service life 75 years (color gradient covering speed levels)

Table 16: Case I design speed results of specific scenarios [kts]

Scenario	VLSFO 25y	Nuclear 25y	Nuclear 50y	Nuclear 75y
A	22.9	24.3	27.0	28.2
B	14.6	17.2	19.9	21.2
C	8.0	10.5	12.6	13.7

As can been seen in the nuclear options, 25, 50, and 75 years of service life, have higher economic speeds than the conventional VLSFO case of 25 years. Results of scenario A and B seem realistic as the conventional VLSFO case with speeds from 15 to 23 knots is considered very representative to current container vessel operation. For example, the Triple-E class of Maersk has a service speed of 16 knots and a maximum speed of 23 knots. Reviewing scenario C, which is the low-speed scenario, it should be noted that the current resistance estimate is done with a basic initial approach aiming for a good accuracy for the higher speed range, as explained earlier in the section Design Speed Calculation Method. As a result, it is too conservative for lower speeds (meaning speeds below 14 knots Fn<0.2). Hence the lower resulting speeds for scenario C. Furthermore, nuclear with 75 years of service life has an increase in economic speed compared to nuclear with 25 years of service life. This confirms the earlier statement about its potential and quantifies the additional gain. Additionally, freight rate seems to have the biggest influence whereas reactor CapEx has a less substantial role in the range investigated in this study.

Case II

For Case II, the results are shown in Figure 10 and the results of the specific scenarios are shown in Table 17.

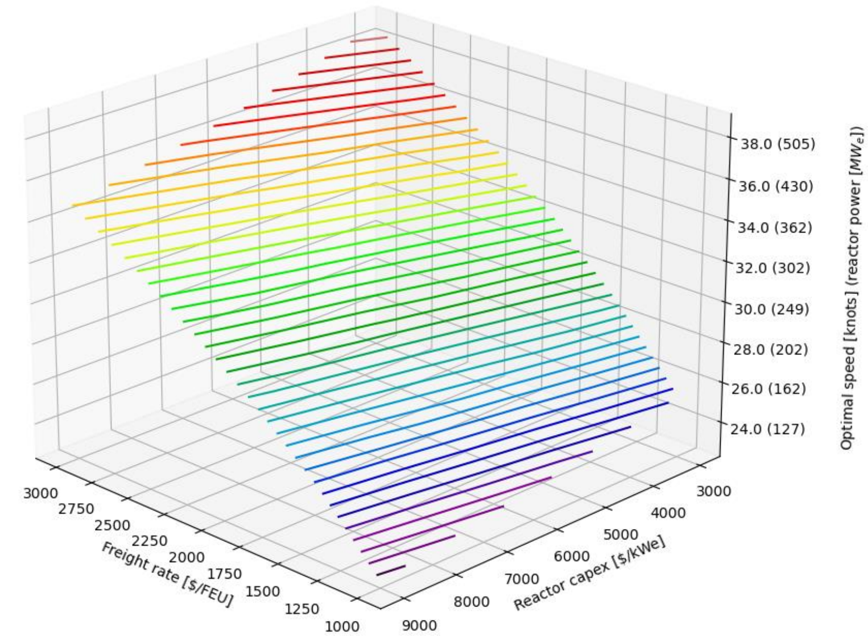

Figure 10: Case II, Nuclear, service life 75 years

Table 17: Case II design speed results of specific scenarios [kts]

Scenario	VLSFO 25y	Nuclear 25y	Nuclear 50y	Nuclear 75y
A	35.9	33.9	37.3	38.8
B	24.6	25.6	29.2	30.9
C	15.3	17.8	21.0	22.6

With Case II covering a substantially shorter distance than Case I, the resulting speeds are clearly higher. This can be explained by the investigated ranges of cost and freight rates. The freight rates are kept the same resulting in the same amount of income. On the other hand, lower cost associated with a shorter distance, lead to higher economic speeds. So, in general similar trends can be observed compared to Case I, where the actual speeds are higher. However, scenario A does not seem representative for Case II for current container vessel operations with speeds up to 36 knots for the VLFSO case. One might consider those respective conditions to be too optimistic with a very low likelihood of occurring. Here the results of scenario B and C are deemed more representative.

Bulker

In this subsection the results of the bulker cases are presented and initially reflected upon. More extensive evaluation is covered in the section Discussion.

Case III

For Case III, the results are shown in Figure 11 and the results of the specific scenarios are shown in Table 18.

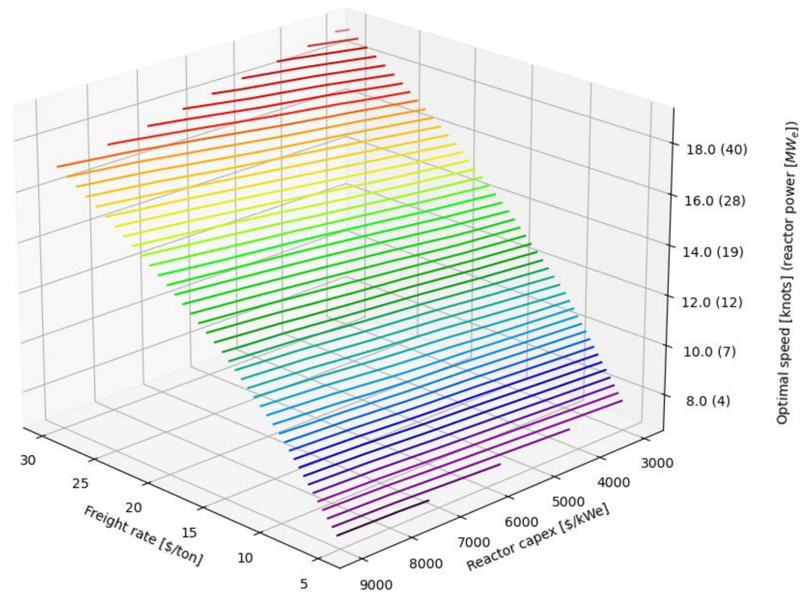

Figure 11: Case III, Nuclear, service life 75 years

Table 18: Case III design speed results of specific scenarios [kts]

Scenario	VLSFO 25y	Nuclear 25y	Nuclear 50y	Nuclear 75y
A	15.2	16.5	18.3	19.1
B	8.9	10.8	12.5	13.3
C	3.7	5.2	6.2	6.8

As can been seen in the nuclear options, 25, 50, and 75 years of service life, have higher economic speeds than the conventional VLSFO case of 25 years. The result of scenario A of the conventional VLSFO case, with 15 knots, are deemed representative as current bulk carrier operations are considered to generally range between 11 and 16 knots. Additionally, freight rate seems to have the biggest influence whereas reactor CapEx has a less substantial role in the range investigated in this study.

Case IV
For Case IV, the results are shown in Figure 12 and the results of the specific scenarios are shown in Table 19.

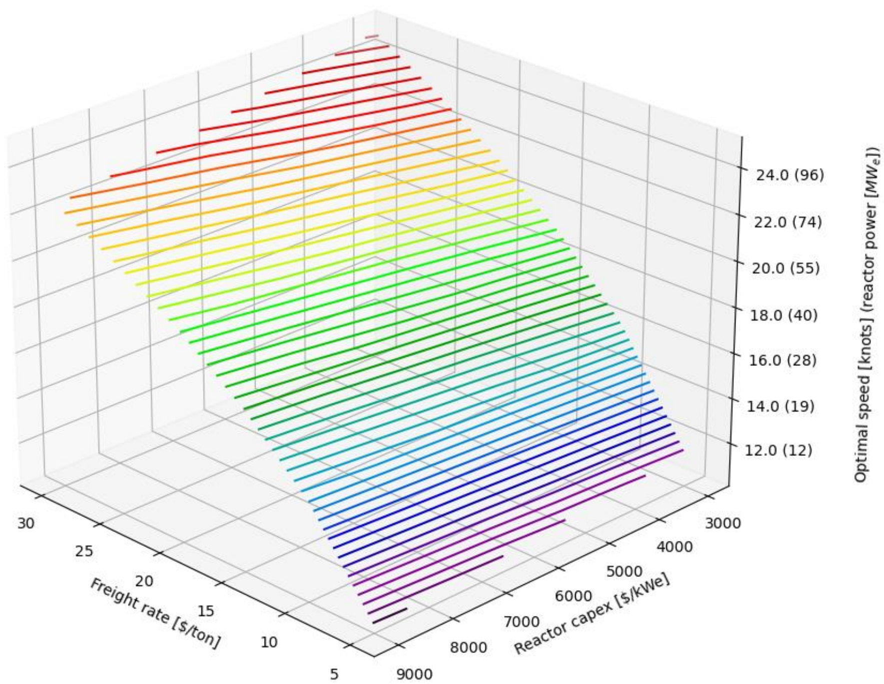

Figure 12: Case IV, Nuclear, service life 75 years

Table 19: Case IV design speed results of specific scenarios [kts]

Scenario	VLSFO 25y	Nuclear 25y	Nuclear 50y	Nuclear 75y
A	23.2	21.8	24.1	25.0
B	14.5	15.2	17.3	18.4
C	6.5	8.1	9.6	10.4

As can been seen in the nuclear options, 25, 50, and 75 years of service life, have higher economic speeds than the conventional VLSFO case of 25 years for scenario B and C. Scenario A does not seem representative for current bulk carrier operations with speeds up to 23 knots for the VLFSO case. Besides that, the shorter distance in Case IV logically has also higher speeds than Case III since the freight rates are kept the same and the effective cost is lower for the shorter distance. The result of scenario B of the conventional VLSFO case, with 15 knots, is deemed representative with respect to current bulk carrier operations.

DISCUSSION

In this section the results are further reflected upon. Additionally, an outlook is given on the design development including considerations for propulsion configurations.

Design Speed

This sub-section evaluates the design speeds of both cases for both ship types and envisions a guideline for future research.

Container

Reviewing the container cases with the specific scenarios, the range between scenario A and B for Case I and the range between scenario B and C for Case II seem most representative for the current container vessel operations. Considering the respective results of these cases and scenarios, it is found that 28-31 knots with a service life of 75 years would be a good range to explore nuclear powered container vessels further. This is a considerably higher speed than conventional container vessels. This is based on the assumption that the service life of the reactor is 75 years which is derived from existing nuclear power plants (Petrakakos, 2024). If the service life of the reactor changes, this design guideline would need to be revisited. As this is an initial design review, further analysis is recommended to cover more details, reduce uncertainty, and confirm or adjust these findings accordingly.

Bulker

Reviewing both bulker cases, similar principle results as with the container cases can be observed. Namely, both nuclear options, 25, 50, and 75 years of service life, have higher economic speed than the conventional VLSFO case, expect in scenario A of the shorter distance case. Furthermore, nuclear vessels with 75 years of service life have an increase in economic speed compared to nuclear vessels with 25 or 50 years of service life. Additionally, freight rate seems to have the biggest influence whereas reactor CapEx has a less substantial role. Considering the respective results of these cases and scenarios, it is found that 18-19 knots with a service life of 75 years would be a good range to explore nuclear powered bulk carriers further. This is a somewhat higher speed than conventional bulk carriers. This is based on the assumption that the service life of the reactor is 75 years which is derived from existing nuclear power plants (Petrakakos, 2024). If the service life of the reactor changes this design guideline would need to be revisited. As this is an initial design review further analysis is recommended to cover more details, reduce uncertainty, and confirm or adjust these findings accordingly.

Sensitivity

This study analyzed a bandwidth of reactor CapEx and freight rate and studied its impact on design speed. Besides these factors, also other cost aspects were quantified based on various references and design guidelines. Primarily the OpEx is considered of interest to be studied further to identify its sensitivity with respect to the design speed. This includes, but is not limited to, operations and maintenance cost of the nuclear power plant, and nuclear fuel cost, which is derived from the level of enrichment, the burnup and the price per kilogram. Further sensitivity analysis will help improve the robustness of the overall assessment. This will support the decision making process for the design speed of nuclear powered vessels.

Design Development

In this section the design development considerations for both the container vessel and bulk carrier are given. This covers main dimensions, resistance, and hybrid propulsion configurations.

Container

For this analysis the main dimensions of the container vessel exceed current port restrictions. Furthermore, a volume and displacement check needs to be done to confirm the cargo capacity (TEU), and adjust main dimensions where needed, to assure it is not too large. Therefore, for further design development it is envisioned to change the dimensions as shown in Table 20.

Table 20: Container vessel development of main dimensions

Parameter	**Nuclear Initial**	**Nuclear Iteration 1**	**Nuclear Iteration 2***	**Port restriction** (Leurs, 2023)
Lbp [m]	475.72	475.72	399.90	Rotterdam
B [m][	55.03	55.03	61.50	Rotterdam
T [m]	20.86	20.86	15.00	Shanghai
Cb [-]	0.59	0.59	TBD	-
Froude number [-]	0.29	0.23	0.25	-
Speed [kts]	38.8	30.0	30.0	-

*Envisioned dimensions based on port restrictions

Reviewing this design development it is noted that the length over breath ratio is reduced from 8.6 to 6.5 which is less favorable with respect to wave making resistance. However, at the same time, the actual Froude number is also reduced as the initial speed of 38.8 knots is reduced to 30.0 knots (derived as rounded average from the earlier identified range of 28-31 knots) based on the economic analysis. Thus, this also implies that the relative part of wave making resistance is reduced in the total resistance. So, these changes are not expected to change the overall total resistance significantly. Regardless, it is recommended to further develop the design, starting with the second iteration to reduce uncertainty, and confirm or adjust these findings accordingly.

Besides the envisioned development in main dimension, the propulsion can also be studied further. It might be possible that the initial defined arrangement of two propellers, as shown earlier in Figure 3, is not optimal for the considered speeds. The speed of 30 knots will require a substantial amount of thrust which thus might opt for a three propeller arrangement to reduce thrust loading coefficients and improve overall efficiency. An initial design of a 3 propeller arrangement is shown in Figure 13.

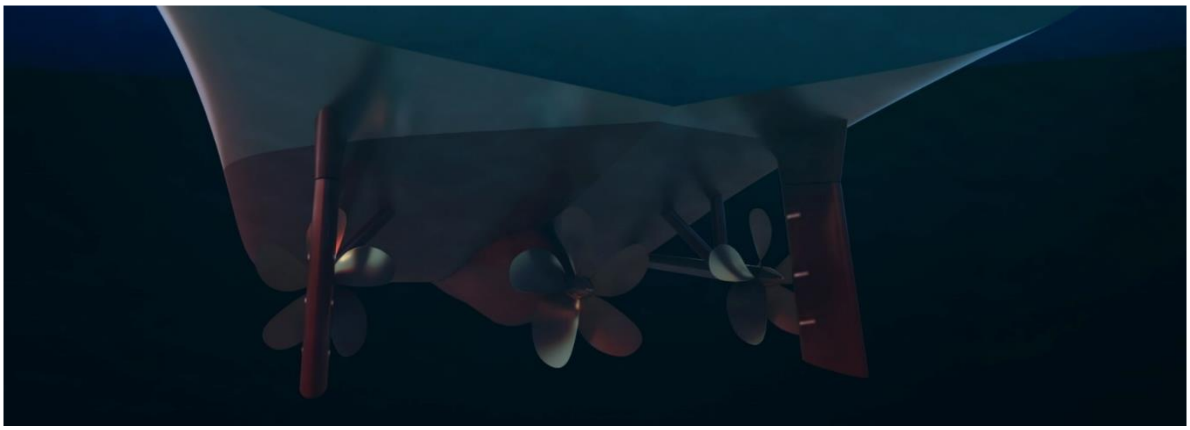

Figure 13: Initial design 3 propeller arrangement *(C-Job Naval Architects Visualization Discipline, 2024)*

The proposed arrangement with more propellers would offer further potential for hybrid propulsion configurations such as, but not limited to:

- 2 electric driven shafts + 1 direct turbine driven shaft
- 2 electric pods + 1 direct turbine driven shaft
- 1 electric driven shaft + 2 direct turbine driven shafts
- 3 hybrid driven shafts (turbine + power take in/off)

To further visualize this vision an initial integrated design of 3 hybrid driven shafts (turbine + power take in/off) is shown in Figure 14, Figure 15 (and Figure 16 under the acknowledgement).

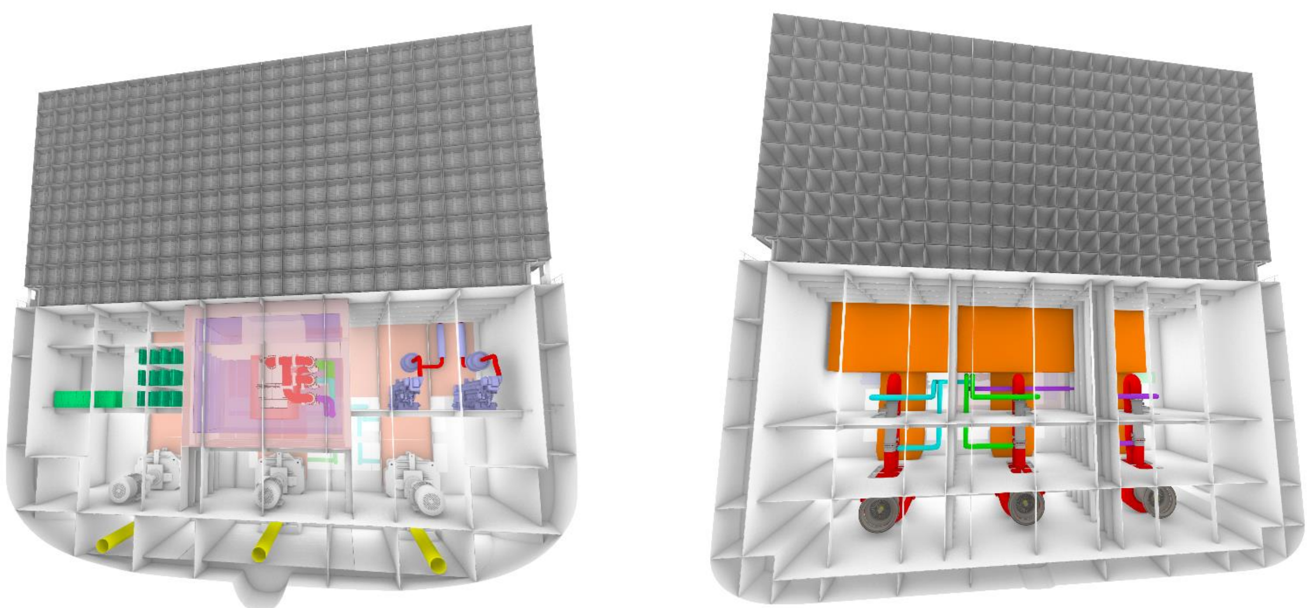

Figure 14: Initial ship design with integrated nuclear power and 3 hybrid driven shafts (turbine + power take in/off) part 1 *(C-Job Naval Architects Visualization Discipline, 2024)*

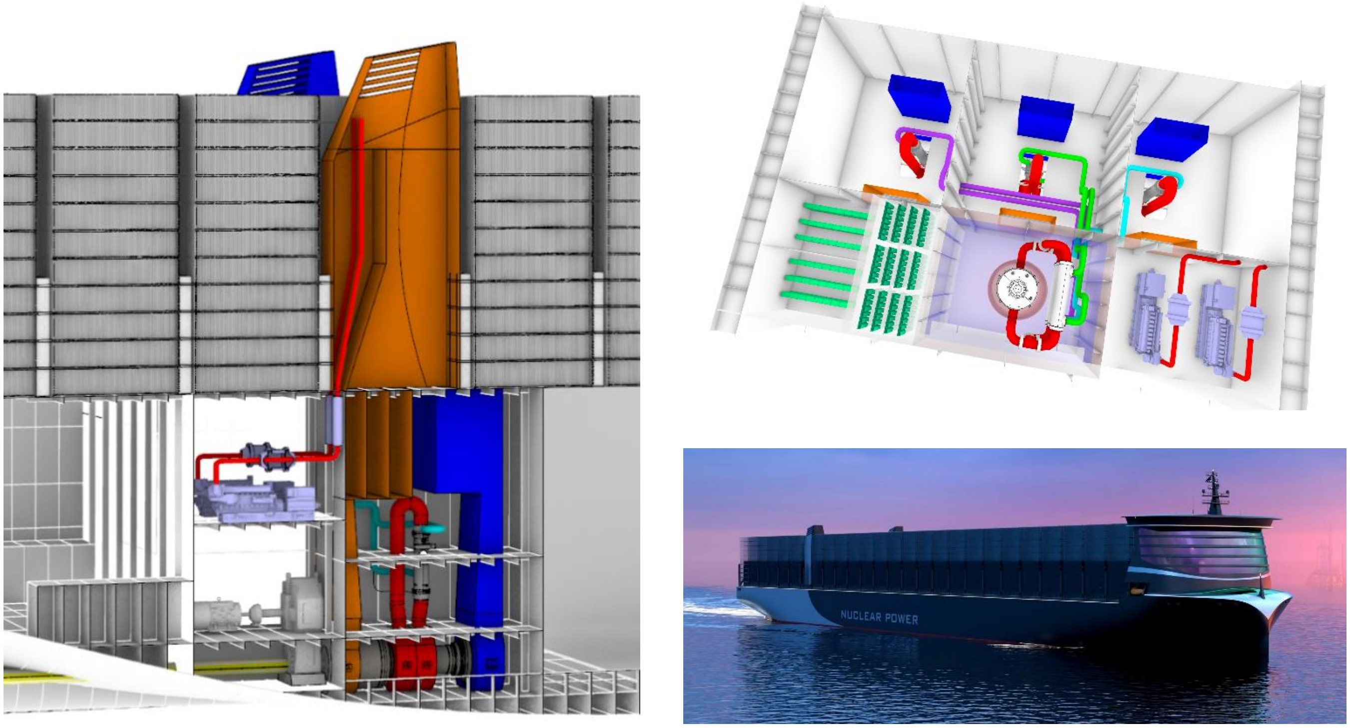

Figure 15: Initial ship design with integrated nuclear power and 3 hybrid driven shafts (turbine + power take in/off) part 2 *(C-Job Naval Architects Visualization Discipline, 2024)*

Bulker

Reviewing the bulk carrier dimensions, no adjustments seem absolutely necessary based on port restrictions. Furthermore, the considered speed range of 18-19 knots, defined in the earlier discussion, would suggest two propellers are adequate. Based on that a number of hybrid propulsion configurations can be considered, such as, but not limited to:

- 2 hybrid driven shafts (turbine + power take in/off)
- 1 electric pod + 1 direct driven shaft line

Contribution and Future Work

The work of (Houtkoop, 2022) identified the initial potential of next generation nuclear technology for shipping with replacement of conventional power generation. The work of (Leurs, 2023) expanded on this for container vessels by developing new build cases and explore their potential focusing on design speed, propulsion and power generation, and ship design. As additional expansion, this study also added the bulk carriers focusing on the same aspects. With this combined material, this study aims to inspire other naval architects and marine engineers to look beyond conventional design and operations, and punch technical boundaries to ultimately make shipping more sustainable.

CONCLUSION

Both nuclear options, 25, 50, and 75 years of service life, have higher economic speeds than the representative conventional VLSFO case. Furthermore, nuclear with 75 years of service life has an increase in economic speed compared to nuclear with 25 and 50 years of service life. Additionally, freight rate seems to have the biggest influence whereas reactor CapEx has a less substantial role. Besides that, the shorter distance cases logically also have higher speeds than longer distance cases since the freight rates are kept the same and the effective cost are lower for the shorter distance.

Considering the respective results of the container cases it is found that 28-31 knots with a service life of 75 years would be a good range to explore nuclear powered container vessels further. For the bulker cases it is found that 18-19 knots with a service life of 75 years would be a good range to explore nuclear powered bulk carriers further. This is based on the assumption that the service life of the reactor is 75 years which is derived from existing nuclear power plants. If the service life of the reactor changes this design guideline would need to be revisited.

In the initial review of options on how to convert nuclear power to propulsion and electrical power each part was evaluated. A primary and intermediate loop was used for heat transfer to the secondary loop to assure containment of radiation. For the turbines, an open Brayton cycle concept with load turbine and heat rejection capability was found to be most suitable, as it has improved load response capabilities and is relatively compact.

RECOMMENDATIONS

In this section the recommendations are given which serve as inspiration for future research and are part of the authors vision and understanding of the topic acknowledging various aspects that require more attention for the next steps.

Cost

The studied bandwidth of reactor CapEx, which included decommissioning cost in this study, is still quite broad and should be narrowed down further to reduce the uncertainty on the total cost of ownership. To do so, more detailed input from nuclear power plant developers is required to evaluate initial investment cost and the connected decommissioning cost at the end of the service life. Additionally, the effects of inflation on these costs over longer periods, considering the 75 years that is investigated in study, should also be incorporated in future work to reduce the uncertainty.

Besides CapEx, also OpEx of nuclear power plants should be studied further to reduce the uncertainty on the total cost of ownership. Especially, operations and maintenance cost of the nuclear power plant, and nuclear fuel cost are considered to be very relevant in future studies.

The effect of higher speeds and potential longer service life of other ship cost components such as the steel hull and other components besides the nuclear power plant should also be included in future studies. Despite the fact that these cost components are anticipated to be smaller than the nuclear power plant, incorporating them will improve the accuracy of the total cost of ownership which is the foundation for investment decisions.

Another cost component that requires more attention is the insurance. At this time, the difference in ship insurance cost between conventional and nuclear-powered ships is unknown and is not included in this study. Nevertheless, considering the sensitive nature of nuclear power, it deserves more attention from an insurance perspective as well. Therefore the respective insurance cost should also be studied.

Regulatory Framework

The current regulatory framework for nuclear powered vessels are outdated and considered a hurdle for nuclear power to be applied in (commercial) marine applications. Therefore, further development of nuclear power on marine applications is needed to clarify various parts on national and international level. This development should include all involved stakeholder such as, but not limited to, equipment manufacturers, ship designers, shipyards, classification societies, shipowners, local governments and nuclear regulators.

Main Particulars

The studied container vessel design has main dimensions that exceed current port restrictions. Furthermore, a volume and displacement check needs to be done to confirm the cargo capacity (TEU). Therefore, it is recommended to further develop the design, starting with the second iteration to reduce uncertainty, and confirm or adjust these findings accordingly. Furthermore, it is recommended to do a more detailed resistance analysis to reduce the uncertainty.

Propulsion Configuration

In this study a fully electric the propulsion configuration was selected as it offers flexibility in arrangement and options for easy integration of peak shaving with batteries for improved load response. Furthermore, it also offers options for reverse cold ironing while in port and easy integration of back-up power by means of diesel generators. Nevertheless, future studies are encouraged to review options to further optimize the nuclear option with for example turbine-direct propulsion, hybrid propulsion or full electrical propulsion without gearbox.

Operational Challenges

Where conventional VLSFO fueled vessels have low CapEx for their marine engines, it is observed that big(ger) engines can be installed with relatively little additional cost. With that, one gains the operational flexibility to adjust speed economically based on freight rate and fuel cost, as part of OpEx. For nuclear powered vessels this operational flexibility is limited as the CapEx of the nuclear reactor is relatively large. Therefore, it is recommended to further study all costs of nuclear marine propulsion where the share of CapEx, fuel, O&M, and others are better understood. Based on that the economic risks can be better assessed in order to determine the actual design speed for a nuclear-powered cargo vessel. An additional challenge, for the container vessel cases, considering their high speeds, is heavy weather conditions were it could be the case that ship speed needs to be temporary lowered to avoid damages caused by such conditions at higher speeds. The potential effect of this should be further studied.

Service Life

The service life of nuclear reactors is understood to be approximately 75 years and thus substantially longer than the service life of a conventional vessels, with approximately 25 years. So in general it seems logical to use the full service life of 75 years of the nuclear reactor on one or more vessels. This is further supported by findings of higher operational speeds, and thus more profitability, for service life of 75 years. However, it is not known what option, on how to facilitate utilization of the nuclear for 75 years, on one, two or three vessels is most economical. Therefore, future studies are encouraged to review these options in order to determine the most attractive strategy.

Ship Types

Besides container vessels and bulk carriers, it is recommended to consider other ship types, such as, but not limited to, tankers and offshore vessels, to further explore the potential of nuclear marine propulsion.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN WRTITING

No AI or AI-assisted technologies have been used by the authors in the receptive research or in writing this paper.

CONTRIBUTION STATEMENT

Author 1, Niels de Vries: Research of the bulk carrier cases, supervision of nuclear marine propulsion and power generation research, supervision of the container vessel cases research, writing and editing of this paper.

Author 2, Koen Houtkoop: Research of nuclear marine propulsion and power generation, writing the referenced thesis report (Houtkoop, 2022) and reviewing this paper.

Author 3, Zeno Leurs: Research of the container vessel cases, writing the referenced thesis report (Leurs, 2023) and reviewing this paper.

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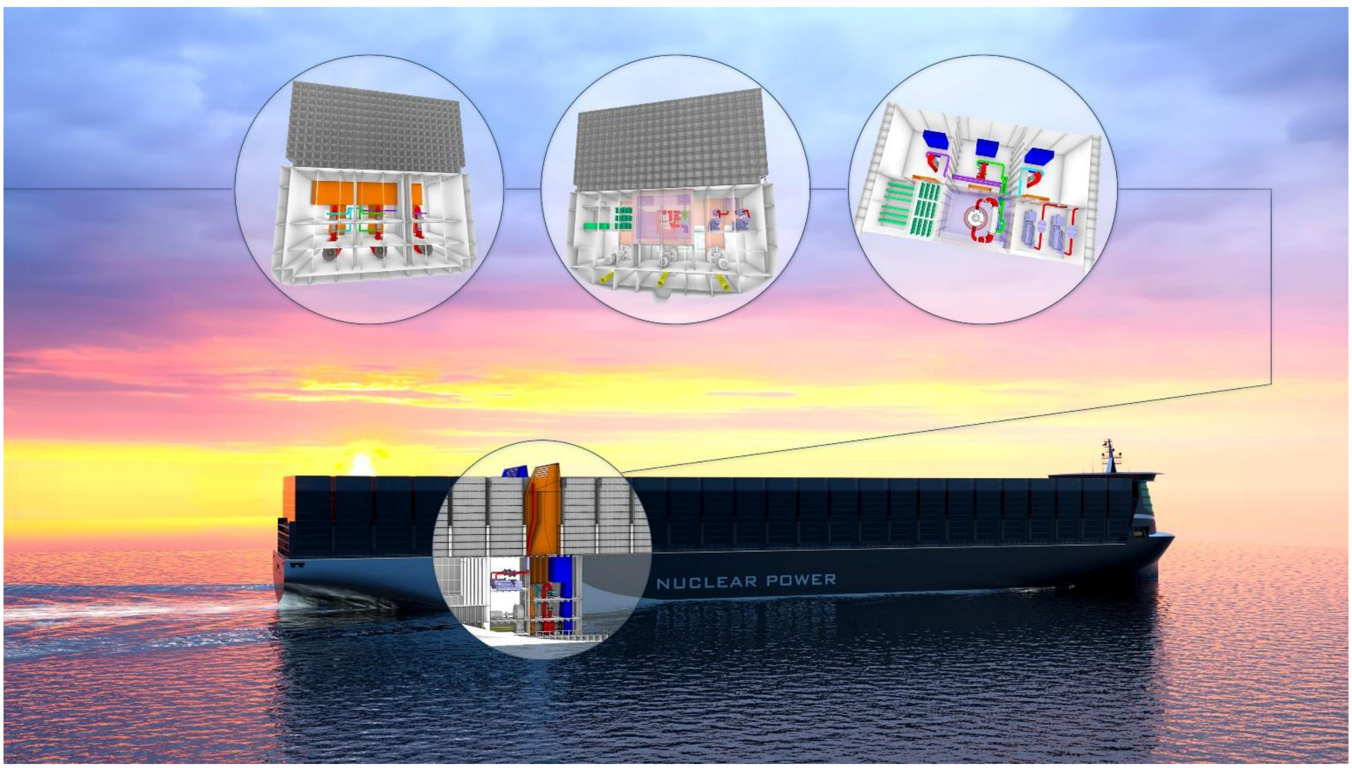

Figure 16: Initial ship design with integrated nuclear power and 3 hybrid driven shafts (turbine + power take in/off) part 3 *(C-Job Naval Architects Visualization Discipline, 2024)*

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