Generation IV (very) Small Modular Reactor technology for Future Surface Combatants

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Synopsis

Nuclear energy has found widespread application in naval and military installations around the world. Recent advancements, particularly in Generation IV nuclear technologies, promise significant improvements in sustainability through reduced nuclear waste production, enhanced economic competitiveness, stronger proliferation resistance, and passive safety features. Despite these benefits, their application in future surface combatants remains unexplored, particularly as modern mission profiles demand elevated power and energy requirements. The primary objective of this paper is to investigate the feasibility of integrating Generation IV Small Modular Reactor ($< 300\ MW_e$) and Very Small Modular Reactor ($< 10\ MW_e$) technologies as power sources for next-generation naval platforms. The study focuses on two reactor designs: the Very High-Temperature Reactor and the Molten Salt Reactor. A detailed analysis evaluates the design implications of adopting these advanced reactor technologies, addressing aspects such as shielding, power generation, distribution, and conversion systems. Emerging technologies, including naval-directed energy weapons and advanced sensor systems, are incorporated to determine the impact of future mission requirements on ship design. A sizing model has been developed to assess the feasibility of integrating these technologies based on power, energy, volume, and weight requirements. The results indicate that the Small Modular Reactor technology can replace conventional gas turbine systems for surface combatants with a displacement of more than 8,000 tonnes. However, very Small Modular Reactor technology faces significant challenges due to its weight and space requirements, particularly for ships up to 16,000 tonnes displacement. Increasing the power output of very Small Modular Reactors offers the potential to reduce shielding requirements and enhance feasibility. A case study on a 9,800-tonne surface combatant design is presented to illustrate the findings. The study emphasises the critical role of energy storage systems in managing variable power demands, especially for combatants equipped with advanced reactor systems combined with directed energy weapons and high-powered sensors. It also demonstrates that Small Modular Reactor configurations are comparable in size and weight to all-electric gas turbine systems, offering a viable alternative for future surface combatants. Although Generation IV (very) Small Modular Reactor systems offer significant potential for enhanced autonomy and future-proofing power capabilities, they present challenges related to weight, volume, and design flexibility. The findings provide a framework for naval capability development, supporting the design of advanced nuclear-powered surface combatants for global navies and broader maritime applications.

Keywords: Nuclear Energy; Generation IV; Small Modular Reactor; Future Surface Combatant; Ship Design

1 Introduction

Naval forces around the world face growing power demands, seek greater operational flexibility, and aim to reduce dependence on fossil fuels. Modern nuclear propulsion systems, particularly Small Modular Reactors (SMR) and very Small Modular Reactors (vSMR), present a promising solution. While conventional marine reactors have served well in strategic nuclear navies, especially in submarines and aircraft carriers, their large size, reliance on active safety systems, extensive crew requirements, and high lifecycle costs make them less suitable for surface combatants in middle-power navies (O'rourke, 2010), for example, the Royal Netherlands Navy (RNLN). Generation IV (v)SMRs offer possibly compact, passively safe, and high-density power alternatives enabling cost-effective and scalable deployment according to the IAEA (2022). For the RNLN, adopting such technology could significantly improve strategic autonomy, reduce emissions, and meet the growing energy demand of future surface combatants equipped with advanced sensors, weapons, and unmanned systems.

Despite the theoretical advantages, there is limited research on the practical integration of Generation IV (v)SMR technology into future surface combatant designs. Most existing studies focus on land-based reactors or traditional naval nuclear propulsion, with little attention paid to the unique design, operational, and survivability challenges posed by integrating SMRs into surface combatants.

The main objective of this paper is therefore to investigate the implications of using Generation IV (very) Small Modular Reactor technology for power generation on the design of a future surface combatant in terms of power, energy, weight and volume.

Authors' Biographies

Ir. G.H. (Gerard) Wiegersma is a graduate of the Delft University of Technology in Marine Technology (2024). Currently, he is a marine engineer for the Royal Netherlands Navy with the Materiel and IT Command.

Ir. N.H.D. (Niels) Gartner is a marine engineer working at the Materiel and IT Command, responsible for battery systems and air quality systems. He graduated with his MSc. Marine technology in 2021 with his thesis on the thermal behaviour of lithium-ion batteries and the implications on submarine system design.

2 System description

The system of interest is the fourth-generation (v)SMR power plant integrated in a future surface combatant. The leading parameters in the design of a surface combatant are displacement and volume. In addition to propulsion and power generation, the Sensor, Weapon, and Command (SEWACO) systems, auxiliary systems, and accommodation require displacement, volume, and position in the combatant (van Oers et al., 2018). The impact on the design of a future surface combatant, which uses (v)SMR technology for power generation, results from all components in the design structure presented in Figure 1.

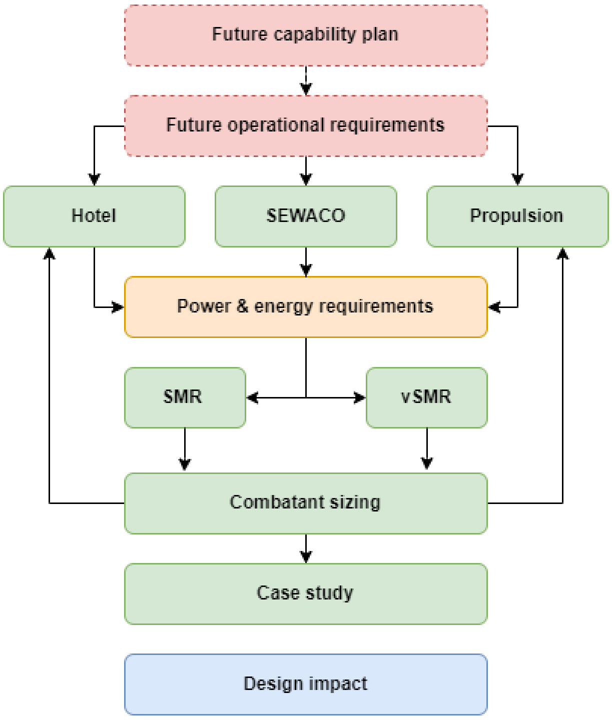


Figure 1: *Schematic design structure*

After establishing power and energy requirements by interpreting an illustrative future capability plan, the model developed in this research will evaluate a chosen SMR and vSMR. This will lead to combatant sizing by iterating over displacement, resulting in a case study of a future surface combatant with an appropriate size to accommodate future SEWACO systems and a fourth-generation (v)SMR power generation system. Impact on the design can be found when the case study compares a conventional Gas Turbine System (GTS) with a (v)SMR-powered combatant.

2.1 Future surface combatant

When considering fourth-generation (v)SMR technology, it is essential to realise that it is in the development or demonstration stages globally, with the first practical prototypes operating around 2028 (IAEA, 2022). In addition to extensive testing and certification processes, investment and political will are required. Realistically, the (Very) High Temperature Reactor ((V)HTR) with a higher technology readiness level may begin to be used in marine applications from 2040, with broader deployment, including the Molten Salt Reactor (MSR), potentially happening in the 2050s.
The main drivers of power demand are the payload and combatant size, mainly determining the SEWACO, hotel, and propulsion load. Emerging weapon and sensor technologies are implemented to position the combatant within the spectrum of future mission capabilities. The future surface combatant will include sensors, naval directed energy weapons, unmanned vehicles and conventional armament. The specifications of these systems and the intended performance of the future surface combatant are addressed in Wiegersma (2024).

2.2 Power train

Power needs to be distributed throughout the combatant. Given the advanced electrical needs of future surface combatants and the relatively low reaction time of (v)SMRs, this paper uses an integrated power system (IPS) as a starting point. Figure 2 shows that regardless of conventional or nuclear power, the power train remains the same when chosen for an IPS.

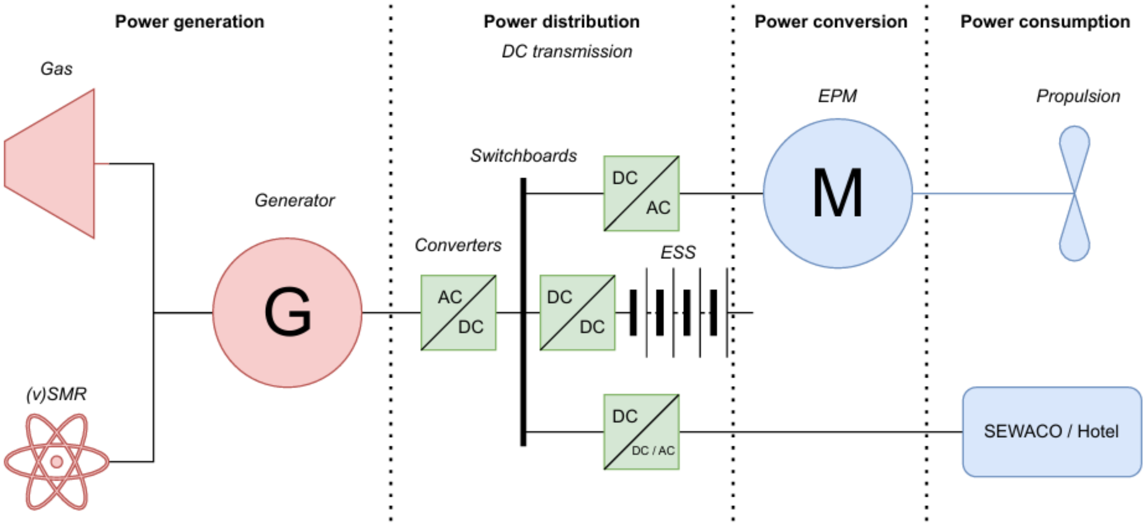


Figure 2: *Schematic power train for conventional (gas) or nuclear (SMR) technology assuming an integrated power system*

Given the power and energy requirements from Figure 1, power is generated either with gas turbines or a (v)SMR. A generator, assumed as an electrical machine, is connected to a DC transmission grid, which manages the power distribution. A generic naval lithium-ion-based technology has been used as the Energy Storage System (ESS) to solve rapid changes in the power demand of a future surface combatant (Wiegersma, 2024). Ultimately, energy is converted into SEWACO and hotel load or propulsion power by an Electrical Propulsion Motor (EPM).

2.3 Reactor selection

The used reactor technology needs to be promising for future naval applications. Only the (V)HTR is promising for vSMR technology (Wiegersma, 2023). To find the implication on ship design while keeping practical relevance, the SMR will be modelled with an MSR, and the vSMR will be modelled with a (V)HTR. Technical data and assumptions will be based on the two following reactor designs described by the IAEA (2022):

SMR is based on the Compact Molten Salt Reactor (CMSR), Seaborg Technologies ApS, conceptual design of a 100 MW_e MSR

vSMR is based on HOLOS-QUAD, HolosGen LLC, a detailed design of a 10 MW_e HTR

The design of the CMSR described in IAEA (2022) and the HTR detailed by Filippone and Jordan (2017) are completely published and provide sufficient information for understanding fourth-generation (v)SMR implementation on future surface combatants.

3 Combatant sizing model

The combatant sizing model is a parametric model that iterates the displacement of the combatant concepts, translating the design structure described in Figure 1. The outcome of the sizing model is used in a detailed case study comparing a conventional and nuclear-powered future combatant.

The concept of combatants is examined in terms of power (MW_e), weight (tonnes), volume (m^3) and energy storage (MWh).

A methodology was developed to conduct this analysis through a sequence of computational steps, visualised in Figure 12. The design flow of Figure 1 in combination with the power train given in Figure 2 leads to the sizing model, which is divided into four parts:

- Power & energy requirements

- Reactor compartment
- Cooling & heat transfer
- Power generation, distribution & conversion

3.1 Model details

The model iterates over displacement in tonnes. Not all systems that are part of the (v)SMR power plant have been previously described but do influence the design of future surface combatants.

3.1.1 Power & energy requirements

The performance requirement described in Wiegersma (2024) is used as input for the sailing speeds. Propulsion variables such as the number of shafts, turbines and emergency generators are considered.

The power and energy requirements are input for the SEWACO load and are assumed constant (not iterated over displacement). The hotel load is corrected with a factor to take the combatant size into account.

The total power demand per combat condition is based on the hotel load, propulsion load and the part-load efficiency. The propulsion load, P_{prop}, is estimated with a parametric model derived from the admiralty coefficient, based on the air-defence and command frigate (LCF) of the Royal Netherlands Navy (Vollbrandt, 2016). The required propulsion power relates to displacement Δ, in tonnes, and the sailing speed v_s, in knots, according to equation 1 given by Woud and Stapersma (2002):

$$P_{prop} \propto \Delta^{\frac{2}{3}} \cdot v_s^3 \tag{1}$$

At lower sailing speeds (< 12 knots), the power demand is in part-load conditions and therefore corrected with a general efficiency curve for EPMs (van Es, 2011).

3.1.2 Reactor compartment

The reactor compartment provides a secure and controlled environment with particular attention paid to ensuring radiation containment and minimising exposure to crew members. It includes the reactor (pressure vessel) and shielding.

Shielding is crucial for protecting the crew from neutron and gamma-ray radiation. The As Low As Reasonably Achievable (ALARA) principle is applied to minimise exposure, ensuring that the occupational dose does not exceed the annual limit of 50 mSv (ICRP, 2007). Water to shield against neutrons is considered unsuitable for fourth-generation (v)SMR primary shielding in naval applications due to the risk of leaking or vaporising. For the neutron shield, high-temperature-resistant concrete or borated polyethylene has been proposed (Rockwell III, 1956). The shielding of γ rays has been accomplished with lead. The shielding is modelled assuming the Point Kernel method according Lamarsh et al. (2001) with equation 2:

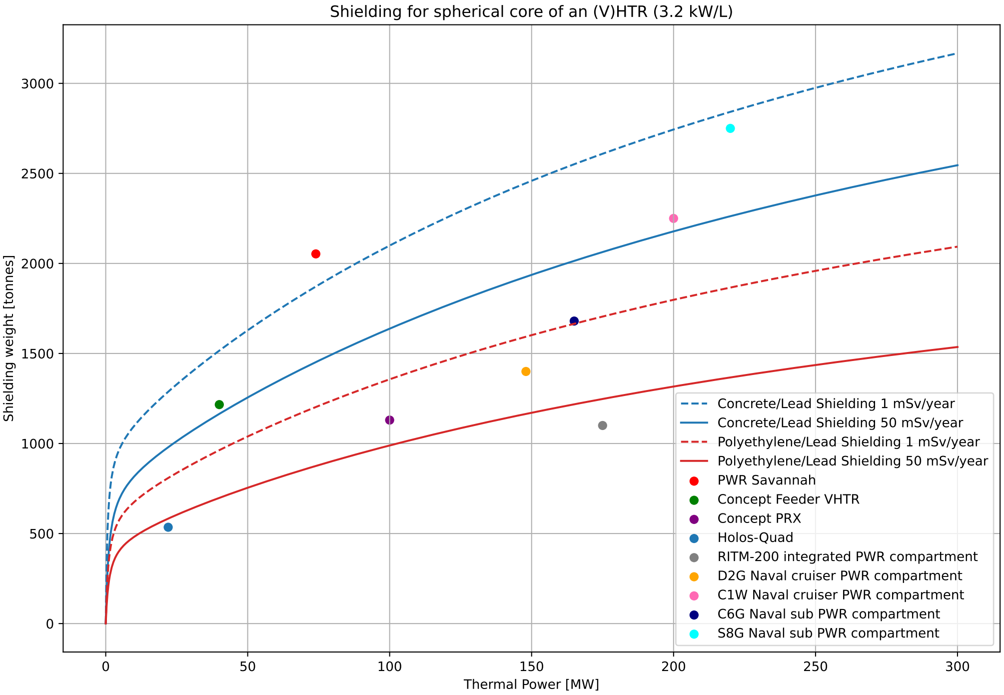
$$\Phi = \frac{S}{4\pi R^2} \cdot T(E,R) \tag{2}$$

where Φ is the dose rate at the receptor point in Sv/s, S the source strength in particles or photons per second, R the distance from the point source to the receptor point in m and $T(E,R)$ the dimensionless energy- and material-dependent transmission factor. This factor T depends on the type of radiation and is described with the removal-attenuation approximation to take neutrons into account and the attenuation with buildup factor calculation for γ-rays described accurately in Lamarsh et al. (2001).

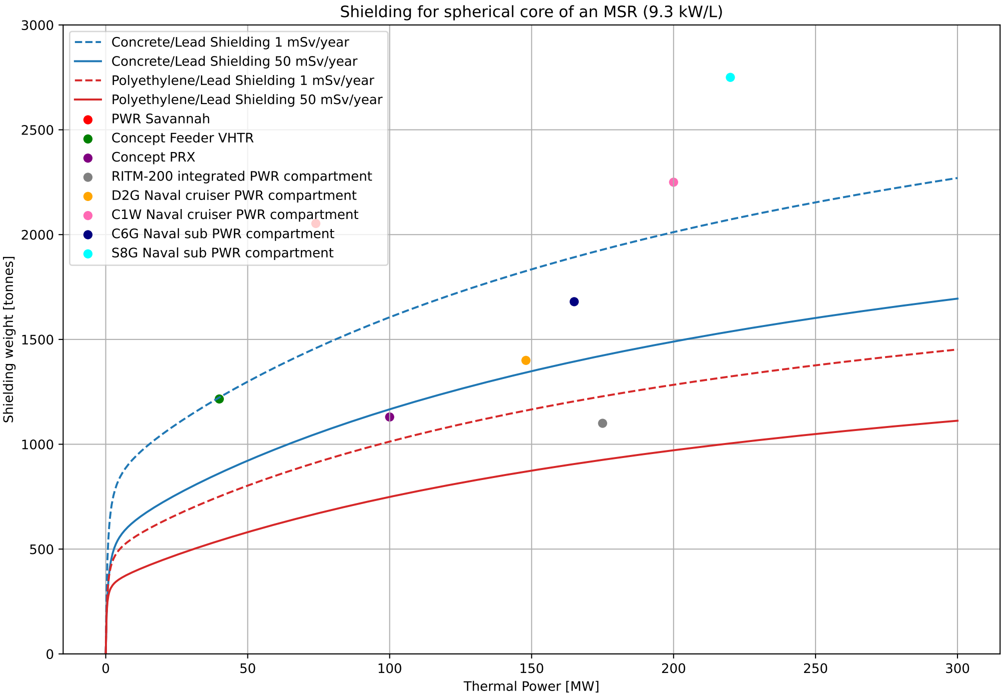
The weight of the shield can be approximated by adding shielding material until equation 2 is satisfied to 50 mSv per year. The result is found in Figure 3, the shielding weight per unit of installed thermal power. The detailed model, including representative values for shielding materials, source terms, reactor geometry, and dose coefficients, is provided in Wiegersma (2024). Data points of relevant marine reactor shielding weights have been added to the Figures 3a and 3b for verification. The limited publicly available reactor shield designs contain different ratios of water, concrete, steel and polyethylene (U.S. Department of the Navy, 2012) (Zou et al., 2022) (Liu et al., 2022). The reactor compartment of naval Pressurised Water Reactors (PWR) contains the structural components associated with specific class reactor vessel complexes, plant piping, and other miscellaneous parts (U.S. Nuclear Regulatory Commission, 2023).

From Figure 3, it is concluded that for both (v)SMRs, the polyethylene with lead configuration offers the lightest design. Due to their lower core density, the heaviest shielding is necessary for (V)HTRs.

A difference in weight is observed between Figure 3a and Figure 3b when the thermal power output increases. This behaviour is observed because the core density of MSRs is higher, influencing both the source strength S and the distance R. This results in a smaller radius, decreasing the amount of required shielding.



(a) *Spherical shielding for (V)HTR*



(b) *Spherical shielding for MSR*

Figure 3: Shielding weight in tonnes per unit of installed thermal power including reference designs

3.1.3 Cooling & heat transfer

Cooling and heat transfer systems are required for the reactor and SEWACO systems. Power generation for the SMR is performed with the indirect closed Brayton cycle, requiring heat exchangers. The use of an intermediate cycle is a ship design choice to prevent radioactive contamination from reaching power systems, introducing safety redundancy and having a mechanical buffer (Houtkoop, 2022). For surface combatants, the intermediate cycle enhances survivability in naval combat situations by isolating critical systems (Wiegersma, 2024). The heat exchangers required for the (v)SMR power plant are visualised in Figure 4.

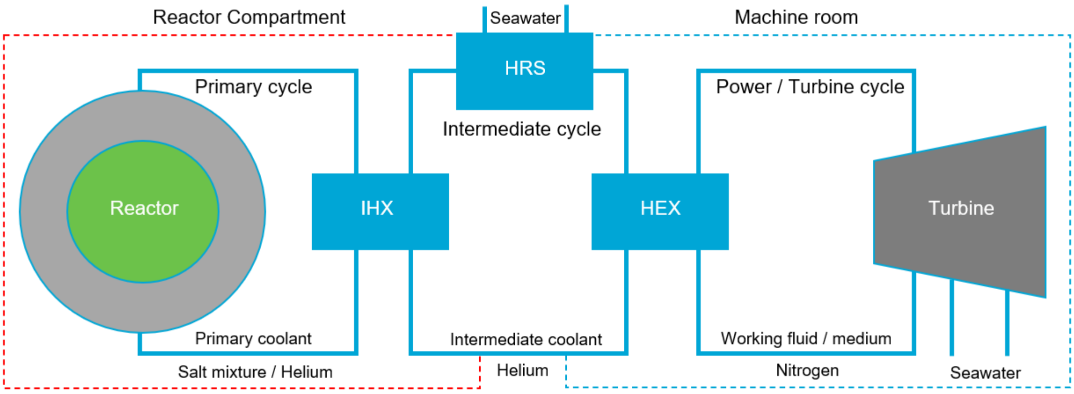


Figure 4: *Schematic of closed cycles and the operating mediums*

The primary cycle uses a primary coolant, a molten salt mixture for the MSR and helium for the (V)HTR. Helium is used for both (v)SMRs in the intermediate cycle due to its chemical inertness, resistance to neutron activation, and excellent thermal conductivity. Nitrogen is used as the working gas in the power cycle because it provides a practical balance between thermal efficiency and system compactness at medium turbine inlet temperatures (500–700°C). This aligns well with current MSR outlet temperatures and supports a simpler, higher-TRL power cycle suited to naval applications (Wiegersma, 2024).

Apart from a Heat Exchanger (HEX), an Intermediate Heat Exchanger (IHX) and a Heat Removal System (HRS) are introduced. The HRS is required to meet the dynamic load profile of a surface combatant. The MSR and (V)HTR can not operate at low power loads ($P < 20\%\ P_{tot}$). The HRS is used to remove the heat directly from the reactor when the reactor is operating in low load ranges, previously described by Houtkoop (2022). This makes it possible to enter a harbour with low power demands. Heat dumping can also be used when the reactor needs to ramp down quickly. Rather than seawater cooling, waste heat could be repurposed via Organic Rankine Cycle systems for auxiliary power, though not included in this design. The HRS is not used for emergencies because the (v)SMR has its passive safety features (Wiegersma, 2023).

The heat exchanger model uses the Log Mean Temperature Difference (LMTD) method (Saari, 2010) to solve δT_m with equation 3 to estimate the required volume and weight for cooling the (v)SMR power plant.

$$Q = U \cdot A \cdot \delta T_m \tag{3}$$

Here, the heat transfer rate Q in MW is given by the reactor calculating the required heat transfer area A in m², where representative values for the overall heat transfer coefficient U and the mean temperature difference ΔT_m are based on Zohuri (2017). The required transfer area A can be limited by introducing compact Printed Circuit Heat Exchangers (PCHE) (Zohuri, 2017) for reactors and heat batteries (Havermans, 2023) for energy weapons. It must be noted that the use of the PCHE type has not been established in reactor technology because it is not included in the ASME Nuclear code (Kalra, 2020).

For PCHEs operating in a helium environment, a typical value of U of $2300\,\mathrm{W/m^2 \cdot K}$ is assumed, while nitrogen environments are estimated at a U of $1000\,\mathrm{W/m^2 \cdot K}$. The mean temperature difference ΔT_m is based on fixed inlet and outlet temperatures relevant to Brayton cycle operation, typically in the range of 300–600°C. A heat exchanger efficiency of 0.95 is assumed for both the Intermediate Heat Exchanger (IHX) and Heat Exchanger (HEX). The compactness factor for PCHEs is taken as $1100\,\mathrm{m^2/m^3}$, allowing estimation of core volume with A. Pressure drops, material fouling, and temperature-dependent fluid properties are neglected, resulting in a minimum theoretical volume for the exchanger core (Holcomb and Cetiner, 2010).

3.1.4 Power generation, distribution & conversion

This study draws on the properties of a helium-driven closed-cycle turbine concept developed by Westinghouse Electric Corp for the U.S. Navy (Spurrier, 1979), recognising that the system was never commercialised. The design philosophy assumes that helium-based turbomachinery meets or exceeds the performance requirements imposed by nitrogen, making the modelled power cycle a conservative representative estimate of closed Brayton cycle capabilities.

Primary electrical machines are used both for power generation as generators and for propulsion as Electric Propulsion Motors (EPM). An analytical sizing model is applied to estimate machine weight and volume based on output power and rotational speed (Wiegersma, 2024). To meet transient power demands, an Energy Storage System (ESS) is included. The ESS compensates for the limited ramping capability of (v)SMR technology by covering short-duration pulse loads (P_{pulse}) from SEWACO systems. The required capacity is derived from the energy surplus or deficit due to ramp-up or ramp-down of the power output $P_{(v)SMR}$ over time, as shown in equation 4.

$$E = \begin{cases} \int_{t_1}^{t_2} \left(P_{\text{pulse}} - P_{(v)\text{SMR}}\right) dt, & \textit{ramp-up} \\ \int_{t_3}^{t_4} \left(P_{(v)\text{SMR}} - P_{\text{pulse}}\right) dt, & \textit{ramp-down} \end{cases} \tag{4}$$

3.2 Conventional baseline model

A baseline design is provided to compare the impact of implementing (v)SMR technology on a combatant ship design. This is challenging for three reasons:

- a fourth-generation (v) SMR-powered combatant nor concept design exists today
- existing nuclear-powered combatants' information is classified
- existing nuclear-powered combatants do not utilise IPS

Therefore, the sizing model will implement traditional gas turbines in the IPS distribution system. The model can choose between the two largest commercial naval turbines, the MT30 from Rolls-Royce (RR) (Naval Technology, 2008) and the marine LM6000 from General Electric (GE, 2018). The model selects the lightest option or combination to fulfil the power demand. More gas turbine types with lower power outputs could be added for weight optimisation, especially for the smaller combatants, but this is not considered.

3.3 Results

By iterating the displacement of a concept future surface combatant, results for power, energy, weight and volume have been found.

3.3.1 Power & energy

The required power and energy for the concept combatant are given in Figures 5 and 6.

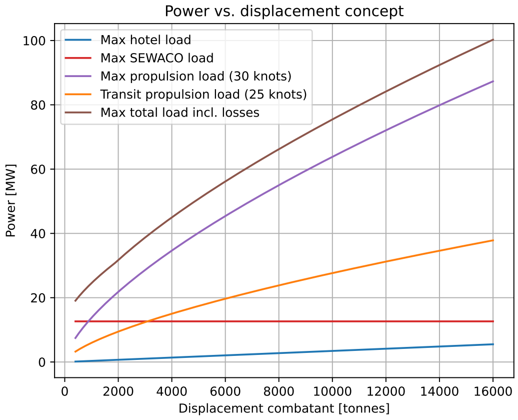


Figure 5: *Power required for hotel, SEWACO and propulsion*

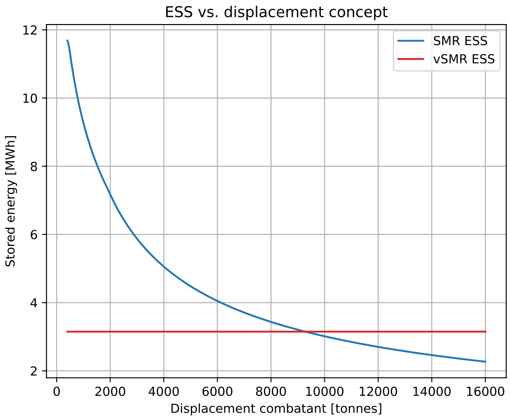


Figure 6: *Required ESS for (v)SMR technology (*$10MW_e$ *vSMR)*

In Figure 5, the maximal loads for the concept combatant are shown. The main conclusion is that propulsion load dominates the total maximum power demand for all combatant sizes. Figure 6 shows the required energy storage to accommodate the SEWACO systems for the given operational profile from Wiegersma (2024). Because the vSMR power plant operates with multiple reactors of equal power output, the ESS capacity does not change. The ESS capacity required for an SMR power plant decreases with displacement. The larger the SMR, the larger its absolute ramp rate (MW/min). A higher absolute ramp rate results in better load-following capabilities, reducing the required ESS capacity. Around a displacement of 9,280 tonnes, the energy storage needed is equal for SMR and vSMR power plants for the given operational profile.

3.3.2 *Weight*

The displacement is iterated over the power plant weight of the specific power configuration divided into an MSR (blue), number *n* of vSMRs (red) and number *n* of Gas Turbine Systems (GTS) (purple) in Figure 7. The weight of the power plant is divided by the displacement of the concept combatant to assess quickly the feasibility. A ratio of 1 means that all the displacement is required for the power plant, which is impractical. No combatant with a higher power plant over displacement ratio above 0.3 has been found in literature or practice. The red dotted line represents this theoretical power plant ratio limit.

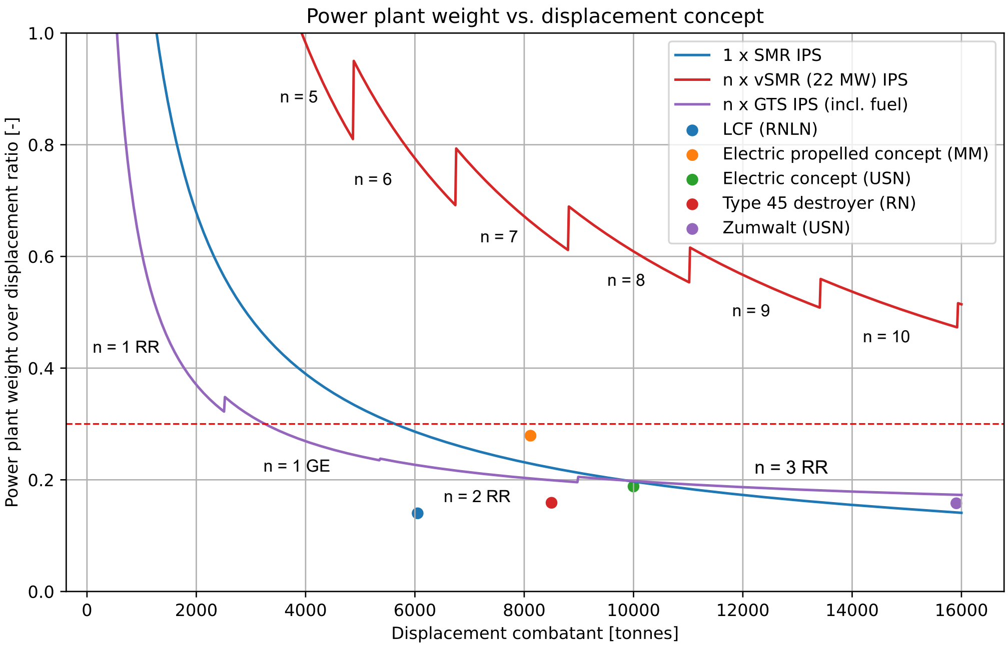


Figure 7: *The weight impact of the power plant on the displacement of the combatant*

The baseline model in this research, the GTS IPS configuration (purple), shows a differentiating preference for the gas turbine manufacturer. It can be seen that with increasing displacement, the baseline is lower than the upper limit of the ratio 0.3. Data points of current and concept IPS combatants, including their fuel storage, have been added to the plot. The LCF has been added as a reference for traditional combatants without IPS (Vollbrandt, 2016). It has been noted that most data points are lower than the baseline. This results from estimations considering the main propulsion and power generation components but lacking data on other critical (auxiliary) components. Because the baseline is conventional, the fuel's weight is considered by reserving 12.5% of the displacement, an estimation in line with combatants used by Western navies. The effect of taking fuel into account impacts mostly the required volume, as can be seen in Figure 8.

The SMR, exemplified by the MSR, imposes a significant weight and volume burden on smaller surface combatants. An equilibrium with the baseline has been found around a displacement of 9,860 tonnes. Previous work by Webster et al. (2007) on PWR technology identified 7,500 tonnes as the minimum viable displacement for a nuclear-powered combatant, based on cost considerations.

The vSMR power plant, using the number *n* of individual Holos-Quads, is not close to the traditional power plant ratio. Each step in the red line represents the addition of a vSMR necessary to comply with the power demand. A vSMR power plant is too heavy for all concept combatants with a displacement of up to 16,000 tonnes. While shared shielding between vSMRs could theoretically reduce material requirements, it is not considered in this study due to the lack of data and increased modelling complexity.

3.3.3 Volume

Figure 8 shows the minimum volume required for the power plant because most components do not include their installation volume. For example, traditional gas turbines require a specific volume for placement and maintenance. A preliminary design is necessary to assess whether the turbine fits. Therefore, the volume in Figure 8 is seen as a minimum.

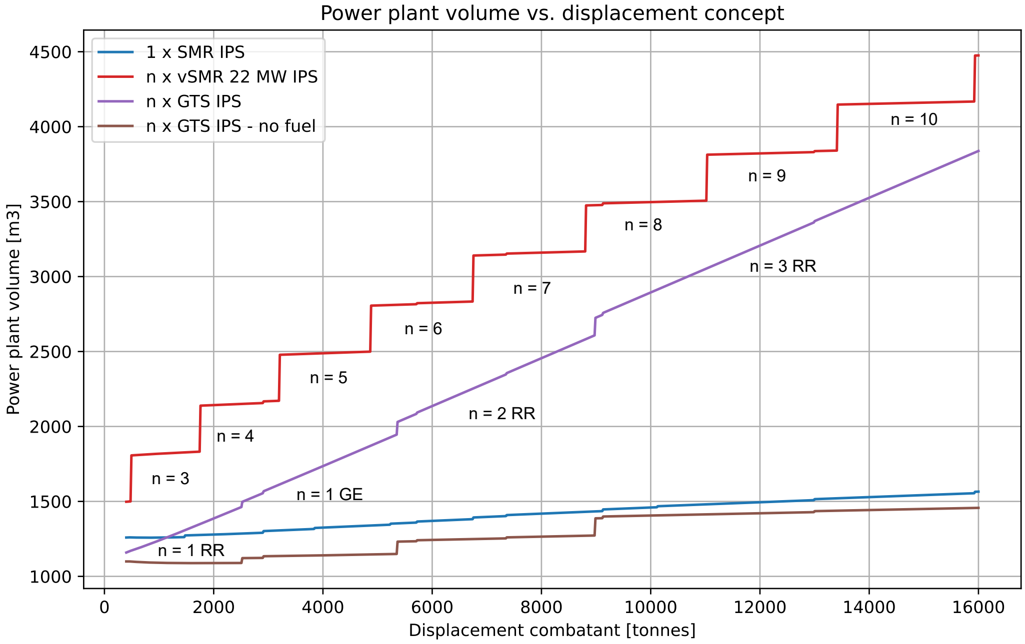


Figure 8: *The volume impact of the power plant on the displacement of the combatant excluding cables, pipes and exhausts*

The main steps caused by *n* vSMRs and gas turbines are visible. Smaller steps are seen because of the fixed sizes for converters and switchboards. When not considering fuel bunkering, the baseline configuration with GTS is the most compact. However, the SMR shows a relatively constant volume of occupation. The vSMR configuration takes the most volume with increasing displacement.

When considering fuel bunkering (purple) with the baseline configuration, it is seen that SMR becomes attractive considering its compactness. However, it must be noted that fuel storage is located in the outer corners of the combatant' hull. The volume saved does not directly result in usable space for payload or ESS. Only by evaluating the design of a combatant can it be determined whether the reduction in fuel storage benefits the (v)SMR-powered combatant.

3.4 Revised input values

When observing Figure 5, it is seen that the propulsion load dominates power plant sizing. Moreover, if the implemented future SEWACO load were doubled, the propulsion load would still dominate the maximum power demand. If future surface combatants reduce their required top sailing speed under the 30 knots limit, SEWACO load will significantly increase their share. SMR technology for future surface combatants, where the propulsion load dominates the operational profile, requires extensive research.

Looking at Figures 7 and 8, vSMRs are unsuitable for the defined future surface combatants. With increasing displacement, the individual weight and space of the vSMR make it unattractive as a naval prime mover. This is mainly due to the required shielding per reactor. Placing multiple smaller reactors on a combatant while keeping it lightweight is challenging. Due to a deficiency of relevant data concerning shared shielding, this paper suggests reducing the shielding weight by increasing the power output per vSMR (exceeding the literature definition of a vSMR where $P_e < 10\ MW_e$). An output power of 55 MW_{th} or 25 MW_e considering an HTR is assumed in Figure 9. By installing 25 MW_e per vSMR, the power plant gets closer to feasible power plant ratios.

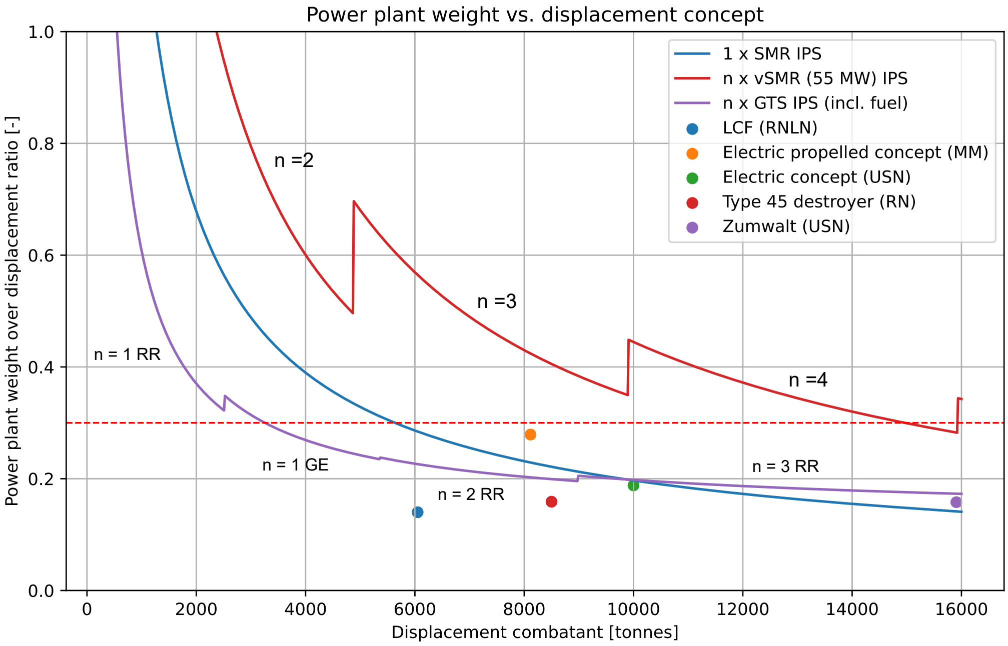


Figure 9: *The weight impact of the power plant on the displacement of the combatant with a revised output power of 55* MW_{th} *for the vSMR*

4 Case Study

After analysing Figure 9, it is decided to observe a future surface combatant with a displacement of 9,800 tonnes. Here, the SMR and the conventional GTS obtain the same power plant weight ratio of 0.2 for this displacement. Because multiple vSMRs of 10 MW_e are challenging due to their weight, the impact of multiple smaller reactors installed in the concept is assessed with 3 vSMR with a power output of 25 MW_e, resulting in a weight ratio of 0.35.

4.1 Main characteristics

The combatant sizing model defines the dimensions with common size ratios for combatants described by Strock and Brown (2008). The future surface combatant is presented in Table 1.

Table 1: *Characteristics of the future surface combatant*

Characteristic	**Value**
Displacement Δ [tonnes]	9,800
Length of waterline Lwl [m]	153.4
Beam B [m]	19.5
Draft T [m]	7.5
Number of shafts [-]	2
Propulsion [-]	Electric (IPS)
Required power [MW_e]	75

Because of the preference for an IPS system, an open-source concept combatant design for such a power distribution system is preferred, introducing the Type 055 destroyer. During the design of the stealth-guided missile destroyer Type 055, the possibility of integrating IPS is used as a reference point according to Caldwell et al. (2020). The Type 055 represents a relevant example of modern naval architecture that balances advanced weaponry, sensors, and potential for future technology integration. Moreover, an open-source 3D model is available (3D Warehouse, 2019) and a preliminary general arrangement is given by Xiangmin (2021). After scaling to the required displacement Δ, Lwl, B and T from Table 1, the conventional baseline is visualised in Figure 10.

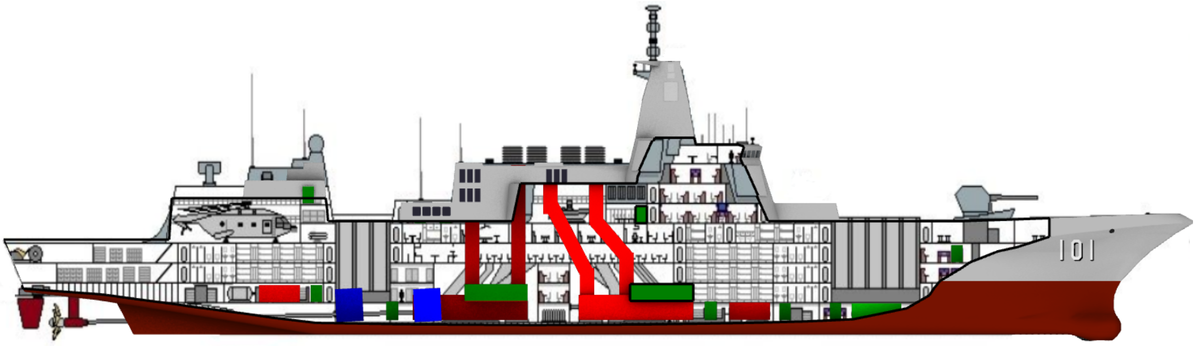
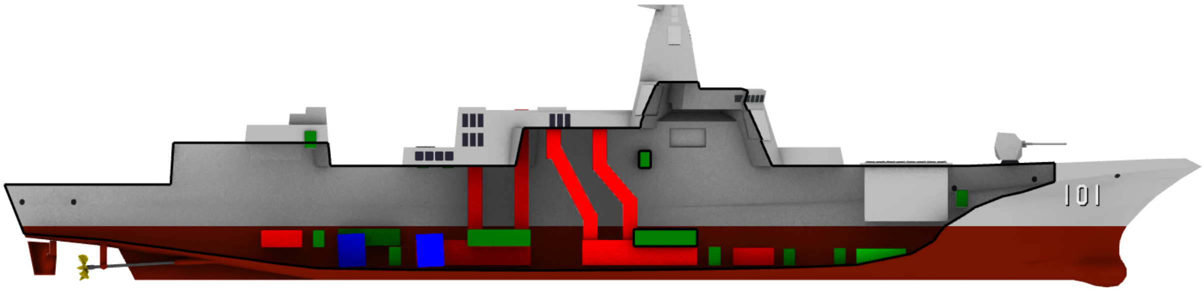


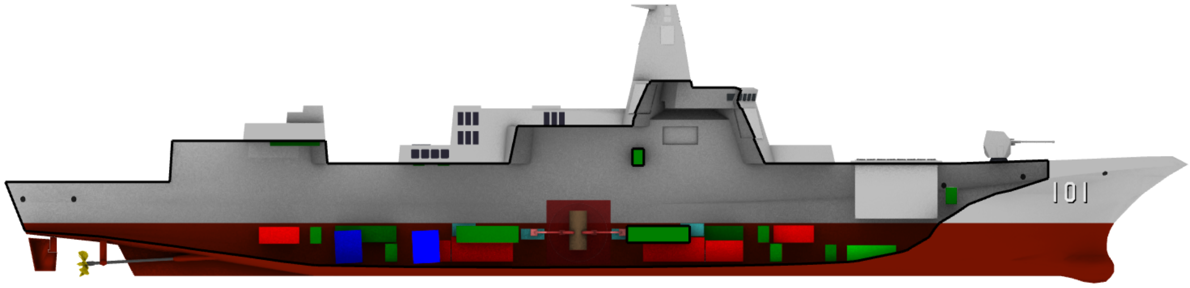
Figure 10: *Side view of the conventional baseline visualising the GTS with IPS, including the preliminary general arrangement. Power generation; red, power distribution; green, ESS; bright green and power conversion; blue.*

4.2 Result

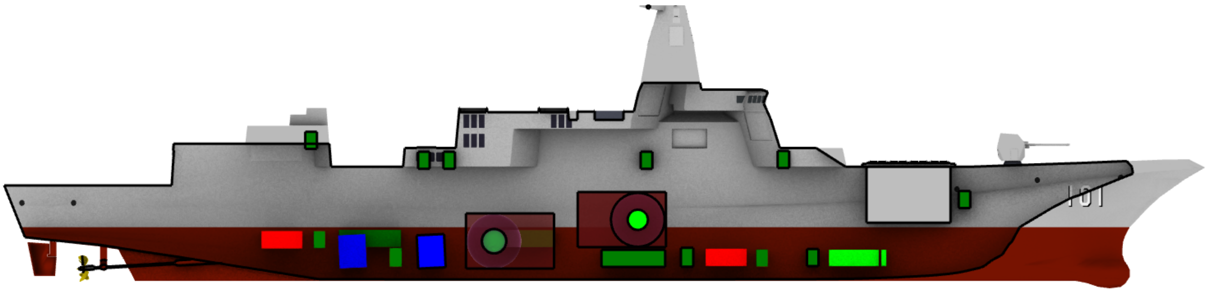
The preliminary power plants with a GTS, SMR and vSMR configuration are shown in Figure 11. Fuel bunkers, SEWACO equipment and chillers are not visualised for the configurations.



(a) Side view with GTS configuration excluding bunkers ($3 \cdot 35.4$ MW$_e$)



(b) Side view with SMR configuration (230 MW$_{th}$)



(c) Side view with vSMR configuration ($3 \cdot 55$ MW$_{th}$)

Figure 11: Preliminary design showing power generation, distribution and conversion components. Power generation: red, power distribution: green, ESS: bright green, power conversion: blue.

Considerable differences can be observed in Figure 11. The (v)SMR designs do not require an exhaust system. The exhaust heat management system integrated into the superstructure is unnecessary and creates more space.

Because of an IPS, many power distribution components can be seen, which require considerable space.
The SMR configuration is of comparable size to the GTS configuration, confirming the observed trend in Figure 8. The SMR is located near the longitudinal centre of gravity of the concept, with the two turbines in separate compartments. The power plant fits entirely in the space traditionally used for power generation when compared with Figure 10. The SMR is not easily removed from its location, reducing modularity. Gas turbines function as relatively stand-alone power generators and generally encounter fewer integrational challenges compared to nuclear systems. SMRs, on the other hand, present greater integration complexity due to their weight and shielding requirements, safety concerns and the need for refuelling.

The vSMR configuration with three reactors requires the most space. Two reactors were placed in the beam of the concept, but longitudinal placement was also possible. More space is necessary for the reactor compartment due to the lower power density of the (V)HTR core. While the SMR is fuelled for extensive periods, the core of a vSMR typically needs to be swapped every 5–8 years due to its smaller core size and therefore its limited fuel inventory. Because of their weight, placement near the LCG of the concept is essential, reducing modularity because of access restriction. Moreover, motions and vibrations induced by the environment are lower in the centre of gravity (Wiegersma, 2023). Therefore, it is believed that the benefit of the possibility of modular vSMRs is reduced when used to comply with the total power demand.

5 Conclusion

To investigate the implications of integrating fourth-generation (very) Small Modular Reactor technology into preliminary future surface combatant design, a sizing model and a case study have been used to quantify the design implications.

5.1 Sizing model

A model is presented to evaluate the sizing of future surface combatants when Generation IV (v)SMR technology is implemented. The model assesses critical parameters such as power, weight, volume, and energy storage requirements, which are crucial for determining the feasibility of integrating (v)SMR technology into combatants. The following conclusions are found:

Dominance of propulsion power: The propulsion load significantly influences the power plant sizing, overshadowing the hotel and SEWACO load. This suggests that for future surface combatants, especially those with high-speed requirements, the propulsion demand will continue to be a prominent factor in the design and selection of power systems.

ESS requirement: Energy storage required for an SMR power plant decreases over displacement due to an increase in absolute ramp rate. The required ESS for vSMR plants is constant due to the fixed power output per vSMR.

Feasibility of SMR technology: SMR power plants are compatible in terms of volume and weight with conventional GTS connected to an IPS for higher displacements ($8,000+$ tonnes) for the defined future surface combatant.

Feasibility of vSMR technology: The model reveals that vSMR technology faces significant challenges related to volume and weight. The analysis indicates that for the defined future combatants, with a maximum weight of up to $16,000$ tonnes, vSMR power plants are not feasible due to their substantial weight and space requirements, primarily driven by the need for extensive shielding.

It can be concluded that SMR technology does impact the design of the defined future surface combatant when evaluating power, energy storage, volume, and weight requirements. The impact of current vSMR technology results in unfeasible concept designs for the defined future surface combatant. Consulting the definition of a vSMR ($P_e < 10\ MW_e$) concludes that small SMRs, for example, with a power output of 25 MW_e, are more suitable than multiple vSMRs for the defined future surface combatant.

5.2 Case Study

A case study on a future surface combatant with a displacement of $9,800$ tonnes has been performed. This result has been compared with a conventional GTS and an SMR of 230 MW_{th} together with a vSMR of 55 MW_{th}. The analysis highlights the impact of volumetric requirements of the (v)SMR power plant on the available space on the surface combatant. An SMR configuration is comparable in size to GTS configurations and suitable for lifetime fuel cycles, highlighting less critical modularity. Conversely, vSMR configurations required more space than GTS configurations, underlining the importance of reactor placement for modularity due to their shorter fuel cycles.

In conclusion, the integration of generation IV (v)SMR technology influences the design of a future surface combatant, necessitating careful consideration of displacement, power distribution, energy storage and propulsion system sizing.

6 Recommendations

Several recommendations can be made to improve the evaluation of the impact on the design of a future surface combatant using Generation IV (v)SMR technology:

- This paper models the (V)HTR and MSR based on findings in the literature. However, noticing that weight is a critical design parameter, other generation IV reactor types could be interesting as well.
- Shielding calculation was performed using the analytical Point Kernel method. Applying Monte Carlo or discrete ordinate methods could result in accurate primary and secondary shielding calculations. These methods require detailed geometry models of the reactor compartment and expertise in nuclear engineering.

  While ships with multiple nuclear reactors operate with shared shielding, knowledge of shared shields is not found in the literature. It is observed that further research on shared shields to reduce the shielding weight is necessary for the feasibility of vSMR technology in surface combatants.
- The choice of working medium depends on an extensive set of parameters. While most implications per medium have been found, turbomachinery is simplified and more practical research into using closed Brayton cycle turbines is required for naval applications. Moreover, the gas leakage from the turbine system can only be validated with prototypes. Significant steps must be made to introduce a closed Brayton cycle with gas instead of steam in the naval industry.
- Because the propulsion power dominates the power demand for future surface combatants, hybrid configurations become interesting to investigate. The possibility of using vSMR for future SEWACO load is mentioned, but not researched in detail on how it affects a surface combatant.
- Historically, the U.S. Navy experience shows that high personnel requirements and costly reactor refuelling significantly impacted lifecycle affordability and fleet sustainability for surface combatants. Understanding these factors is critical to evaluating the long-term viability of nuclear propulsion beyond its technical performance.

A Combatant sizing model

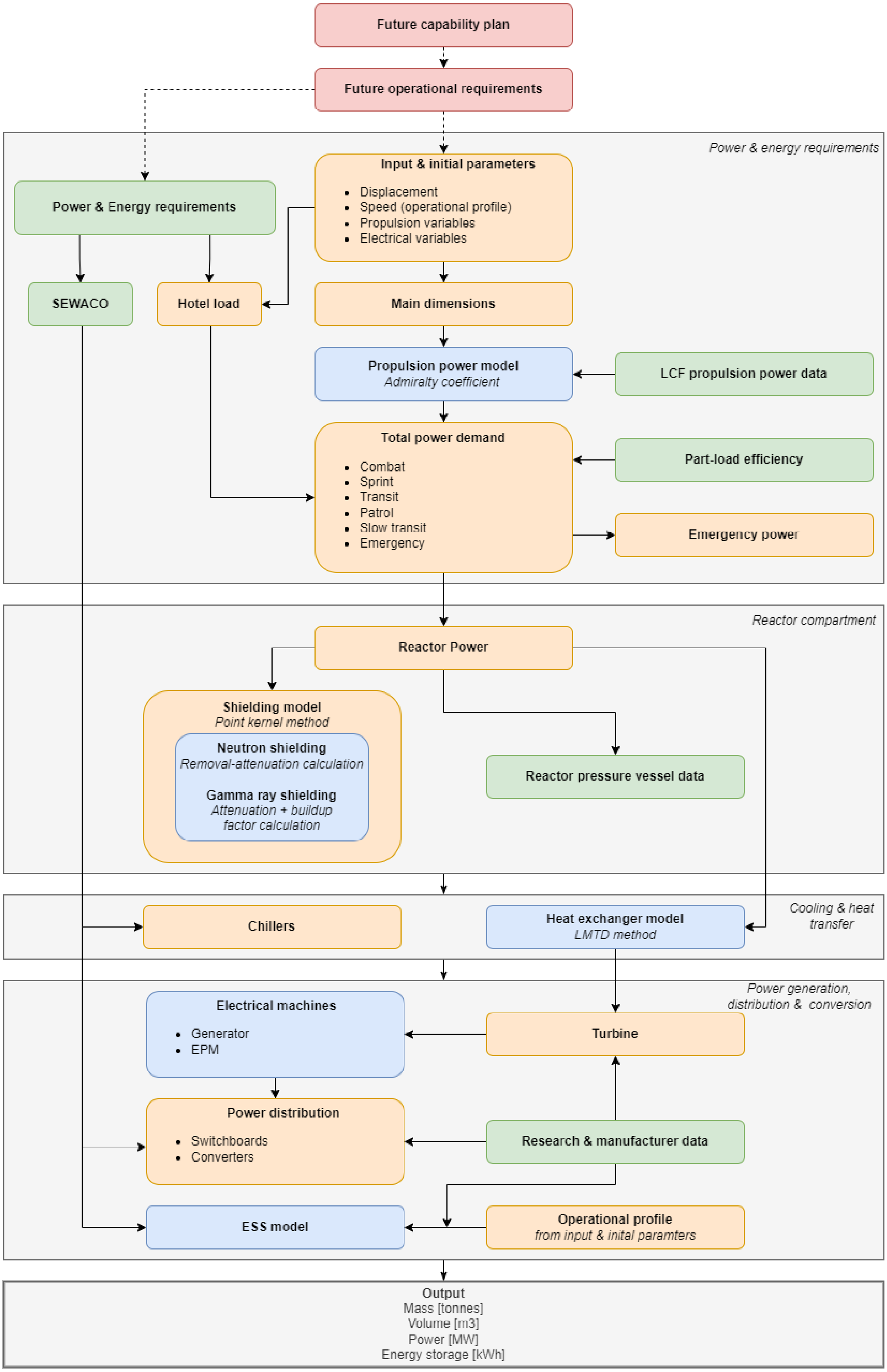


Figure 12: *Overview of the sizing model. Unmodeled design drivers; red. Data files from calculations, literature or manufacturers; green. Straightforward calculations; orange. Complicated models; blue.*

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