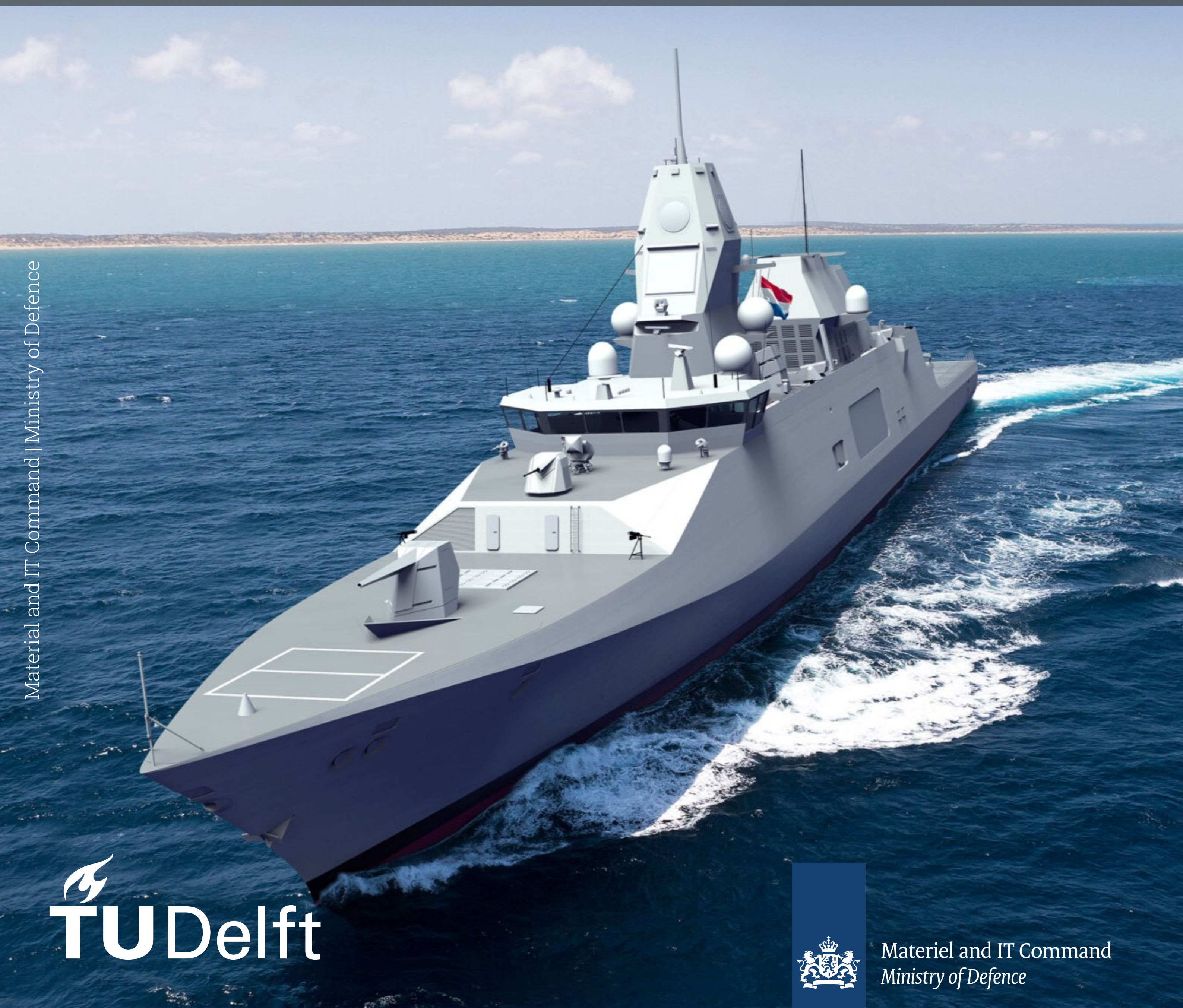
Generation IV (very) Small Modular Reactor technology for Future Surface Combatants

G.H. Wiegersma



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

by

G.H. Wiegersma

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Cover: An artist's impression of the future ASW frigate that COMMIT is developing for the RNLN and the Belgian Navy. Ministry of Defence (2023)

Materiel and IT Command
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”We have to find a different way
to power the things we need to power”

Ray Mabus,
75th United States Secretary of the Navy
2011 ARPA-E Innovation Summit

”Nuclear power is one hell
of a way to boil water”

Often attributed to:
Albert Einstein,
Theoretical physicist

”To design a ship,
you first design a ship”

Overheard amid the hallway whispers,
COMMIT

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Abstract

Nuclear energy has found widespread application in navies across the globe. This thesis explores the potential integration of generation IV (very) Small Modular Reactor (SMR) technology for future surface combatants, focusing on the Very High-Temperature Reactor modelled as vSMR and a Molten Salt Reactor as SMR. The design impact of using generation IV (v)SMR technology for power generation on future surface combatants was unexplored. An estimation of future power and energy requirements and a detailed investigation of the reactor compartment is performed. It includes shielding, power generation, distribution, and conversion systems. Emerging naval-directed energy weapons and advanced sensor technologies are implemented to position the combatant within the spectrum of future mission capabilities.

A sizing model evaluates the feasibility of (v)SMR integration in terms of power, energy, volume, and weight. An indication of the available weight for (v)SMR technology is searched by iterating over the displacement of future surface combatants. For the defined future surface combatant, naval SMR power plants are compatible in terms of weight with conventional all-electric gas turbine-driven combatants with displacements above $8,000$ tonnes. The model reveals that vSMR technology faces significant challenges related to weight despite its potential benefits in terms of redundancy and modularity. For combatants up to $16,000$ tonnes, naval vSMR power plants are not viable due to their substantial weight and space requirements, primarily driven by the need for extensive shielding. Increasing the power output per vSMR reduces the required shielding and provides an alternative solution.

A case study explores a preliminary design of a future surface combatant with a displacement of $9,800$ tonnes. The study suggests that the propulsion demand significantly impacts the size of the power plant. This results in the need for energy storage systems that manage variable power demands, particularly for SMR technology integrated into large surface combatants. Unlike vSMR naval power plants, SMR technology is comparable in size to the all-electric gas turbine power plant of conventional surface combatants.

The study assesses the effectiveness of the preliminary design in terms of survivability, mobility, range and endurance. It is estimated after capability prioritisation that (v)SMR technology and conventional gas turbine configurations have an equivalent survivability impact. A critical trade-off is highlighted between enhanced endurance and range against challenges, such as an increase in weight, volume requirements, and compromises in mobility compared to conventional gas turbine systems. The choice between SMR and vSMR technologies further complicates this balance by choosing between compactness and load response. A essential conclusion is that generation IV (v)SMR technology can enhance a future surface combatant's autonomy and future power load capabilities without compromising its effectiveness.

The Royal Netherlands Navy can use the results as an indicative substantiation for developing generation IV (v)SMR-powered future surface combatants. Moreover, it can help initiate a future naval capability plan and contribute to the realisation of generation IV (v)SMR power generation for the maritime sector.

Preface

While writing this thesis, I have to consider I am about to end my time as a student. Regardless, I hope my sense of humour has not been lost, nor that of the reader. After moving to Delft and, to many people's surprise, making it to the final hurdle, I found two ways to describe the phenomena *thesis*. The definition of a *thesis* suggests that I, as the author of this *thesis*, have conducted extensive research on a topic, either contributing to the existing body of knowledge for the beautiful marine technology sector or have simply lost my sanity. Either way, I have found my interest: building boats.

I want to express my gratitude towards Niels Gartner for introducing me to COMMIT and for the time he has sacrificed to keep my graduation going. I would not like any other daily supervisor than Niels, who kept me focused and made our time together enjoyable while warning for the phenomena *thesis*. I thank Hedde van der Weg for investing his effort in all our *ship design* discussions. We have concluded that the best way to design a combatant is by designing one; it is ironic how this sounds so easy. I want to address that all my colleagues at the Department of Maritime Systems, especially the Bureau of Marine Engineering, made me feel *commit*ted and supported during my time at COMMIT.

From the TU Delft, I want to thank Jaap Gelling, Klaas Visser and Henk Polinder. After finding a *radiant* graduation assignment at COMMIT, Jaap immediately supported me while his agenda was telling something differently. Thanks for all the coffee and good conversations about our interest: boats. While retired, I appreciate Klaas's interest in my thesis. I hope you will find time to travel with the camper. Henk, you have helped me understand and accept the definition of *thesis*. I thank you for your guidance and increasing my academic skills.

Because I originally think and talk in Frisian: Efkes yn de memmetaal! Oan myn âlders, myn *lytse* broerke, myn pakes en beppes: betanke foar alle stipe. Thús soe thús net wêze as by oankomst der nochter frege wurdt of dy stúdzje yn Delft al ris ôf is, of ik noch kom helpe yn de einekoai. Ek al bin ik de lêste jierren in stik minder yn it heitelân, it feit dat jimme der altyd foar my binne is wat om tige tankber foar te wêzen.

I thank my friends for surviving me while exploring the definition of *thesis*. I am thankful for the time we spent on other essential things. Without you all, I would sit in the maritime hallway for another year.

Finally, but most importantly, I would like to thank Ella. I am grateful we carried the second definition of *thesis* together. Moreover, my last years as a student were incredible because of you.

G.H. Wiegersma
Delft, May 2024

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Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
AIM	Advanced Induction Motor
ALARA	As Low As Reasonably Achievable
APARD	Active Phased Array Radar
ASME	American Society of Mechanical Engineers
ASW	Anti-Submarine Warfare
CEA	French Alternative Energies and Atomic Energy Commission
CF	Compactness Factor
COMMIT	Material and IT Command
DC	Direct Current
DEOS	Defense Energy and Environment Strategy
EM	Emergency Motor
EPM	Electrical Propulsion Motor
EPS	Energy Production Systems
ESS	Energy Storage System
FC	Fuel Cycle
GE	General Electric
Generation IV	Fourth Generation
GES	Integrated Energy Systems software tool
GTS	Gas Turbine System
HEL	High-Energy Laser
HEX	Heat Exchanger
HPC	High Pressure Compressor
HPM	High-Powered Microwave
HPT	High Pressure Turbine
HRS	Heat Removal System
HTR	High Temperature Reactor
HTGR	High Temperature Gas-cooled Reactor
HTS	High-Temperature Superconductor
HVAC	Heating, Ventilation, and Air Conditioning
IHX	Intermediate Heat Exchanger
IPS	Integrated Power System
LCF	Air Defense and Command Frigate
LCG	Longitudinal Center of Gravity
LPC	Low Pressure Compressor
LMTD	Logarithmic Mean Temperature Difference
MM	Italian Navy

Abbreviation	Definition
MVDC	Medium Voltage Direct Current
MSR	Molten Salt Reactor
NDE	Naval Directed Energy
PCHE	Printed Circuit Heat Exchanger
PLAN	Chinese People's Liberation Army Navy
PM	Permanent Magnet
PT	Power Turbine
PWR	Pressurised Water Reactor
RN	Royal Navy (United Kingdom)
RNLN	Royal Netherlands Navy
RPM	Revolutions Per Minute
RR	Rolls Royce
SEWACO	Sensors, Weapon Systems and Command Systems
SMART-L	Signaal Multibeam Acquisition Radar for Tracking
TEU	Twenty-foot Equivalent Unit
TNO	Dutch Organisation for Applied Scientific Research
TRISO	TRi-structural ISOtropic
TRL	Technological Readiness Level
TU Delft	Delft University of Technology
UK	United Kingdom
US	United States
USN	United States Navy
UXV	Unmanned Vehicle
(v)SMR	(very) Small Modular Reactor
VLS	Vertical Launch System
(V)HTR	(Very) High Temperature Reactor

Symbols

Symbol	Definition	Unit
P_{tot}	required total power	$[MW]$
P_{prop}	propulsion power	$[MW]$
P_{SEWACO}	mission system power	$[MW]$
P_h	hotel power	$[MW]$
v_s	sailing speed	$[knots]$
P_{Brake}	brake power	$[MW]$
C_{adm}	admiralty coefficient	$[-]$
f_{hotel}	hotel load factor	[-]
E	energy	$[MWh]$
$P_{(v)SMR)}$	reactor power	$[MW]$
P_{pulse}	pulse power	$[MW]$
$D_{max,allowed}$	maximal allowed radiation dose	$[mSv]$
$D_{received}$	radiation actually received per year	$[mSv]$
f_O	occupancy factor	[-]
Q	heat transfer rate	[MW]

Symbol	Definition	Unit
U	overall heat transfer coefficient	$[W/m^2 \cdot K]$
A	heat transfer area	$[m^2]$
$\dot{m}_i$	mass flow (hot or cold fluid)	$[kg/s]$
$c_{p,i}$	specific heat constant (hot or cold fluid)	$[J/(kg \cdot °C)]$
$T_{h,i}$	temperature hot fluid ingoing	$[°C]$
$T_{h,o}$	temperature hot fluid outgoing	$[°C]$
$T_{c,i}$	temperature cold fluid ingoing	$[°C]$
$T_{c,o}$	temperature cold fluid outgoing	$[°C]$
h_h	convection heat transfer coefficient hot fluid	$[W/(m^2 \cdot K)]$
h_c	convection heat transfer coefficient cold fluid	$[W/(m^2 \cdot K)]$
t	plate thickness	$[m]$
k	thermal conductivity	$[W/(m \cdot K)]$
P	power	$[MW]$
T	torque	$[N \cdot m]$
n	rotational speed	$[rpm]$
n_f	number of fields	$[-]$
$a_{ramp,ESS}$	ramp rate	$[MW/min]$
P_{th}	thermal reactor power	$[MW]$
f_{ESS}	available power factor for ESS	$[-]$
f_{ramp}	ramp rate factor	$[\frac{\%}{min}]$
ELC	end of lifetime capacity	$[-]$
η	efficiency	[-]
Δ	displacement	$[tonnes]$
η_{TRM}	transmission efficiency	$[-]$
δT_m	average (mean) temperature difference	$[°C]$
η_b	battery efficiency	$[-]$

1 Introduction

Background

The importance of considering modern nuclear marine power generation technology for military use is directly connected to the required strategic autonomy of a surface combatant. Nuclear-powered combatants can significantly improve their and the fleet's strategic autonomy due to their ability to sail without refuelling and available power capacity. Additionally, the Dutch Ministry of Defence needs to comply with DEOS (Defensie Energie en Omgeving Strategie), which states in 2050, a reduction of 70% in the use of fossil fuels relative to 2010. Nuclear-powered ships could be a solution that lowers emission levels of pollutants and greenhouse gases compared to conventionally-powered ships.

The Royal Netherlands Navy (RNLN) is aware of this potential. Due to the physics of fission, the operational range is increased with unparalleled flexibility regarding mission requirements. The real-time response regarding global mission theatres is fast due to energy independence. A high energy-dense combatant with no operational refuelling leads to longer operating time and higher sailing speeds for more extended periods than conventionally-powered designs. Additionally, more power is available for future energy consumers, including sensors, unmanned vehicles and energy weapons. The tactical performance of a surface combatant increases because it has a reliable and stable power source suitable to generate power for future warfare platforms. Traditionally, nuclear power systems are complex and considered expensive for implementation on surface combatants. However, the modular application of nuclear technology offers new potential for naval designs.

Small Modular Reactors (SMRs), which resemble concept generation IV nuclear reactors, are designed to be smaller, more flexible, and safer than traditional nuclear reactors known to be used. Reactor concepts that are part of the fourth-generation family are defined as innovative nuclear reactors expected to facilitate energy to society in the future. An SMR is described as having a power output of 10 to 300 electrical megawatts and using passive safety features. Delivering less than 10 megawatts of electric power is considered a very Small Modular Reactor (vSMR). SMRs with lower power outputs can be used in various applications, including a future surface combatant with an increasing electrical demand for power.

Motivation

Currently, there are various options and configurations for future nuclear, marine propulsion and power generation systems. However, the impact of a fourth-generation (v)SMR system on a surface combatant remains unclear. Additionally, the knowledge of all separate systems required for successfully operating nuclear ships is available around the globe. Yet, the RNLN's experience with naval nuclear power is negligible, let alone the performance of a future surface combatant using generation IV (v)SMR technology. No research has been performed on the design of a surface combatant when an IV-generation (v)SMR is implemented, while the technology is promising for strategic autonomy, meeting future power demand and climate goals.

Research objective

The main objective of this research is to investigate the implications of installing generation IV (v)SMR technology into future surface combatants. Literature research sub-questions and the objective of the follow-up research will partially answer the main thesis question:

What are the implications of using generation IV (very) Small Modular Reactor technology for power generation on the design of a future surface combatant?

Uncertainties accompany the implementation of fourth-generation (v)SMR technology on future surface combatants. The technology is mainly focused on land-based applications. Understanding should be created on the properties of relevant (v)SMR technologies suitable for naval application. The implications associated with implementing (v)SMR technology are important for the combatant's design. Additionally, future operational requirements determine the operational profile of the combatant. Improved sensors and advanced warfighting capabilities result in a high and dynamic power demand. The heat from the nuclear reactor needs to be converted to usable energy for all power consumers. For these mentioned reasons in this paragraph, sub-questions are identified and presented in the literature report structure [1].

The literature report uses the following sub-questions as guidelines to identify the performed work related to fourth-generation (v)SMR technology for future surface combatants:

- *Which generation IV (v)SMRs are feasible to install and operate in future surface combatants?*
- *How can implementing a generation IV (v)SMR affect operational design considerations by improving the combatant's capabilities?*
- *What naval propulsion and power systems are suitable for generation IV (v)SMR technology?*
- *What are the key ship design elements for generation IV (v)SMR technology?*

After thoroughly studying the available literature, three research gaps have been found.

1. Size and weight estimations of generation IV (v)SMR technology for naval application have not been made. Introduction to (v)SMR technology in marine applications has been done [2]. However, the impact for surface combatants is expected to be different due to the challenging operational requirements and the combatant's differing general arrangement.
2. Assessment has not been made on whether a future surface combatant can incorporate (v)SMR power generation without losing its effectiveness on the battlefield.
3. The survivability of (v)SMR technology in warfare environments is unexplored. No research indicates shock and vibration resistance of naval implemented (v)SMR technology induced by warfare circumstances.

The follow-up research objective is specified based on the first and second identified research gaps. Shock and vibration resistance of generation IV (v)SMR technology is not within the focus of this study. Survivability will be considered. The objective of the follow-up research is to enhance the understanding of meeting the power needs of a future naval combatant while incorporating (v)SMR technology and maintaining operational effectiveness, as well as how this is related to the size and weight of the technology.
The relevance of this research is that it provides a better understanding of the design process of (v)SMR-powered surface combatants. Additionally, this research can serve as an instrument for the initial dimensioning of a fourth-generation (v)SMR naval propulsion and power generation system. The sequence outlines the essential criteria:

1. The suitable naval (v)SMRs must match the future surface combatant regarding power demand.
2. Power generation must embrace the combatant's signature and survivability capability.
3. The (v)SMR with the integrated power systems has to comply with the dynamic power profile of installed SEWACO systems.
4. The propulsion and power generation system must be compact to integrate into future surface combatants without overtaking the system space needed to comply with the intended operational capabilities.

Therefore, the objective of the follow-up research is as follows:

Develop a future surface combatant preliminary design powered with generation IV (v)SMR technology to find the implications on ship design.

Based on the objective, sub-questions are formulated and answered for each chapter.

Chapter 3: *How can a future surface combatant be defined?*

Chapter 4: *What are a future surface combatant's power and energy requirements?*

Chapters 5, 6 & 7: *What propulsion and power generation systems, including the generation IV (v)SMR, are required?*

Chapter 8: *Is generation IV (v)SMR technology feasible for integration into a future surface combatant?*

Chapter 9: *What is the effectiveness of the selected (v)SMR-powered future surface combatant?*

The approach for the follow-up research will start by defining the structure needed to meet the objective. The future surface combatant's mission type, payload, and performance will be described. Two nuclear reactors are modelled as SMR and vSMR. Power requirements are defined by determining the propulsion, sensors, weapon systems, command systems (SEWACO) and hotel load. Energy requirements are defined by specifying a future operational profile and selecting an energy storage system. The reactor compartment for the nuclear reactor, including shielding, is considered. Systems necessary for generating, distributing and converting power are identified and represented. A combatant sizing model has been modelled to evaluate if (v)SMR technology is suitable for integration. From the model, an appropriate surface combatant is sized and computed in detail as a case study to assess the effectiveness and, eventually, feasibility.

Thesis structure

This thesis is a graduation project on fourth-generation (v)SMR technology integrated into future surface combatants for power generation. Delft University of Technology (TU Delft) collaborates with the Material and IT Command (COMMIT) on this graduation project to contribute to the realisation of fourth-generation nuclear propulsion and power generation for the maritime sector.

This thesis is divided into a literature review and a design study. A brief overview of important information covered by literature is given in chapter 2. Chapter 3 gives the design structure of this thesis. It also defines the future surface combatant, which could benefit from fourth-generation (v)SMR technology. Chapter 4 establishes a future surface combatant's power and energy requirements. The power plant configuration is also addressed. Chapter 5 describes the preliminary design of a generation IV reactor compartment and chapter 6 the power generation system. Chapter 7 focuses on required power distribution and conversion systems. Chapter 8 searches for a suitable surface combatant to be evaluated. Iterating the critical design parameter displacement results in a recommendation for a concept case study performed in chapter 9. Chapter 10 answers the main thesis question with a conclusion and provides recommendations.

Part I

Literature

2
Literature review

Part I summarises the literature report covering relevant nuclear technology, naval operational design and naval (v)SMR power implementation. Essential information needed to understand the research objective or technology involved in this thesis is shortly addressed in this chapter, called literature review. For a more detailed description of the state-of-the-art, see the literature report [1].

2.1. Nuclear technology

For this thesis, basic knowledge regarding nuclear technology is recommended. The literature report, section 2.1, gives an introduction to nuclear reactors.

Generation IV (very) Small Modular Reactor technology

SMRs are advanced nuclear reactors that produce up to $300MW_e$ per unit [3]. Micro reactors, in this thesis very Small Modular Reactors (vSMR), produce up to $10MW_e$ per unit. An SMR is defined as follows [3]:

- small, physically a fraction of a conventional nuclear power reactor
- modular, reactor components are standardised and factory-assembled with the option to group reactors to form a large power plant.
- reactor, harnessing nuclear fission to generate heat to produce energy

The vSMR is defined as:

- factory fabricated, same as for the SMR
- transportable, often the size of a TEU container unit
- self-adjusting, limited specialised human operators and utilise passive safety systems

The IV generation represents the future wave of nuclear reactor designs. The four key principles of the IV generation reactors are [4]:

- sustainability
- safety and reliability
- economic competitiveness
- proliferation resistance and physical protection

Fourth-generation reactors introduce passive safety features. All generation IV (v)SMR designs have enhanced safety attributes primarily due to passive safety systems, meaning the reactor can operate normally and predictably in extreme circumstances and handle human error.

The literature report concluded that the (Very) High-Temperature gas-cooled Reactor (V)HTR and the Molten Salt Reactor (MSR) are promising fourth-generation (V)SMRs suitable for naval application. The characteristics of the potential naval (v)SMRs are shown in table 2.1.

Table 2.1: *Characteristics of potential naval (v)SMR (reproduced from literature report [1])*

Reactor type	**MSR**	**(V)HTR**	**vSMR**
Neutron spectrum	thermal/fast	thermal	thermal/fast
Fuel cycle	open/closed	open	open
Burnup [GWd/ton]	$90+$	$90-200+$	$60-80$
Refuelling process	online/offline	online/offline	offline
Min refuelling cycle	4 days	$1.5-2$ years	3 years
Max refuelling cycle	lifetime	lifetime	$5-8+$ years
Safety	active/passive	active/passive	active/passive
TRL	4-6	7-8	7-8
Load following	Good	Average	Good
Load range	$20-100$%	$15-100$%	$0-100$%
Load response (ramp rate)	5%/ min	5%/min	10%/min
Operating temperature	< 800°C	$< 700-1000$°C	$500-800$°C

(V)HTR

The (V)HTR operates at high temperature and fuel efficiency while having inherent safety features. TRISO fuel particles or a prismatic block core can be used, where the last option is possibly resistant against ship motions. The (V)HTR has a high degree of passive safety in avoiding the release of fission products under all circumstances. Its load response and the current TRL make it a short-term solution for naval applications.
The reactor design used for a (V)HTR is chosen in section 3.3.1.

MSR

The MSR offers unique advantages, such as inherent safety through negative temperature coefficient reactivity and efficient online fuel reprocessing. The fast neutron spectrum seems suitable for naval applications to increase load response options. While MSRs are still in the development phase and face challenges related to materials and corrosion, they hold significant promise for future naval use, especially in load-following operations. The characteristics of the MSR surpass the safety characteristics of other fast reactor types, avoiding coolant difficulties in warfare environments.
The reactor design used for an MSR is chosen in section 3.3.1.

vSMR

Reactors defined as vSMR are characterised by their relatively small size, simplified designs, and modular nature, allowing efficient deployment in various settings. Redundancy and load-following properties can be improved when multiple vSMRs are combined for the desired total power out. The design principle is in accordance with SMRs but provides lower power outputs. Different types of coolant, including light water, helium, molten salt and liquid metal, are adopted by vSMR. Most developers are focused on gas and heat pipe-cooled designs. The MSR does not have a vSMR version, unlike the (V)HTR which is suitable for vSMR.

2.2. Naval operational design

Historic observations regarding nuclear-powered combatants and nuclear ship design considerations are covered in the literature report sections 3.1 and 3.3 [1].
Emerging weapon and sensor technologies, including sensors, Unmanned Vehicles (UXV) and naval-directed energy weapon systems, increase power demand. Specific short-term energy storage is needed to include these Sensors, Weapon Systems and Command Systems (SEWACO). It is concluded that High Energy Laser (HEL) and High Powered Microwave (HPM) systems are highly prioritised to integrate in future combatants to position the combatant within the spectrum of future mission capabilities.
The power required for SEWACO systems is explained in section 4.1.3

2.3. Naval (v)SMR power implementation

A foundation for understanding naval (v)SMR-powered propulsion systems has been provided [1]. The power plant configuration used in this thesis is given in section 4.3.
A basic understanding of possible power generation options to convert heat into power has been given. Section 6 explains the choice for the closed Brayton cycle.
Several Energy Storage Systems have been identified. The implementation is addressed in the section 4.2.2.

2.4. Ship design approach

The critical elements of SMR technology concerning naval ship design can be defined with five essential design basics [1]:

- platform size: displacement
- platform energy demand: slow or fast
- energy utilisation: dynamic or constant
- mission capabilities: high or low SEWACO requirement
- platform resilience: in terms of survivability

The elements utilised in this thesis are covered in chapter 3. The platform to be defined as a future surface combatant is described in section 3.2.

Part II

Design study

3

Design structure & Future surface combatant

3.1. Design Structure

Part II aims to find the implications on the design of a future surface combatant where fourth-generation (v)SMR technology is considered for power generation. The leading parameters in the design of a surface combatant are displacement and volume. Besides propulsion and power generation, SEWACO systems, auxiliary systems and accommodation require displacement, volume and a position on the combatant [5].
A design study will contribute to establishing an overview of the qualitative impact of the choice of fourth-generation (v)SMR technology for future surface combatants on its required power, size, displacement and survivability. Part II will describe the design methodology and discuss the results provided with a conclusion. A case study was performed in chapter 8, using a developed parametric design model. The structure of part II is presented in figure 3.1.

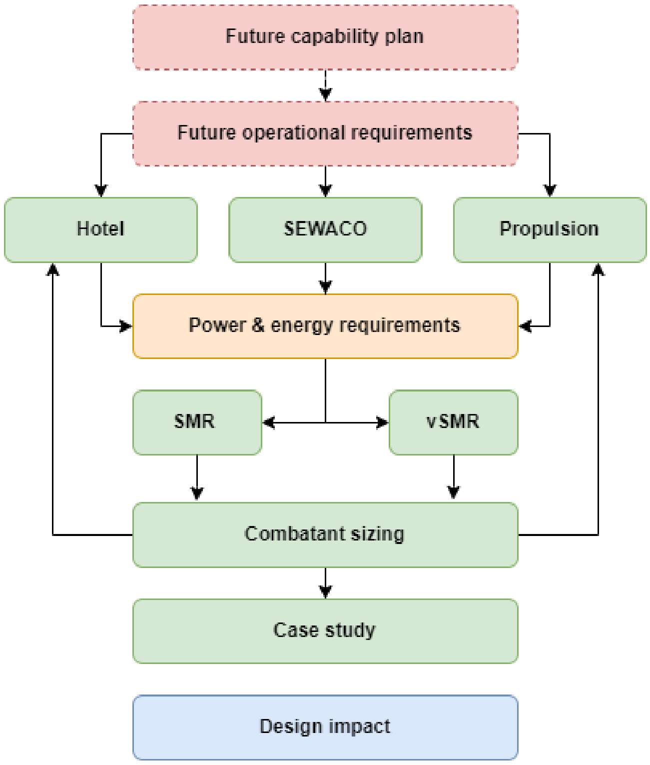

Figure 3.1: *Schematic design structure*

After establishing power and energy requirements, the model will evaluate SMR and vSMR power generation systems. This will lead to combatant sizing, which results in a case study. The impact on the design of a future surface combatant results from all components in the design structure.

3.2. Future surface combatant

When considering fourth-generation (v)SMR technology, it is essential to realise that it is in developmental or demonstration phases globally, with the first practical prototypes operating around 2028 [4]. Besides extensive testing and certification processes, investment and political will is required. Realistically, (V)HTR with a higher TRL may begin to be used in naval applications from 2040, with broader deployment, including the MSR, potentially happening in the 2050s.
A typical operational life of 30+ years means that future surface combatants must comply with future capabilities. Therefore, defining a future capability plan that can translate into operational requirements is essential. However, neither a capability plan nor future operational requirements are known to the public. Power and energy requirements are derived to define a future surface combatant without translating a capability plan, a process shown in figure 3.2 explained in detail in chapter 4.

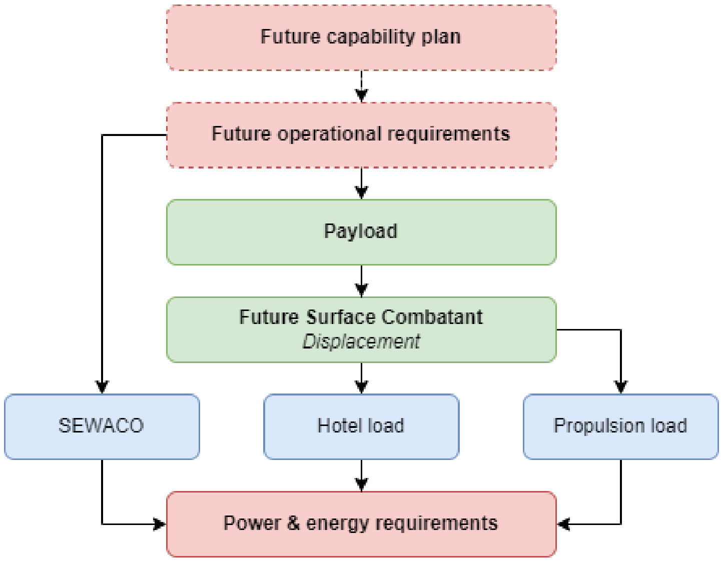

Figure 3.2: *Power and energy requirement derivation*

It is shown that a future surface combatant will be defined by the combatant's payload and size expressed in displacement. The payload for a surface combatant refers to the equipment, systems, weapons, and other resources carried onboard that contribute to its mission effectiveness. Usually, the payload would indirectly influence the combatant's size. This research assumes that the operational requirement resulted in a desired payload regardless of the combatant's size. It is up to the ship designer to fit the payload in the combatant.

To conclude, the main drivers of power demand are the payload and combatant size. The combatant's mission type determines the required mission systems, described in section 3.2.1.

3.2.1. Combatant mission type

Many nations commit to global operations, primarily in concert with multi-mission flexible multi-national task forces [6]. The need for multi-mission flexibility has arisen from today's mission unpredictability. Capabilities demanded of a multi-mission globally-deployed combatant are listed in part I and can be provided with three different combatant roles [6]:

1. Single
2. Changeable
3. Multi

Single-role combatants ensure overall capability coverage for all possible missions by deploying a variety of specialised combatants. This strategy enhances survivability by distributing the full capability across multiple combatants. However, it takes considerable time to assemble the correct capable task force.

Changeable-role combatants aim to alter their primary capabilities by changing modular mission packages. While the combatant remains equipped for the intended role, transitioning to a different role requires time and global logistical support in relevant operational areas. Having theoretical unlimited endurance with nuclear reactors might not benefit this ship type. As seen with the Littoral Combat Ship program, complicated logistics with different mission packages, including design flaws and the required specialised flexible crew, led to failing weapon systems and increased cost [7].

Multi-role combatants combine mission capabilities, adding complexity and contributing to the overall cost increase. Therefore, multi-role combatants are seen as high-value targets, necessitating enhanced survivability. However, at the fleet level, the cumulative benefits include increased flexibility and autonomy, which align with the benefits of nuclear power. Generally, by adding mission capabilities, the size driver for multi-role combatants is the necessary deck space to accommodate SEWACO systems.

Looking at the role of most Western navies, a multi-role combatant seems to align with the expected capabilities [6]. The notional future combatant in this thesis will obtain the following mission profile:

- Air & surface defence against traditional and unmanned threats
- Act as a ballistic & hypersonic missile defence platform
- Increased situational awareness

3.2.2. Payload & performance

Emerging weapon and sensor technologies identified in part I are implemented to position the combatant within the spectrum of future mission capabilities. The future surface combatant will include the following SEWACO systems:

- Sensors
  - Long-range radar system (L-band)
  - Active Phased Array Radar (X & S-band)
  - Electronic warfare system
  - Sonar
- Weapons
  - High Energy Laser (HEL), capable of ballistic missile defence
  - High Power Microwave (HPM) weapon, 360 degree coverage against air & surface threats
  - Vertical Launching System (VLS) modules for air and surface warfare
  - Conventional armament, close-in weapon systems
- Vehicles
  - Helicopter(s)
  - Unmanned vehicles (UXVs)

The future surface combatant is expected to comply with different mission states, each with its objectives. This is translated into a threshold performance requirement described in table 3.1.

Table 3.1: *Threshold performance of a future surface combatant*

Mission	Speed (knots)	Weapons	Sensors	Vital Loads	Non-vital Loads
Slow *(port)*	7	Off	Low	Medium	High
Patrol	12	Medium	High	High	Medium
Transit *(cruise)*	25	Off	Medium	Medium	High
Sprint to station	30	Medium	High	High	Medium
Battle	29	High	High	High	Medium
Emergency	10	Low (critical)	Low (critical)	High	Off

The threshold performance will be used as input for the operational profile of the combatant explained in section 4.2.1 and presented in appendix A. For each mission, the load state of weapons and sensors is given. The hotel load is divided into vital and non-vital loads.

3.2.3. Combatant size

The combatant size will be addressed in terms of displacement. The main drivers of the displacement of a multi-role combatant are:

- Payload, often require power and deck space
- Power generation, influenced by the power demand of propulsion and the payload
- Endurance, normally depending on speed
- Survivability
- Crew, accommodation including life support systems

Displacement needs to be chosen to evaluate a future surface combatant. However, the relation between the desired payload and the required displacement is unknown. Therefore, the combatant is sized until the power plant and payload fit in the preliminary design, as explained in chapter 8.

3.3. Reactor power plant

A nuclear reactor has to be selected to be implemented in a future surface combatant. After the power and energy requirements are established in chapter 4, the power plant of an SMR and vSMR will be derived within the structure described with figure 3.3.

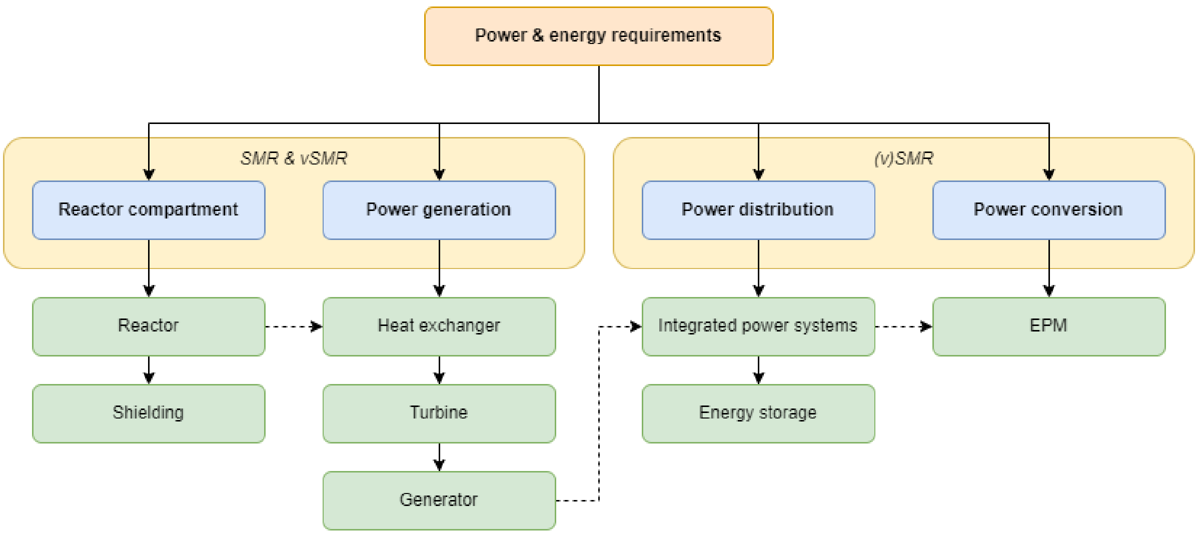

Figure 3.3: *Design structure for the SMR and the vSMR*

It is seen in figure 3.3 that the requirements can be used to define each component. The dotted line in figure 3.3 represents the design flow used for the parametric study to size the future surface combatant given in chapter 8. The requirements will be used as input for the reactor compartment and as a check for the other components.

To find the impact of generation IV (v)SMR technology, an SMR and a vSMR are implemented in a future surface combatant. The reactor and power generation are different for an SMR and vSMR, described in detail in chapter 6. The power distribution and conversion are assumed to be similar for both reactor technologies when an electric propulsion layout is considered, described in chapter 7.

3.3.1. Reactor selection

The used reactor technology needs to be promising for future naval applications. Only the (V)HTR is promising for vSMR technology. Therefore, 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 [4]:

SMR is based on the 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 $10\ MW_e$ HTGR

The CMSR is comparable with the MSR from THORIZON. However, more public details are available from Seaborg. The layout is given in figure B.2
Looking at the implications on ship design, the U-Battery and eVinci could be studied as vSMRs. However, the detailed design of the Holos-quad is completely published and thus serves as a better source of information [8]. The layout is given in figure B.1.
As addressed in part I, reactor designs using heat pipes for heat transfer might be better resistible against motions and vibrations, as further research recommends. The CMSR and the HOLOS-QUAD are believed to be well-developed designs suitable for understanding fourth-generation (v)SMR implementation on future surface combatants.

The modelled reactors will differ in the following characteristics:

- Output power
- Power density (kW/L)
- Temperature (difference)
- Coolant
- Fuel properties
- Control

The reactor characteristics are indicated in table 2.1. More details are provided in the literature report [1].

3.4. Conclusion

This chapter outlines the design and operational considerations for integrating fourth-generation (v)SMR technology into future surface combatants. A structure has been proposed to evaluate the influence of (v)SMR technology on designing a future surface combatant. It has been established that displacement and volume are primary design parameters, significantly influenced by propulsion, power generation, and onboard systems requirements. The chapter identifies the fundamental role of power and energy requirements in defining the capabilities of a future surface combatant, acknowledging the challenge posed by the lack of publicly available future capability plans or operational requirements.
The future surface combatant is a notional multi-role combatant obtaining air and surface defence while increasing situational awareness. Emerging naval-directed energy weapons, such as the High Energy Laser and High Power Microwave, with sensor technologies, are implemented to position the combatant within the spectrum of future mission capabilities. The combatant will be sized accordingly by specifying the payload and expected performance.

Both the SMR and the vSMR will be modelled. The study will focus on the CMSR and Holos-Quad reactor designs, chosen for their developmental maturity and suitability for naval applications. To conclude, this chapter establishes a framework for assessing the design and operational impacts of integrating (v)SMR technology into future multi-role surface combatants, highlighting the critical role of power and energy requirements and focusing on the CMSR and Holos-Quad reactor designs for practical application.

4

Power & energy requirements

Power requirements are instantaneous needs for electricity or propulsion. They determine the capacity of the power generation and distribution systems.
Energy requirements are the total energy consumed over time. They are crucial for calculating conventional surface combatants' endurance and fuel capacity.

4.1. Power requirements

The required power P_{tot} for a combatant is described with equation 4.1.

$$P_{tot} = P_{prop} + P_{SEWACO} + P_h \tag{4.1}$$

Where:

P_{prop}: propulsion power
P_{SEWACO}: sensor, weapon and command system power
P_h: hotel power

4.1.1. Propulsion power

The required propulsion power relates to the sailing speed according to equation 4.2 [9].

$$P_{prop} \propto \Delta^{\frac{2}{3}} \cdot v_s^3 \tag{4.2}$$

Where:

Δ: displacement
v_s: combatant speed

The propeller interaction with the ship and the prime mover is not considered. Only the power observed at the prime mover will be used, not the power put into the water with a propeller. This simplifies the scaling process of preliminary designs. The observed power measured at the engine shaft, the effective engine power, is often called brake power, P_{brake}. When the hull shape is assumed constant while scaling in terms of displacement, equation 4.3 can be used for a preliminary brake power estimation. The transmission efficiency represents the effectiveness of power transfer from the source to the output, considering power train losses.

$$P_{brake} = \frac{\Delta^{2/3} \cdot v_s^3}{C_{adm} \cdot \eta_{TRM}} \tag{4.3}$$

Where:

C_{adm}: admiralty coefficient
η_{TRM}: transmission efficiency, assumed to be 0.9

The admiralty coefficient in equation 4.4 can be used to estimate the power to be installed when combatants of similar dimensions are known. When data from an existing hull is known for the whole resistance curve, the coefficient can be calculated in different operating conditions.

$$C_{\text{adm}} = \frac{\Delta^{2/3} \cdot v_s^3}{P_B} \tag{4.4}$$

A parametric model to predict the brake power for a future surface combatant, given $\Delta_{concept}$, has been made based on equations 4.3 and 4.4 by implementing the brake power curve of the LCF [10]. Figure 4.1 gives an example of a brake power prediction for a combatant of $10,000$ tonnes by scaling the LCF hull.

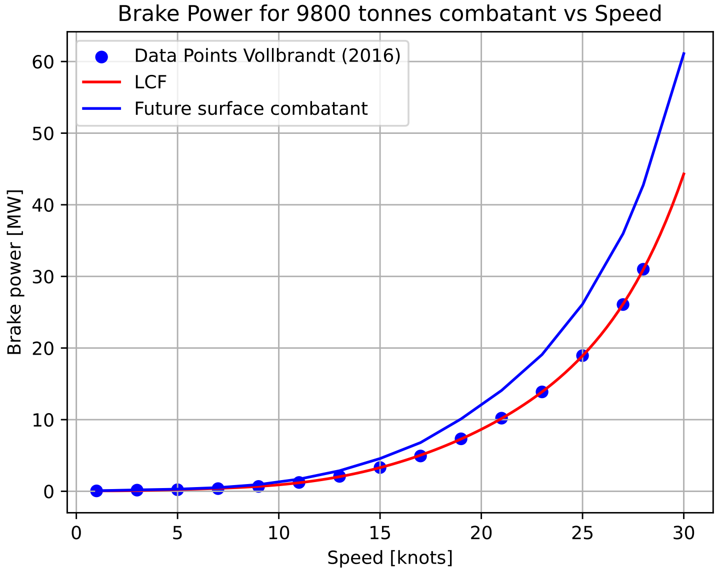

Figure 4.1: *Brake power estimation*

Scaling the brake power with the admiralty coefficient is valid for Froude numbers up to 0.3. The required power increases at a higher rate than v^3 for higher values of the Froude number. Therefore, the estimated brake power in figure 4.1 is an indication and equal to the power required for propulsion. For a detailed design, extensive model test data is considered necessary.

4.1.2. Hotel load

The electrical load other than propulsion and SEWACO on a traditional powered combatant is called hotel load. While the hotel changes over time, it is often assumed to behave constantly independent of the sailing speed and is seen as a baseload generated with diesel generators. For RNLN combatants, the hotel load averaged over 24 hours is not higher than $2MW$. The distribution of systems within the total installed electric load can be seen in figure 4.2.

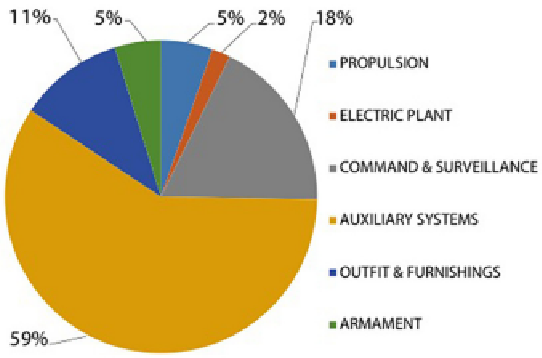

Figure 4.2: *Proportional distribution of the total installed electric load on the F105 [11]*

With a displacement of 6391 ton, the Spanish combatant F105 has installed a total of $9,015kW$ and is estimated to consume a maximum of $2.8MW$ [11]. A multi-purpose frigate of $4,700$ tons introduced by the Royal Canadian Navy shows a constant average electric load of $961kW$ regardless of the sailing speed in normal operations [12]. The data behind figure 4.2 is analysed and used to estimate the hotel load per mission state, as seen in appendix A. To consider concept sizing, the hotel load per mission state for future surface combatants will be corrected with equation 4.5.

$$f_{hotel} = \frac{\Delta_{concept}}{\Delta_{F105}} \tag{4.5}$$

Figure 4.2 will differ for a future surface combatant. While combatants will use armament and command & surveillance, these loads are expected to become higher and more dynamic related to operational missions. The pie chart in figure 4.2 will also differ for a (v)SMR-powered combatant. The power required for the balance of the plant is expected to be higher because of the required pumps in the reactor's primary and secondary coolant loops. The required load for auxiliary propulsion systems is estimated to be $4.5kW/MW_{th}$ for VHTRs and $5.5kW/MW_{th}$ for MSRs [2]. This load will change per sailing speed because of the relation with the thermal output of the reactor.

4.1.3. SEWACO load

The SEWACO load is for mission-specific sensors, weapons and command systems. Besides conventional armament, energy weapons are expected to dominate this category. Advanced radar & control systems in search/track mode differ by a couple of megawatts. Independent of the sailing speed, the SEWACO load can be constant, like the hotel load, but it changes rapidly to dynamic load cases in combat or patrol scenarios. This effect is considered with table 3.1. The power per system per mission state is given in table A.1. The total nominal required power for SEWACO is 13.8 MW, comparable with other studies integrating future mission systems [13] [14]. Assumptions are addressed in this section. Details are found in appendix A.

The considered NDE weapons are modelled as depicted in figure 4.3.

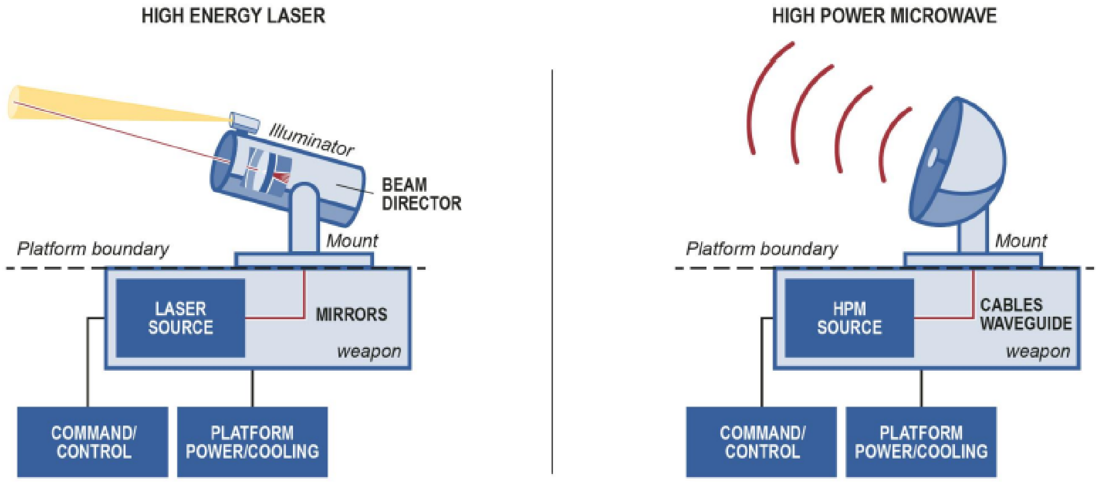

Figure 4.3: *Illustration of modelled HEL and HPM systems [15]*

High Energy Laser (HEL) and High Power Microwave (HPM) systems need high power and energy levels in short windows. The output power of the weapon will come from a capacitor or pulsed alternator for fast power release [16]. As seen in figure 4.3, the sources, also called pulse-forming networks, are not considered because of the involved complexity and manufacturer preference. The SEWACO load for the HEL and HPM system include the command & control and the platform power loads. With the power of the ESS and the reactor power plant, the employment of NDE weapons should be limited to 10 minutes within any given hour [17]. This timeframe is anticipated to be sufficient for the majority of combat situations.

It is assumed that two HEL systems are necessary to comply with ballistic missile defence. Depending on the development, HPM systems might be integrated within high-powered radar systems, reducing the size of installation required. However, separate units are considered to challenge the future surface combatant's power system. Four HPM systems are installed for 360 degree coverage against air and surface threats (UXV swarms).
Also, the combatant is equipped with conventional armaments, requiring non-pulsed and relatively low electrical load. UXVs are modelled as a charging load. Re-charging of UXV systems will occur in low-conflict mission states. Ten Verticle Launch System (VLS) modules are implemented so the surface combatant can act as a missile defence platform. Two radar systems are distinguished for long and medium-range detection. The systems are assumed to be highly upgraded and derived from the SMART-L and APARD, currently used by the RNLN. A bow-mounted sonar is modelled as a constant load.

4.2. Energy requirements

Energy requirements are essential and significantly impact executing endurance estimations regarding fuel capacity for a traditional combatant. Where nuclear-powered combatants seem to have infinite energy for a given operation, the future surface combatant challenges this statement. Due to pulse-forming loads on the power distribution system induced by NDE weapons, (v)SMR might not be fast enough to ramp up to these power levels, leading to ESS requirements. The impact on ESS requirements for combatants with traditional gas turbines and pulse loads has been researched [18]. It can be calculated by integrating the difference between the pulse and the delivered output power, as seen in figure 4.4.

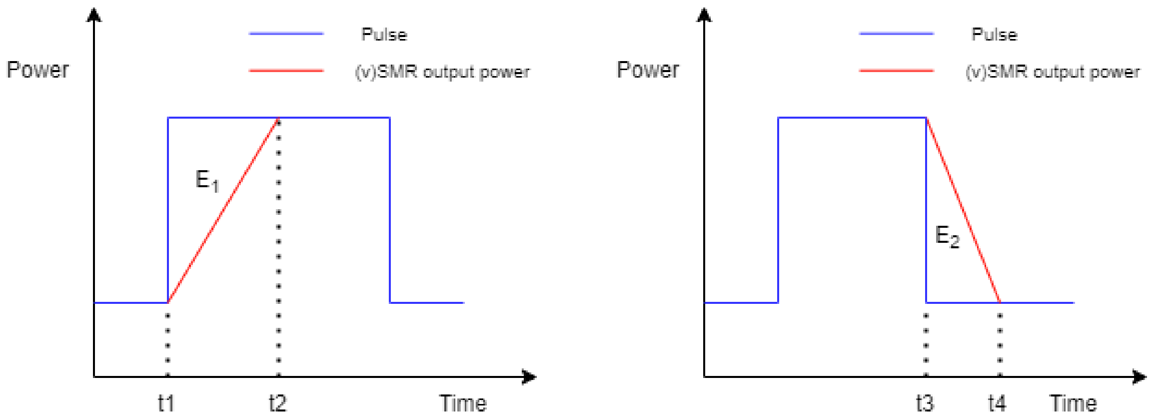

Figure 4.4: *Example power profile during ramp up (left) and ramp down (right) period*

Here, the ramp rate is assumed to be linear. This is not completely accurate for gas turbines and nuclear power plants but is considered adequate for the preliminary design phase.

During a ramp-up period, the required ESS capacity E_1 is calculated with equation 4.6.

$$E_1 = \int_{t1}^{t2} \left(P_{pulse} - P_{(v)SMR}\right) dt \tag{4.6}$$

During a ramp-down period, the required ESS capacity E_2 is calculated with equation 4.7.

$$E_2 = \int_{t3}^{t4} \left(P_{(v)SMR} - P_{pulse}\right) dt \tag{4.7}$$

From figure 4.4, it can be concluded that the (v)SMR ramp rate limit defines the total ESS capacity required. The ESS capacity requirement decreases with higher ramp rates and lower pulse load. The pulse load can be defined with an operational profile of the future surface combatant.

4.2.1. Operational profile

The operational profile of the future surface combatant is directly translated from table 3.1. The speed, hotel, and SEWACO load per mission state determine the power demand within a specific time domain. The operational profile used in this research to examine the performance of the (v)SMR-powered combatant is given in appendix A.

With the operational profile, changed sailing behaviour with a nuclear combatant is considered by increasing the transit speed compared to traditional combatants. It is expected that with a combatant not needing fuel replenishment, the crew will sail more often at higher speeds, as confirmed by historical observations with nuclear-powered cruisers [19]. The top speed is a minimum of 30 knots to keep up with carrier battle groups. The patrol, emergency, and port entering speed are assumptions based on the Royal Netherlands Navy operational experience.

4.2.2. Energy Storage System

In the literature report, several ESS technologies have been identified [1]. Because the optimisation of ESS technology for a future surface combatant is not within the scope of this thesis, one viable system suitable for surface combatants is integrated with the (v)SMR power plant. Pulse-forming networks are not considered, making flywheels, capacitors and pulsed alternators unsuitable as bridging energy storage requires other properties. Batteries are considered suitable as bridging energy storage systems. According to previous analyses, lithium-ion batteries have a payback interval within the service life of a surface combatant, combined with their high specific energy density, which makes them an affordable option in terms of cost, size and weight for most naval applications [20]. Therefore, this thesis assumes a generic naval lithium-ion-based technology to solve the energy requirements of a future surface combatant.

Battery system description

The cell is the fundamental unit of any battery system, comprising a cathode, an anode, an electrolyte and a separator. Lithium-ion cells are grouped into modules designed to achieve the desired voltage and energy capacity. Modules include thermal management systems to maintain optimal operating temperatures and protect the cells from overheating [21]. Modules are assembled into racks, which are larger structural units that provide mechanical support, electrical interconnections, and further thermal management. Finally, racks are installed within compartments to isolate the battery system from the marine environment, protecting against moisture, salt, and other corrosive elements. Details can be found in previous work [22].

Battery compartment

The required volume for a battery compartment depends on the system's volumetric energy density and required capacity. A surface combatant's ESS needs high power and high energy capacity. Suitable racks have been given in table 4.1. Here, the C-rate equals the charge or discharge current divided by the battery capacity.

Table 4.1: *Lithium-ion battery rack specifics based on [23] [24]*

Manufacturer and model	C-rate	Energy Density (Wh/L)	Specific Energy (Wh/kg)
Samsung P3-R076	$2-3$	106	103
Corvus Orca	3	88	77
Samsung U6-R035	6	43	63

Considering packing factors, an energy density of $100Wh/L$ is estimated for battery compartments in future notional submarines [21]. While different space requirements and regulations apply for surface combatants, this estimation is not unrealistic but might increase for future naval applications.

4.3. Power plant configuration

After power and energy requirements are set, it is crucial to determine how the power will be divided. The first nuclear-powered combatants used direct geared turbine drives. Because of the increasing electrical mission loads, hybrid and electric drives are suitable for future surface combatants. Emergency power can be supplied relatively easily to an Electric Propulsion Motor (EPM), avoiding the need for a complex gearbox design. Both configurations allow for energy storage integration. The propulsion configurations have been presented in figures C.2 and C.3, appendix C.

Given the advanced electrical needs of future surface combatants and the relatively low reaction time of (v)SMRs, this report uses as a starting point an Integrated Power System (IPS) based on the following assumptions:

- Dynamic allocation of electrical power from the (v)SMR provides operational flexibility to meet changing needs, which is critical for energy-intensive systems such as SEWACO and NDE weapons.
- IPS is scalable for future applications and facilitates easier integration and upgrading of new technologies and systems, as the power distribution is already optimised for integrated electric power.
- IPS simplifies the configuration, which could reduce the size of the system and reduce maintenance. An example is turbine standardisation. Considering two propeller shafts to obtain high sailing speeds and complying with redundancy reasons, hybrid configurations require two turbines (or one large turbine with a complex gearbox) for propulsion and at least a third turbine for electrical power generation. Full electric drive scales the number of turbines to comply with power load and redundancy requirements.

Utilising an IPS increases the electromagnetic signature of the combatant. This increases the need for magnetic signature management which requires a degaussing system [25]. Currently, no IPS has been implemented in combatants employed by the RNLN. Besides technical challenges, in-depth research regarding costs should be performed.

4.4. Conclusion

This chapter determines the power and energy requirements for future surface combatants. The total required power has been divided into propulsion, mission system (SEWACO), and hotel loads.
Using a parametric model based on the Admiralty coefficient with existing combatant data, the propulsion power based on sailing speed and displacement can be estimated. The hotel load is estimated by evaluating conventional surface combatants and correcting the required load by a displacement factor.
The SEWACO load has been defined based on unknown future operational requirements. The required load is an estimated base load. Pulsating power levels have been excluded from the scope. Therefore, the power needed is fixed for all mission systems.
Energy storage will be derived by integrating the pulsating behaviour of the operational profile over time. It can be concluded that the (v)SMR ramp rate limit defines the total ESS capacity required. It is found that the greater the allowable ramp rate and the lower the pulse load, the lesser the ESS capacity requirement. This means that the ESS capacity for vSMRs remains constant as the power output and ramp rate are constant.
The (v)SMR-powered combatant's power demand is determined by the speed, hotel, and SEWACO load per mission state, resulting in a load profile used to assess performance. The chapter proposes lithium-ion technology as a viable solution for ESS, considering its energy density and specific energy in combination with its load response.
Finally, the chapter proposes an Integrated Power System (IPS) for future surface combatants, arguing its operational flexibility, scalability, and efficiency advantages.
To conclude, a methodology has been established to estimate propulsion, hotel, and SEWACO loads. The critical role of ESS in managing peak demands has been identified, and a strong case has been made for adopting an IPS configuration.

5
Reactor compartment

This chapter describes the preliminary design of the reactor compartment considering a fourth-generation SMR and vSMR. A schematic overview is shown in figures 5.1 and 5.2. The reactor layout is discussed in the literature report [1]. This chapter describes the impact of shielding in terms of weight and volume on the ship design.

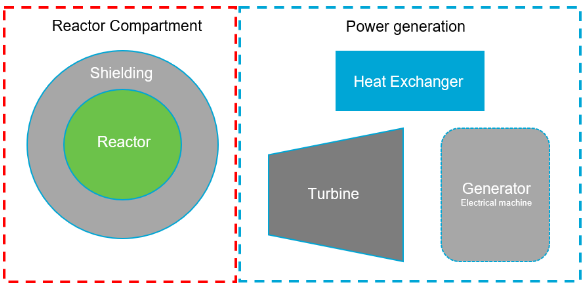

Figure 5.1: *SMR reactor compartment*

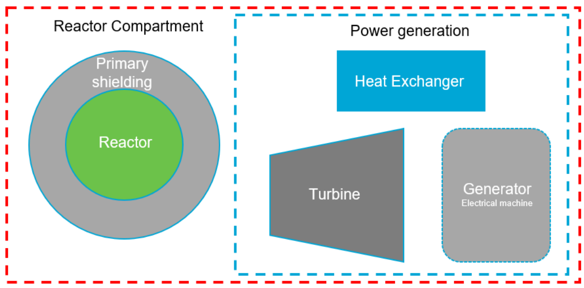

Figure 5.2: *vSMR reactor compartment*

It becomes apparent that there is a significant difference between SMR and vSMR reactor compartments in locating power generation differently. This chapter will address the differences after the general method is explained.

5.1. Reactor compartment design

As shown in figures 5.1 and 5.2, the reactor compartment consists of the reactor and shielding. The purpose of the reactor compartment is to provide a secure and controlled environment for the combatant's nuclear reactor. It is designed to ensure radiation containment for potential accidents or malfunctions. The compartment may include shielding materials to minimise radiation exposure to crew members. The reactor compartment includes at least the reactor with its (pressure) vessel, shielding and piping for the reactor coolant. This report simplifies the reactor compartment into the reactor pressure vessel and shielding. The size and weight of the reactor pressure vessel are estimated with literature [1]. The SMR design may include the steam generator, heat exchanger, and coolant pump/blower. It is observed when designed for power generation, most vSMR designs include the turbine and alternator within the reactor compartment to allow a compact design. To a certain extent, all components within the reactor compartment are exposed to radiation, within certain limits of becoming radioactive. It is essential to distinguish the reactor compartment from other compartments because of the risk of contamination when accidents occur.

5.2. Shielding

Naval personnel must be protected against the adverse biological effects of neutrons and gamma-ray radiation of the (v)SMR. Also, attenuation of neutron and γ rays is needed to reduce the impact of radiation damage to reactor components, nuclear heating in unwanted regions and activation of reactor compartment components. A schematic of a reactor compartment is visualised in figure 5.3. The elements and terminology will be explained throughout this chapter.

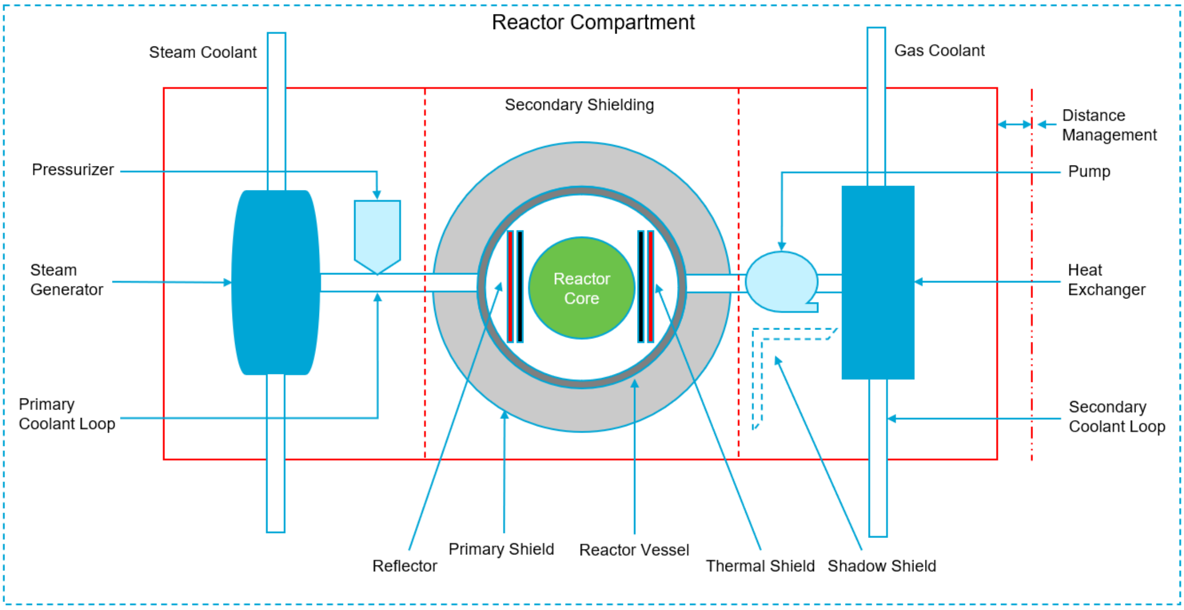

Figure 5.3: *Schematic of a reactor compartment shield with water (left) and gas (right) coolant*

Figure 5.3 shows two different coolants, water and gas. This design choice is explained in detail in chapter 6.

5.2.1. Radiation exposure

In practice, the guiding principle of radiation safety is As Low As Reasonably Achievable (ALARA) [26]. This results in three basic protective measures in radiation safety.

- Time
- Distance
- Shielding

All three measurements are directly related to the obtained doses from a nuclear reactor plant. Regardless of the measurements taken, exposure limits for a radiation worker and the general public are given in table 5.1.

Table 5.1: *Radiation exposure limit excluding natural background ambient radiation*

	Radiation worker	General public
Maximum exposure per year	50mSv	1mSv

The general public is constantly exposed to radiation doses from natural background radiation and medical procedures. The limits prescribed in table 5.1 can be placed into perspective. The average ionising radiation exposure to Dutch residents is estimated at around 2.5 mSv (millisieverts) per inhabitant a year [27]. In comparison, fleet personnel in the US Naval Nuclear Propulsion Program monitored in 2022 received an average of 0.06 mSv a year while shipyard personnel were exposed to an average of 0.11 mSv a year [28]. Onboard the RN's Astute submarines, over 75% of the crew would get a more significant dose from background radiation staying ashore than from the reactor while onboard [26]. This is obtained by proper shielding in combination with time and distance management.

To save weight, it has been decided that naval applications allow for a radiation worker exposure limit. However, this does not mean the crew's safety is at risk, as seen with equation 5.1 [29].

$$D_{max,allowed} = D_{received} \cdot f_O \tag{5.1}$$

Where:

$D_{max,allowed}$: the maximal allowed radiation dose from table 5.1
$D_{received}$: radiation actually received per year
f_O: occupancy factor based on the time spent near radiation sources

The inverse square law dictates that exposure decreases with increased distance from the radiation source. The occupancy factor considers time and distance based on the ALARA principle. An example calculation is given in appendix D. The example of a fictional crew member working at different distances for different periods of time near the reactor concludes that the maximum dose rate at the edge of the shield can be 46 times higher than the maximum exposure limit of a radiation worker. For this simplified example, the dose received per year is almost the same as the exposure limit for the general public. This means that the fictional crew member, being navy personnel, can almost be replaced by a civilian.
More detailed calculations are recommended. However, the impact of considering ALARA shows that safety is not at risk when assuming a radiation worker exposure limit for naval applications.

5.2.2. Naval shielding

Combatants powered with (v)SMR technology face a unique challenge for radiological safety engineers.

- All personnel work and live relatively closely near the reactor core compared to land-based applications.
- Shielding thickness and use of heavy material is limited onboard a combatant, considering space and weight limitations.
- The added weight needs to be distributed properly regarding the strength and stability of the combatant.

It is concluded that the design constraints are weight, volume and location. This results in a solution that balances ship and radiological safety within the combatants' environment.

5.2.3. Principles of shielding

The principles of shielding are essential to understand when utilising nuclear power. The principles are explained in detail in appendix E. The most important considerations are summarised:

- The shield design must account for neutron and γ-ray radiation.
- The shield is divided into two parts, the primary and the secondary shield. Primary shielding reduces the neutron flux to levels preventing plant components from activating. Secondary shielding must bring neutron flux and γ-ray production to safe levels, defined with table 5.1.
- The design of the primary shield depends on full power operation and after-shutdown conditions.
- Secondary shield considerations affect the design of the surface combatant in terms of reactor placement, equipment protection, coolant requirements, maintenance requirements and activation problems.
- The reactor compartment's location and the radiation exposure levels influence the design of the combatant.

5.2.4. IV-Generation (v)SMR shielding considerations

Experience with most shielding is obtained with earlier generations of nuclear reactor technology like the PWR. Fourth-generation (v)SMRs have different characteristics compared to conventional reactors.

Thermal & Fast reactors

Due to the presence of a moderator, thermal reactors slow neutrons down to energy levels between $0.025 - 0.625eV$ where fission takes place [30]. Fast reactors, with the absence of a moderator, operate in the fast region ($100keV+$) where the neutron peak in the energy spectrum of the MSR appears around $20 - 100keV$ [30]. Because most fast reactors have an increased power density compared to thermal designs, the neutron flux level increases [31]. In thermal reactors, mostly fast neutrons, which do not collide or are deflected, escape the reactor core in relatively small numbers.

An optimal solution for shielding thermal reactors is based on slowing neutrons down with elastic collision induced by hydrogen. Fast reactors use a hybrid combination of heavy and hydrogen-containing materials to have an effective shield.

Temperature

Fourth-generation (v)SMRs operate at high temperatures ($500°C+$) and affect shield design. The materials surrounding the reactor must be able to withstand these temperatures. High temperatures mean high heat build-up. This heat is generated by neutrons and γ -rays. The heat in surrounding materials can be reduced with thermal shields surrounding the core. A layer, or layers, of high-density material located within a reactor (pressure) vessel and in the biological shield reduce radiation heating in the vessel and the biological shield [32]. However, thermal shields function by capture or elastic collisions, which means an increase in capture γ-rays affecting the design of the biological shield.

Thermal shield designs are governed by induced stresses in the reactor vessel and the coolant pipes [32]. The use of high-temperature-resistant materials creates the need for advanced thermal shield designs. It also limits water as a shielding material in the primary shield. Under any accident, the shield must not lose its shielding ability, allowing for emergency repair missions if necessary. In some reactor designs, the primary shield is cooled with water. However, using water in the primary shield or as shield coolant is risky when shielding naval (v)SMRs.

Looking at the Maximum Core Temperature under Loss of Coolant Accident (LOCA) of the HOLOS-QUAD where it is passively cooled by air, a maximum temperature of $1127°C$ is obtained, which decreases after 60 seconds [8]. If the primary shield contained water as liquid and thermal shielding was not designed accordingly, the primary shield would vaporise. Losing the primary water shield during an accident, such as a LOCA or after being hit, can seriously threaten the crew's safety. Cooling the primary shield creates another risk regarding radioactive safety because the shield would be damaged by thermal stresses when this cooling system fails. These considerations have not been covered in the literature.
Therefore, this report considers water (liquid) unsuitable for fourth-generation (v)SMR primary shielding in naval applications.

Primary coolant loop

Fourth-generation (v)SMRs have different primary coolant loops. The MSR uses a molten salt mixture with the radioactive fuel. This produces delayed fission neutrons and activation γ-rays outside the primary shielding. To allow for maintenance near the primary coolant loop, shadow shields between the reactor and secondary shielding can be used. It can be concluded that the MSR shield design become complex because of the radioactive molten salt mixture.
(V)HTRs use mostly helium as the primary coolant. Helium, which is inert and chemically stable, does not form associated radiation risks in the reactor compartment. It is concluded that the (V)HTR allows for standard shielding solutions.

5.2.5. Radiation transport model

Shield designers have access to various radiation transport models utilising diverse techniques to compute the radiation flux from a source once it has undergone attenuation by shielding. Two extreme conditions are used in shielding calculations: bulk shielding (shielding around the core) and streaming problems (gaps, ducts and coolant pipes) [33]. Radiation shielding analysis technology can be classified into three categories increasing in complexity and computing time [34]:

1. **Point kernel method**, based on the Boltzmann equation, is an analytical model which represents the total flux as the product of the uncollided flux with a buildup factor with great practical value considering the accuracy, computational time and simplicity used in two calculations [33] [29]:
   - *Removal-Attenuation* considers fast neutrons and uses removal cross-sections of shield materials to estimate the dose rate at a point.
   - *Attenuation + buildup factor* combines a removal-attenuation and a multi-group calculation to provide the spatial distributions of neutrons of all energies throughout the preliminary primary shield.
2. **Monte Carlo method** is a probabilistic model employed for gamma and neutron shielding analysis in complex geometric configurations. It involves tracking particles across spatial volumes and simulating interactions with materials based on interaction probabilities.
3. **Discrete ordinate method** is a numerical method utilised for gamma and neutron transport. This approach involves applying transport equations on meshes overlaid on the spatial problem and discretising the angular variable.

While this report searches for the impact on ship design, a size and weight estimate of the nuclear shielding is valuable. It is seen that, without geometric reactor configurations including the reactor compartment layout and basic well-tested nuclear material data, accurate models like Monte Carlo or the Discrete ordinate method can not be applied to gain these insights within a reasonable time.
Therefore, the Point kernel method is used for neutron and γ shielding to obtain the preliminary design of a fourth-generation (v)SMR reactor shield. Streaming problems will not be calculated due to complexity reasons. Instead, only the bulk shielding condition is evaluated.

Simplifications & Limitations of point kernel method

- The point kernel method assumes a point source of radiation, which may not fully represent the spatial distribution of the actual radiation source. This assumption does not fully capture the reactor geometry and distribution details in complex radiation fields.
- The point kernel method assumes isotropic emission of radiation from the source while anisotropic characteristics and inelastic collisions might be expected in the shield.
- Scattering of neutrons is not included in this model. The neutron flux is estimated to be too high at the shield's surface.

5.3. Shielding model

In this thesis, the shielding model is an analytical method to estimate the shield thickness, which can be translated into weight and size inspired by literature [4] and is based on previous work [2]. The shielding model will simplify the (v)SMRs, using a standard uranium fuel (U-235). The MSR and (V)HTR will be modelled with the general parameters from the CMSR and the Holos-Quad. The input values from the different reactors can be found in the appendix F. No distinction is made between thermal or fast reactors. The same calculation method applies. The shield model is simplified to a spherical core as visualised in figure 5.4 and is less complex than the reactor compartment depicted in figure 5.3.

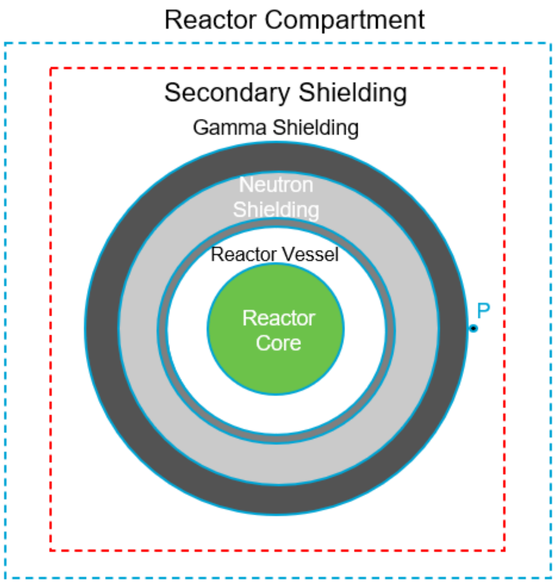

Figure 5.4: *Schematic of a spherical reactor core surrounded by a spherical shield*

The fully surrounding shield excludes any entrances for coolant pipes and fuel rods. Within the reactor vessel, no reflector or thermal shield is present. Any equipment normally present in the reactor compartment is not taken into account.
In the shielding model, the thickness of the shield is increased until the dose rate, measured in point P, is below the maximum exposure limit per year. For naval applications, this is the maximum exposure of radiation workers from table 5.1.

Because detailed radiation fluxes are unknown, the contribution of neutron and γ exposure is estimated to be 50% [2]. In point P, half of the maximum exposure limit is reserved for neutron exposure and the other half for γ radiation. The estimation might not be sufficient for all fast reactor designs with a higher energy spectrum.
The effect of secondary shielding is ignored and the reactor compartment could be entered safely during operation regarding neutron and γ exposure. Coolant activation is not within the scope of bulk shielding calculations. This model can estimate the size and weight of a preliminary (v)SMR shield as seen in figure 5.5 and 5.6. The calculation steps can be found in appendix F.

5.3.1. Neutron shielding

The neutron shield will either consist of high-temperature resistant concrete or borated polyethylene regarding the risk of high temperatures under accidental circumstances. Lamination of both materials would be more effective against neutron radiation, but this report does not consider optimising the shielding weight.

The fast neutron dose rate will be calculated at the shield's surface in point P, explained in appendix F. This calculation is an iterative process by adding shield thickness until half of the maximum exposure limit is reached.

Simplifications & limitations of removal-attenuation calculation

- The method typically works with a single energy group, neglecting variations in the energy spectrum of the radiation.
- The method focuses on estimating dose rates at specific points in space and does not provide a detailed spatial distribution.
- The accuracy of results depends on the quality and accuracy of the cross-section data.

- ALARA implementation is not possible leading to a conservative estimation. An iterative process is used to achieve safe dose rates outside the shield. However, modern tools calculate the expected dose for each crew member and make sure the shield meets, with the help of ALARA, the radiation criteria.

5.3.2. Gamma shielding

The gamma dose rate will be calculated at the shield's surface in point P, explained in appendix G. This model adds a layer of lead to the neutron shield against γ-ray exposure. First, the build-up flux of γ-rays at the shield surface needs to be determined. The concrete or polyethylene affects this flux and the absorption of neutrons leads to capture γ-rays production. The gamma calculation is executed with the attenuation and buildup factor theory, meaning that γ-rays will be categorised into energy level groups. The prompt fission γ-rays' spectrum rises sharply around $0.3meV$ and diminishes slowly around $7meV$ [29]. As can be seen in table G.1, the numbers emitted per fission can be placed in discrete energy intervals. After the contribution of all γ rays per energy group is known, the γ flux can be converted to an exposure rate.
Lead, with a halving distance of 1 cm, is added iteratively until half of the maximum exposure limit is reached.

Simplifications & limitations of removal-diffusion calculation

- The procedure involves grouping gamma rays into discrete energy intervals which do not fully capture all details. More groups could be used to increase the accuracy.
- It is assumed that γ-ray production comes into an equilibrium when operating. Rapid power changes and shutdown conditions are not evaluated.
- While the method allows for the calculation of capture γ-rays, it is seen as unattainable because this depends on the capturing nucleus. Unfortunately, the provided look-up table does not include all elements to model concrete and polyethylene [29]. Therefore, a full γ radiation analysis is impossible, and only prompt γ rays are considered.

To account for capture γ-rays, borated polyethylene is used. First, the polyethylene slows down neutrons and boron subsequently captures the thermalised neutrons.

5.3.3. Results

The material needed to shield against neutron and γ radiation has been expressed in weight over installed thermal reactor power in figures 5.5 and 5.6. Per maximum exposure limit, the shield using concrete or polyethylene has been plotted.
Data points on the shielding weight of commercial nuclear ships, marine concepts, and entire naval reactor compartments have been added to the figures. The reactor compartment of naval PWRs contains the activated structural components associated with specific class reactor vessel complexes, plant piping, and other miscellaneous parts [35]. While the plotted reference masses for naval PWR technology are the whole reactor compartments [36], an indication of the order of magnitude of shielding weight is seen. A study suggested that the Holos-Quad needed 70 cm of steel shielding during operation, resulting in 535 tonnes plotted in figure 5.5 [8]. A Holos-Quad shield containing $50/50$% steel and concrete of 165 cm required for full power operation was also found in literature [37].

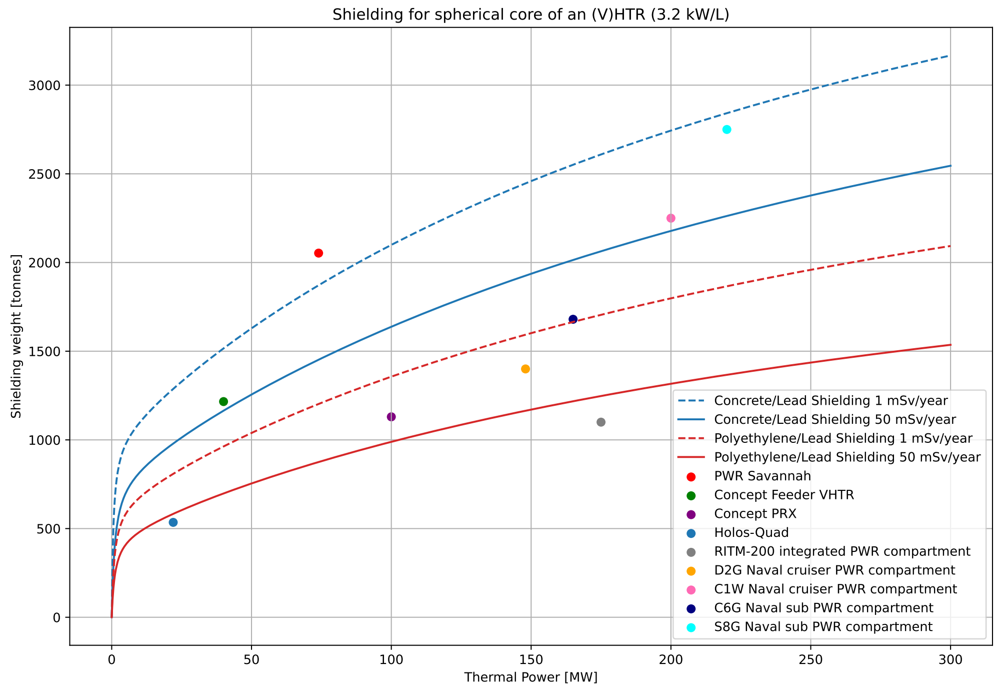

Figure 5.5: *Shielding weight over installed thermal power for a (V)HTR including reference designs*

The shielding weight varies enormously for the spherical shielding of a (V)HTR. The difference between a polyethylene and a concrete shield can quickly become $1,000$ tonnes for higher reactor outputs. The same difference is found when comparing the civilian with the radiation worker exposure limit. Apart from the first commercial nuclear-powered vessels, most data points are within the range of the shield model. While all naval PWR compartments are within the boundaries of the shield model, the Russian RITM integrated PWR compartment is below the lightest polyethylene shield result. Detailed shielding information has not been found.

In general, it is observed that shielding becomes relatively lighter for increased thermal power. According to figure 5.5, vSMRs with a thermal power up to $25MW_{th}$ require immediately a large amount of shielding.

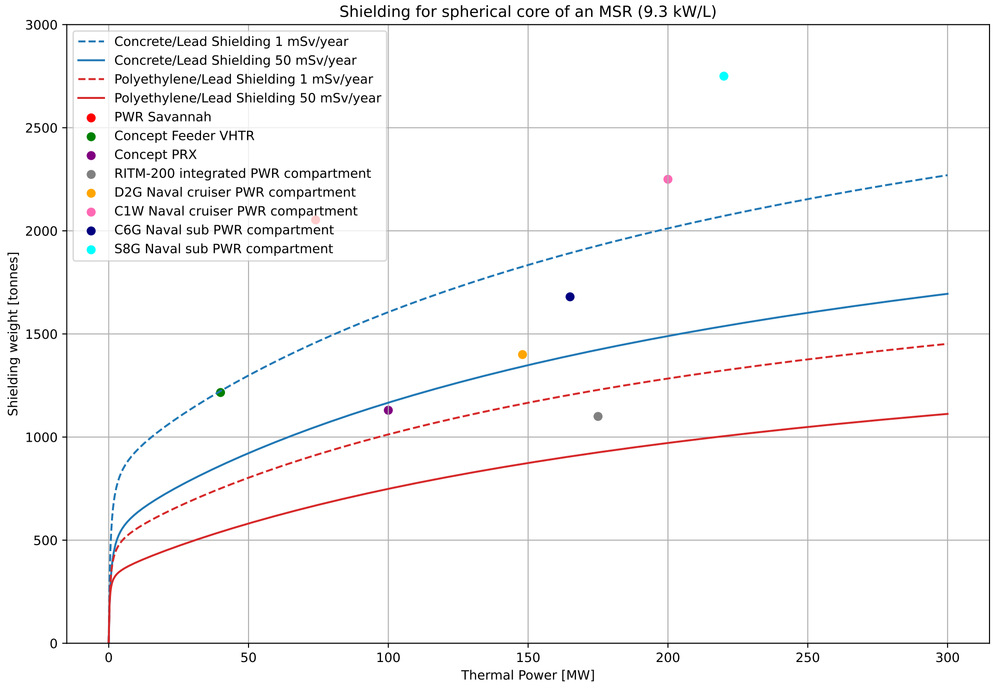

Figure 5.6: *Shielding weight over installed thermal power for an MSR including reference designs*

When the thermal power output increases, the spherical shield for an MSR varies less than for a (V)HTR. This behaviour is observed because the core density of MSRs is higher. This results in a smaller radius, decreasing the amount of required shielding. In practice, considering the radioactive coolant loop, the MSR will move closer to the required weights of (V)HTRs.

Still, MSRs have the potential to become lightweight reactor designs when compared with the available data points. Even the heaviest shielding configuration is lower than the S8G naval submarine compartment. The difference between concrete or polyethylene shielding is less than obtained with the (V)HTR. This is also found for the difference in applied exposure limit.

The shielding weight and size for the MSR and (V)HTR are given together in figure 5.7. Here, the maximum exposure limit of $50mSV$ is applied.

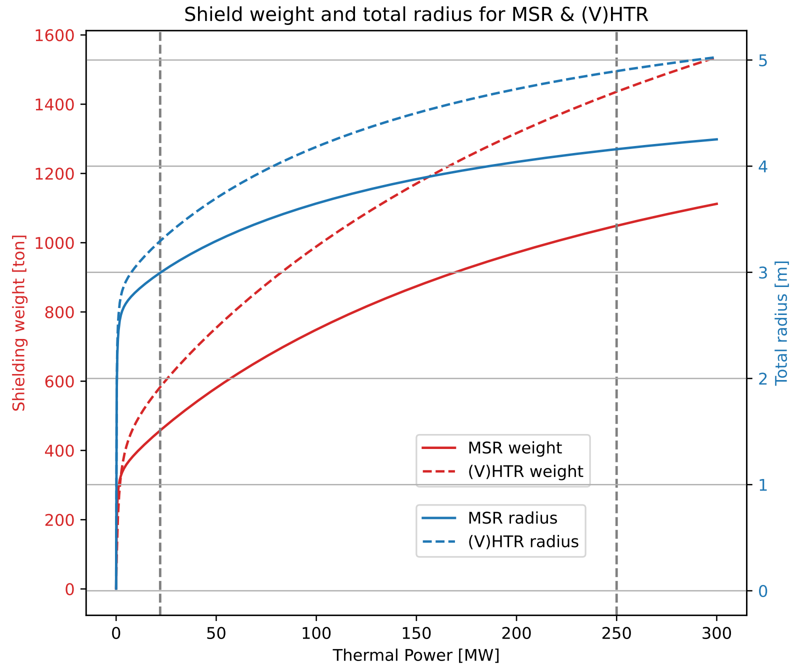

Figure 5.7: *Shielding weight and radius over installed thermal power for an MSR and (V)HTR*

In figure 5.7, it is seen that the weight increases gradually over thermal power output while the required radius at the beginning is instantaneous. The behaviour of the required radius is presented in appendix H. For both (v)SMRs, the size of the shield, including the core, is considerable. The vertical dotted lines represent the Holos-Quad and the CMSR.

5.4. Discussion

The stated *shielding materials study* can not be consulted to verify the weight plotted for the Holos-Quad found in the literature. Therefore, it is expected that the weight of the Holos-Quad is a bare minimum because lead against γ-radiation is not considered.

In practice, a shield design is obtained after many optimisation interactions. Many examples of Monte Carlo simulations and optimisation algorithms are used to reduce weight and volume. For the shield in the Savannah reactor, if current optimisation methods were used, the size and weight could be reduced by 31.0 and 9.0%, respectively [38]. The effect of using lamination of materials, such that the attenuation of neutrons and γ-rays proceed at the same rate through successive layers, the weight and size of the shield decreases [29].

5.5. Conclusion

This chapter outlines the preliminary design of the reactor compartment for a fourth-generation SMR and vSMR. It details the differences between SMR and vSMR reactor compartments. The reactor compartment contains the reactor and shielding with particular attention paid to ensuring radiation containment and minimising exposure to crew members through adequate shielding.
Shielding is crucial for protecting the crew from neutron and gamma-ray radiation. The ALARA principle has been used to prove that a maximum exposure limit of $50mSv$ can be used for naval applications. Water as coolant is considered unsuitable for fourth-generation (v)SMR primary shielding in naval applications due to the risk of leaking or vaporising.

The shielding model assumes the point kernel method with the removal-attenuation calculation to take neutrons into account and the attenuation with buildup factor calculation for γ -rays. For the neutron shield, high-temperature-resistant concrete or borated polyethylene has been proposed. The shielding of γ rays has been accomplished with lead. For both (v)SMRs, the polyethylene with lead configuration offered the lightest and most compact shield design. Due to their lower core density, the heaviest shielding is necessary for (V)HTRs. The results regarding shielding have been verified with relevant reactor shield designs and naval nuclear reactor compartments.
In conclusion, this chapter provides a comprehensive overview of the reactor compartment for SMR and vSMR applications in combatants, concentrating on the necessary shielding requirements.

6
Power generation

This chapter describes the preliminary design of power generation considering a fourth-generation SMR and vSMR. From the perspective of designing a combatant, this chapter provides valuable insights into the required systems. For the SMR, energy conversion takes place separately in the power generation compartment. This includes heat exchangers, turbines and generators, as shown in figure 5.1. All components are physically separated from the reactor compartment. This compartment can be divided into sub-compartments if redundancy and vulnerability studies are applied to the design.
For the vSMR, power generation occurs within the reactor compartment seen in figure 5.2. Differences with SMR power generation will be addressed in each section.

6.1. Closed Brayton cycle

A closed power conversion loop is preferred to reduce future surface combatants' signatures. Applying an open Brayton cycle, releasing the heat in the environment significantly increases the combatants' signatures and is not desired. The main drivers for the power generation system of a surface combatant are the size, weight and system autonomy. This has potentially an impact on the design of a nuclear-powered combatant. In this report, the closed Brayton cycle differs for the SMR and the vSMR and is separately addressed.

6.1.1. SMR cycle

This section will explain the indirect cycle configuration consisting of three closed cycles with their operating mediums, visualised in figure 6.1.

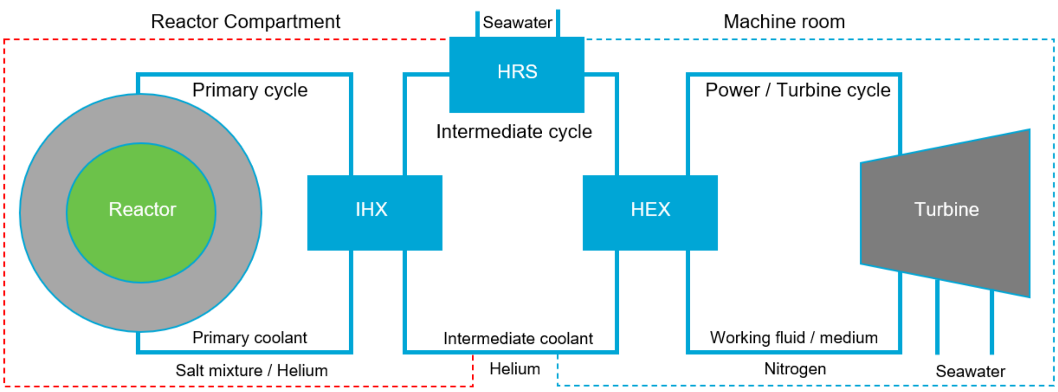

Figure 6.1: *Schematic of closed cycles and the operating mediums*

The primary cycle uses a primary coolant, a molten salt mixture for the MSR and the (V)HTR helium. The reactor fabricator or the nuclear engineer decides this. However, the use of an intermediate cycle

is a ship design choice. 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. As seen in table 2.1, the MSR and (V)HTR can not operate at low power ($P < 20\% P_{tot}$). The HRS is used to remove the heat directly from the reactor when the reactor is operating in low load ranges. This makes it possible to enter a harbour with low-demanded power. Heat dumping can also be used when the reactor needs to ramp down quickly. The HRS is not used for emergencies because the (v)SMR has its passive safety features [1].
The intermediate coolant is helium. The working medium operates in the power cycle, also called the turbine cycle. The ship designer can choose between different turbomachinery operating with other working mediums decided by a turbomachinery fabricator.

Cycle type

In general reactor designs, two types of cycles exist. The nuclear reactor can operate with a direct or indirect cycle. The primary coolant operates as the working medium with a direct cycle. While increasing efficiency, the direct cycle regarding safety concerns is not adopted for SMRs in this report. When installed in a surface combatant, the direct cycle would involve water ingress risks when it is located in his compartment. It is concluded that the direct cycle is promising for land-based SMR applications.

An indirect cycle uses at least a primary and a power cycle. An example of an indirect cycle is given in figure 6.1. Because surface combatants enter high-risk environments, the reactor compartment and the machine room must be separated. This reduces the risk of radioactivity contamination. This separation can only be obtained with an indirect cycle. Therefore, all surface combatants with an SMR should use an indirect cycle, reducing the overall efficiency but increasing safety.

Primary cycle

The primary reactor coolant is an important design choice for the reactor engineer. Historically, steam (water) has been used. Fourth-generation (v)SMRs also propose gas coolant or salt mixtures [4]. The fabricator of the (v)SMR states the primary reactor coolant. The CMSR adopts a salt mixture, and the (V)HTR uses a primary helium loop.

Intermediate cycle

The intermediate cycle is introduced for surface combatants for two reasons:

1. An intermediate cycle separates the reactor compartment and the machine room, ensuring that the radioactive primary coolant does not come into direct contact with the power generation components. This reduces the risk of activation and contamination of system components. Ideally, when a chemical stable and inert medium is used, no radioactive contamination in the machine room is possible when something occurs within the primary or intermediate cycle.
2. An intermediate cycle allows for shutting down the power cycle. When the power cycle is not operating, the HRS can remove the heat produced by the reactor in the intermediate cycle. This feature is especially needed when the nuclear reactor has a minimum load and the surface combatant wants to operate in lower load cases. It is noted that excessive heat removal by any heat removal system increases the signatures of the combatant by pumping detectable warm seawater overboard. This is assumed to be negligible compared to detectable heat from a traditional exhaust.

This report considers helium, nitrogen and super-critical CO_2 (sCO_2) as possible coolants for generation IV (v)SMR technology [1]. Helium is preferred as an intermediate coolant for naval SMRs for the following reasons:

1. Helium has low neutron absorption characteristics and low activation properties unlike steam, nitrogen or sCO_2. No activation management, strategies to control and mitigate the activation of materials within the reactor compartment, in the coolant cycle is necessary, resulting in higher system autonomy. The intermediate cycle enters the reactor compartment through the secondary shielding. An inert medium is essential when implementing an MSR because the radioactive primary cycle leaves the primary shielding. The intermediate cycle can be contaminated if not appropriately shielded by an accident.

2. Helium has excellent thermal conductivity, allowing efficient heat transfer.
3. Helium is chemically inert and non-corrosive. The coolant does not react with components, which results in less maintenance requirements, unlike steam and sCO_2.

System size can be reduced when using sCO_2. However, using helium in the intermediate cycle is expected to increase safety, reduce maintenance costs, increase system autonomy, and allow efficient heat transfer.

Power cycle

The heat transferred to the intermediate cycle heats the power cycle to drive a turbine system. The specific power cycle depends on the choice of working fluid. The power cycle for the SMR-powered combatant is a closed Brayton cycle using a gas instead of steam (water) as a working medium for the following reasons:

- Compact design, observed in part I, because of high power density due to high pressure, high temperatures, low density of working gases and low mass flow rates.
- Reduced regular maintenance requirements when using non-corrosive gases, increasing operational autonomy. Unexpected maintenance with closed-cycle turbines is complicated due to the necessity of a steel pressure vessel.
- Lower pressure operation compared to the (superheated) steam cycle, simplifying system components and reducing leakage risks.

While closed Brayton cycles with gas as a working medium can increase efficiency, chapter 7 gives examples of marine applications where comparable efficiencies are obtained with steam. It must be noted that the highest efficiencies with closed Brayton cycles are calculated for large power systems ($300MW_{th+}$). In the gas-turbine industry, it is known that when the system size reduces, the turbomachinery efficiency decreases, which results in the cycle net efficiency reduction [39]. The major reason for the turbomachinery efficiency reduction due to size is the increased losses which generate irreversibility in the turbomachinery [40]. Therefore, lower cycle efficiencies are expected for (v)SMRs compared to large land-based applications found in the literature.

The risk of steam ingress in the primary cycle and water chemistry management is handled by adding an intermediate cycle. Therefore, efficiency and increased safety by using gas as a working medium over steam (water) are invalid arguments.

In near-term applications where plant simplicity and TRL are important, a simple Rankine cycle without reheat is preferred and explained in further detail in appendix I.

Power cycle working medium

Several gases such as helium, nitrogen and sCO_2 can be used as a working medium [1]. When detailed characteristics of the SMR are known, thermodynamic analysis can conclude suitable operating mediums depending on coolant characteristics and the reactor outlet temperature [41].
At turbine inlet temperatures exceeding $700°C$, helium emerges as a superior option for the closed Brayton power cycle compared to air, nitrogen and sCO_2 [42].
Nitrogen can replace helium as an alternative working medium at turbine inlet temperatures ranging from approximately 500–$600°C$. It can also be utilised at extremely high turbine inlet temperatures of around $900°C$ instead of sCO_2 [42].
sCO_2 is a suitable working medium for a closed Brayton cycle utilising medium temperature heat sources in the 450–$700°C$ range.

Combined with the CMSR operating at $600 - 700°C$, which results in power cycle temperatures of around $600°C$, the most efficient and compact power conversion system with a relatively high TRL can be designed using nitrogen as a working medium. The benefits and drawbacks of sCO_2 and helium are addressed in appendix I.
Regarding thermal efficiency and compactness, applying the nitrogen cycle in surface combatants is the bridging technology to the sCO_2 cycle. Helium shows favourable characteristics when used at

higher temperatures of $700°C+$. Utilising a mixture of nitrogen and helium could benefit the power cycle. While the properties of gas mixtures are known [43], the application has been limited for space power applications where the power demand is relatively low. Because of the lower temperature range of current MSR concepts, naval applications implementing fourth-generation MSR technology should employ a nitrogen power cycle first. Turbomachinery manufacturers employing nitrogen, hydrogen, sCO_2 or any suitable gas mixture should validate this statement. .

6.1.2. vSMR cycle

The design driver for vSMRs is size. Therefore, many designs utilise a direct cycle, which reduces volume and weight due to exempting an IHX and integrating the HEX into the reactor core [44]. Because of their inertness, only gases such as helium or sCO_2 are used as a coolant and working medium for a direct cycle. The direct cycle of the vSMR derived from the Holos-Quad is visualised in figure 6.2.

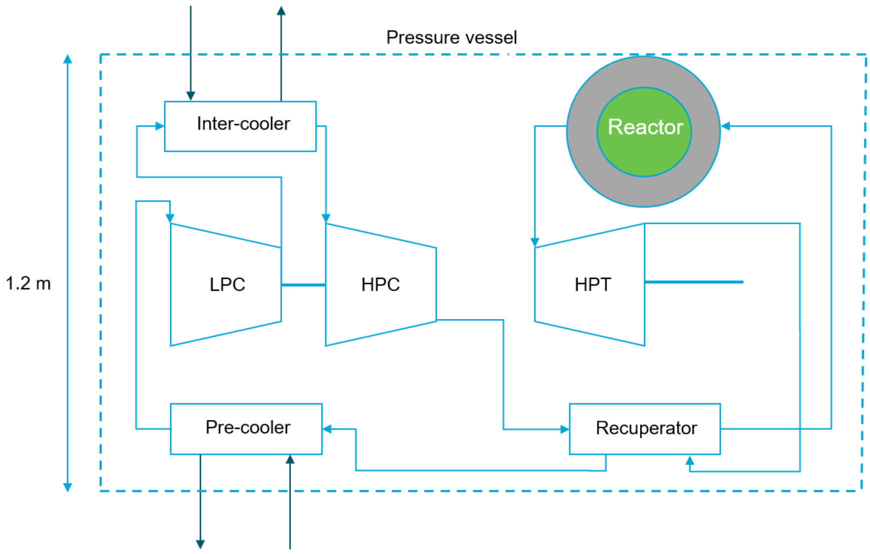

Figure 6.2: *Schematic of the vSMR direct closed Brayton cycle*

To eliminate risks such as radiation leakage and water ingress, the entire cycle is within the nuclear isolation boundary, limiting access. Therefore, the Holos-Quad core uses TRISO fuel and claims to implement multiple redundant and independent containment structures, pressure boundaries, radiation and neutron shields and ballistic shields [8]. This is why vSMRs are not likely to be refuelled in the combatant but instead removed as a whole.

The vSMR, based on the Holos Quad, uses helium as a coolant and working medium. Details of the design of the direct closed cycle of the Holos Quad are researched [8].

6.2. Heat exchanger

A heat exchanger is a heat transfer device that exchanges heat between two or more fluids [45]. The amount of heat exchangers required for a fourth-generation SMR is illustrated in figure 6.3. A vSMR lacks the intermediate cycle and the Heat Removal System (HRS).

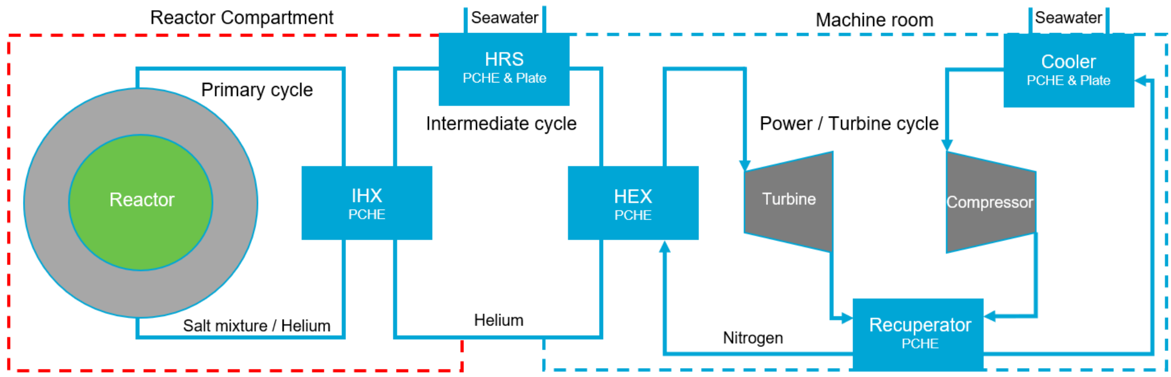

Figure 6.3: *Schematic of required heat exchangers*

The IHX transmits heat from the SMR to the intermediate cycle. When a salt mixture is used, the melting point of the coolant must be carefully monitored. The salt mixture solidifies if one of the flows is under the melting point. Therefore, relatively high temperatures $(400°C+)$ are required in the IHX for an MSR.

The HRS cools the heat the SMR generates when operating at minimal load. The HRS operates independently concerning the power cycle and cools the intermediate cycle with seawater. The HRS will be sized according to the primary cycle's minimal operational load, including an efficiency and redundancy factor.
The HEX transfer the heat to the power cycle. It operates with a high-temperature difference, benefitting the efficiency of the power Brayton power cycle.
The cooler is part of the gas turbine, between the turbine and the compressor. Depending on the number of stages within the turbomachinery, the cooler can be divided into a pre- and inter-cooler, visualised in figure J.1. In a closed Brayton cycle, most heat is rejected by the cooler.
To minimise the temperature difference in the HEX and to increase efficiency, a recuperator can be added to the power cycle. In closed Brayton cycles designed for fourth-generation (v)SMR technology, a recuperator is frequently found because of the increase in power density of the system [4]. The main challenge of recuperators is their size due to increased contact area. The reason for this effect is the low heat transfer rate between the considered gases compared to the working medium and other types of medium [40].

6.2.1. Heat exchanger type

Two types of heat exchangers are suitable for the required cooling capacity in propulsion systems [45]. Each type has several possible design layouts.

- Tubular type
  - Double pipe
  - Shell & tube
  - Helical coil
- Plate type
  - Plate & frame
    - Gasketed
    - Welded
  - Plate fin
  - Printed Circuit

The shell and tube heat exchanger is the most common type found in industry. They are suitable for high temperatures $(900°C+)$ and pressure $(30MPa+)$ in nuclear applications. The helical coil is suggested when compactness is important because of the similarities with the shell and tube type but with

an increased overall heat transfer coefficient U $[W/m^2 \cdot K]$ and a higher heat transfer surface area per unit volume expressed as the Compactness Factor (CF) [m^2/m^3]. Maintenance is more complicated due to the coil within the shell.
The helical coil has been proposed for SMR technology due to its reliability and wide application in temperature and pressure [46].
The Printed Circuit Heat Exchanger (PCHE) is a compact heat exchanger type made by diffusion-bonded plate stacking. PCHEs are typically built from stainless steel and can operate from cryogenic to high temperatures ($900°C+$) and pressures up to 60 MPa. Meanwhile, PCHEs (0.2 tonnes/MW) can be four to six times smaller and lighter than conventional designs like the shell and tube type (13.5 tonnes/MW) depending on the used materials and working fluids [45]. Typically used in offshore applications, PCHEs are mentioned for generation IV SMR systems but so far not implemented in the ASME Nuclear code [47].
A plate-fin heat exchanger is proposed for the IHX of the MSR because of the required material properties of the corrosive salt in the primary cycle and low operational pressure [48]. The alloy Hastelloy is often suggested as a material that can handle high pressure, high temperatures, and corrosive fluids to a certain degree. Diffusion-bonded methods used for the PCHE are questionable and in development, which could be avoided using the plate-fin type.

6.2.2. Methods of heat exchanger model

The heat transfer area must be calculated to estimate the required heat exchanger size. First, the heat transfer rate must hold equation 6.1.

$$Q = U \cdot A \cdot \delta T_m \tag{6.1}$$

Where:

Q: heat transfer rate
U: overall heat transfer coefficient
A: heat transfer area
δT_m: average (mean) temperature difference of two fluids

Secondly, derived from the first law of thermodynamics, Q must comply with the hot and cold fluid streams described with conservation equation 6.2.

$$Q = \dot{m}_{\mathrm{h}} c_{\mathrm{p,h}} \left(T_{\mathrm{h,i}} - T_{\mathrm{h,o}}\right) = \dot{m}_{\mathrm{c}} c_{\mathrm{p,c}} \left(T_{\mathrm{c,o}} - T_{\mathrm{c,i}}\right) \tag{6.2}$$

Where:

$\dot{m}_{\mathrm{i}}$: mass flow (hot or cold fluid)
$c_{\mathrm{p,i}}$: specific heat constant (hot or cold fluid)
$T_{h,i}$: Temperature hot fluid ingoing
$T_{h,o}$: Temperature hot fluid outgoing
$T_{c,i}$: Temperature cold fluid ingoing
$T_{c,o}$: Temperature cold fluid outgoing

Specific heat constants depend on the temperature and the pressure of the fluid.

Overall heat transfer coefficient

To size a heat exchanger properly, both U and δT_m are necessary to model correctly and in an iterative process. Determining the value of U is thus mainly a function of the exact physical geometries and flow directions and velocities in the heat exchanger [49]. The coefficient U for heat exchangers with equal heat transfer areas is determined with equation K.3.

$$\frac{1}{U} = \frac{1}{h_h} + \frac{t}{k} + \frac{1}{h_c} \tag{6.3}$$

Where:

h_h: convection heat transfer coefficient hot fluid
h_c: convection heat transfer coefficient cold fluid
t: plate thickness
k: thermal conductivity

The higher these coefficients, the higher U will become, resulting in easier heat transfer. Estimating the correct convection heat transfer coefficients at the heat transfer surface is challenging because it depends on the flow type, explained in further detail in appendix K.
Based on previous work, this report will estimate the CF and U. In table 6.1, these parameters are given for He and $N2$.

Table 6.1: *Overal heat transfer coefficient U and compactness factor CF for different heat exchangers and working mediums*

He environment [50]	Shell & Tube (He/He)	Helical coil (He/He)	PCHE (He/He)	
$\mathrm{U(W/m2 \cdot\ K)}$	475	1200	2300	
$\mathrm{CF(m2/m3)}$	75	80	1100	
N2 environment [51]	PCHE (Na/N2)	Recuperator (N2/N2)	Pre-cooler (N2/N2)	Inter-cooler (N2/N2)
$\mathrm{U(W/m2 \cdot\ K)}$	2500	500	1000	1040
$\mathrm{CF(m2/m3)}$	715	1000	715	715

It can be seen that the PCHE, both in the helium and nitrogen environment, have higher values for CF and U compared to the tubular-type exchangers. Both parameters depend on the medium used in the heat exchanger and must be examined carefully before applying sizing methods.

Mean temperature difference

Determining δT_m is complicated because the matter can be described with various temperature distributions following different heat exchanger arrangements. The following models can be used.

- Simplified analytical model [49]
  - LMTD method
  - ϵ-NTU & P-NTU method
- Nodalised analytical model
  - KAIST-HXD algorithm [40] [51]
  - HX solver [52] [44]
- CFD

A nodalised model like the KAIST algorithm or the HX solver does not only estimate δT_m but can iteratively size the core of the heat exchanger including pressure loss optimisation [40]. Nodalised and CFD models cannot be applied without a mechanical design involving the channels' number, diameter, and length within a heat exchanger. Therefore, the simplified LMTD method, assuming a counter-flow arrangement, is applied to obtain a preliminary design of the minimal size of the required volume and weight for the heat exchangers. The efficiency of the IHX and HEX is assumed to be 0.95.

Simplifications & limitations of LMTD method

- Only the core of the heat exchanger is examined, no inlet ducts and other structural components
- Pressure drop within the heat exchanger is neglected
- Only conduction of heat is considered, radiation is not taken into account
- No heat transfer between the fluid streams and the outside environment

- No leakage between the fluid streams and the outside environment
- No heat conduction along the length of the heat transfer area A
- Fluid flows are equally distributed
- Fluid properties are considered constant

These assumptions result in a model without losses found in practice and a constant value for U throughout the heat exchanger. Pressure drops are not considered because such analyses require a concept geometry. The values for the SF and U are assumed from table 6.1 to calculate A resulting in the volume of the heat exchanger. The acquired size is the core of the heat exchanger without considering fabrication standards. In practice, the heat exchanger system will be larger and heavier because of the casing and necessary connection pipes.

6.2.3. Heat exchanger size model

The size model finds the required volume to transfer all heat from the reactor to the power cycle. In general, figure 6.3 is applicable, detailed values with all components can be found in appendix K. Several assumptions have been made:

- All heat exchangers are modelled according to PCHE type properties except a part of the coolers (HRS, pre- and inter-cooler). PCHE heat exchangers can not be used with seawater because the coolant needs to be extremely clean due to blockage of the fine channels by impurities [45]. The helical type is suggested to handle seawater impurities in combination with the high pressure of the gases [53]. However, size reduction is found when applying a two-stage heat exchanger. In the two-stage heat exchanger, the gas medium is cooled with a closed (pure) water loop connected to a plate-type heat exchanger capable of using seawater as coolant, see figures K.1 and K.2.
- Inlet and outlet temperatures are fixed, see appendix K. The temperatures are estimated after evaluating a concept marine helium gas turbine suitable for naval application[54].
- All specific heat transfer coefficients have been estimated according to the used medium and related temperature.
- Pressure drop (losses) between heat exchangers, pipes, valves and other components are neglected. After a preliminary geometry has been designed, the heat transfer area is expected to increase when evaluated with pressure drops.
- Required pipe diameter concerning bulk fluid velocity has not been evaluated. Flow requirements regarding the size of heat transport systems for different mediums can be found in literature [55]. It is expected that efficiency can be increased when the mass flow is observed [44].

The listed assumptions result in a minimal core size of the required heat exchangers. The use of the PCHE type has not been established in reactor technology because it is not included in ASME Nuclear code [47]. Seawater-capable plate heat exchangers exist, but the mass flows should be evaluated before application [56].

6.2.4. Result

The required heat exchanger volume and weight to cool the (v)SMR plant is given in figure 6.4.

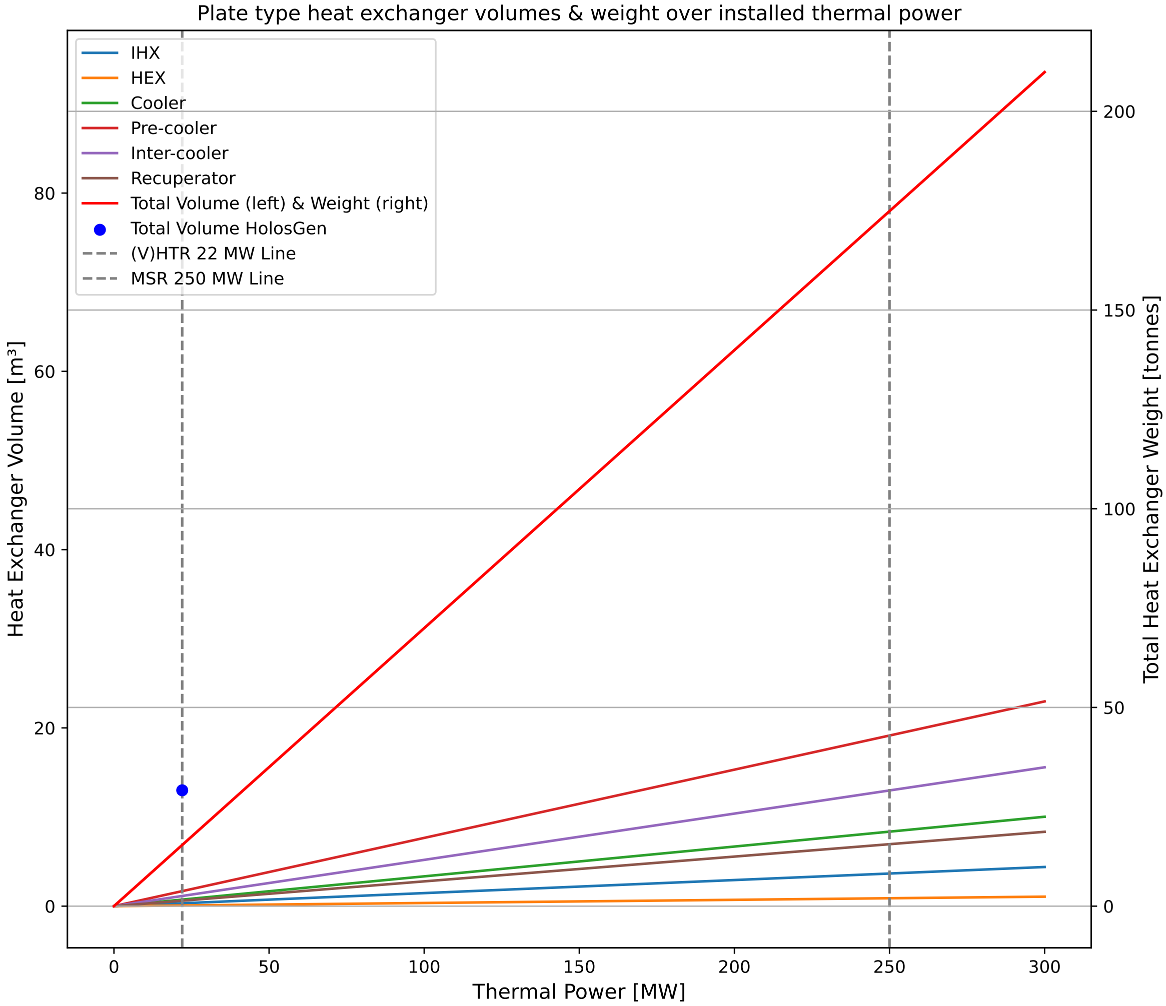

Figure 6.4: *Heat exchanger volume (left) and weight (right)*

In figure 6.4 the relation between heat exchanger volume and weight is directly seen. The pre-cooler requires the most volume. The volume of the Holos-Quad has been estimated from the detailed design and is higher than the predicted volume by the model [8]. Due to neglecting pressure loss over the heat exchanger, the model estimates smaller heat exchangers for lower thermal power levels than feasible.

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6.3. Turbine

Turbines refer to the turbomachinery needed to convert nuclear heat into rational or electric power. In this research, the turbine includes the compressor and turbine stages. In a closed Brayton cycle lacking a combustion stage, the multi-shaft turbomachine, including the compressor and expander stages, can be called a compander [44]. To prevent confusion, this research uses the term turbine to address all turbomachinery involved.

Turbomachinery design is very complicated since design parameters are coupled to each other or influenced by various physical boundaries such as rotor stability, cooling flow path and minimising external losses [40]. Thermodynamic cycle calculations highly depend on detailed specifications such as shaft power, mass flow, inlet temperature, pressure ratio and polytropic efficiencies. However, going into a detailed turbomachinery design process is not within the scope of this thesis.

Preliminary turbomachinery designs are mainly based on the similarity concept [51] [40]. The size

of a preliminary turbine engine can be estimated using the specific speed and the specific diameter. However, system size in volume and weight requires an extensive analysis [57].
Without extensively analysing turbomachinery, the impact on the combatant's design can be found by evaluating existing systems. This approach has been used for a nuclear-powered dredger [47].

6.3.1. SMR turbine

Marine closed Brayton turbine systems employing nitrogen are limited apart from steam engines.
For this research, it is chosen to implement the properties of a helium-driven closed-cycle turbine for marine propulsion developed by Westinghouse Electric Corp for the US Navy [54]. The design philosophy is that employing helium will meet or exceed the requirements imposed by nitrogen on turbomachinery. In other words, the power cycle is a conservative estimation demonstrating the potential of a closed Brayton cycle. Figure 6.5 presents the turbine in detail.

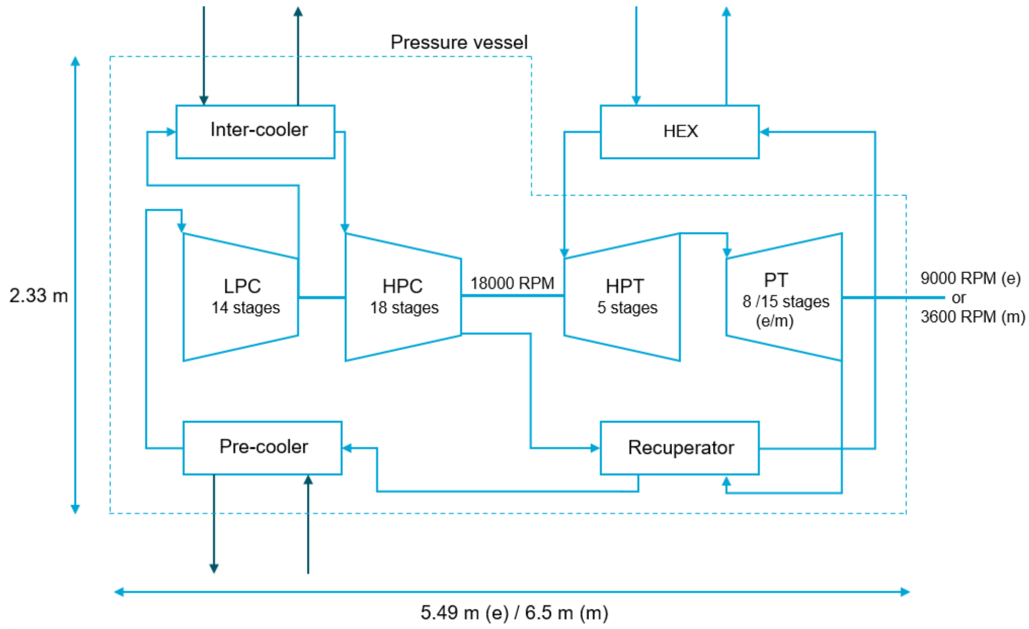


Figure 6.5: *Schematic of the helium power cycle of a marine turbine delivering* $52.2MW$ *mechanical (m) or electric (e) power inspired by [54]*

This compact closed-cycle gas turbine for naval propulsion has never been implemented due to the low inlet temperature of PWR technology. It generates $52.5MW$ with $30°C$ sea water temperature with a specific weight of $0.79kg/kW$ (41 ton). In comparison, a marine steam turbine with a rated power of $44 - 50MW$ weighs 370 ton ($7.4kg/kW$) [58]. The volume of the turbine system is derived from the dimensions in figure 6.5.

Inspired by aero-derivative turbines, the whole turbomachinery rotating assembly can be exposed for inspection and maintenance. The compact turbine reaches a maximum efficiency of 37% with $30°C$ seawater which can be observed in figure J.1.
This plant efficiency will be lower when integrated with the CMSR and coupled with the intermediate cycle due to lower operating temperatures and heat exchanger losses. The heat exchangers are arranged around the turbomachinery and accommodated inside an enveloping pressure vessel forming a power conversion assembly module.

6.3.2. vSMR turbine

Turbine sizing calculations for the Holos-Quad are not provided. It is known that smaller turbines have increased losses due to irreversibilities in the turbomachinery [40]. To overcome this, it is expected that the volume of compressor and turbine stages needs to be higher than scaled with the Westinghouse turbine.

6.4. Electrical machines

The primary electrical machines are used for power generation as generators and power conversion as EPMs. Because the generator and the EPM have the same working principle, both are covered in this section. The results for the generator are given in this chapter and the results for the EPM are in section 7.2. Electrical machines are not sized differently for SMR or vSMR systems.

6.4.1. Electrical machine size model

Determining the dimensions of an electrical machine poses significant challenges. While certain physical principles and limitations influence specific dimensions, designers still have considerable freedom in deciding them. The size and weight can be estimated in three ways:

- Data analysis, using manufacturer information.
- Empirical relations, from the Integrated Energy Systems software tool (GES) developed by TNO [59].
- Analytical model, using theoretical background [60] in combination with available data [61].

Specific data from manufacturers is not sufficient for a ship designer. From analysis, it is concluded that the empirical relations do not represent current electrical machines, especially at higher power outputs [61]. Moreover, future electrical machines when (v)SMR technology is operational are even harder to represent. Therefore, an analytical estimation will be made with the model based on previous work [60] [61].

Simplifications

- Assumption of ratios like machine length over diameter and rotor over stator volume are based on manufacturer data.
- Fixed value for the cooling volume factor is assumed, overlooking the potential variability in cooling methods and their impact on machine dimensions.
- The limitation of publicly available input data decreases the reliability of the parameter estimations.

6.4.2. Size & weight

To estimate the size and weight of future naval EPM and generators, the calculation will only include modern electrical technologies from AIM, PM and HTS machines to estimate relevant parameters. The detailed model containing all electrical machines can be found in literature [61].

The rotational speed in RPM and torque are the primary factors in determining the dimensions of an electrical machine, crucial for calculating the power of the machine in equation 6.4 [9].

$$P = T \cdot 2\pi \cdot \frac{n}{60} \tag{6.4}$$

Where:

P: Power
T: Torque
n: rotational speed

The relation between the weight in tonnes of the electrical machine and the required torque is given in equation 6.5 and based on previous work [61] [59].

$$W = \left(27.2 \cdot T^{-0.43}\right) \cdot T \tag{6.5}$$

Where:

W: Weight

The method to determine the volume, length, diameter (width) and height are addressed in appendix L.

For this analysis, it is assumed that generators and EPMs have different rotational speeds. In practice, the used turbine determines the design of the generator. Because of the well-developed gas turbine generator sets, 3600 RPM is a common rotational speed for naval generators [62]. The EPM will be described in section 7.2.

6.4.3. Result

Figure 6.6 gives the volume and weight of a generator with a shaft speed of 3600 RPM. Data to verify the results has been added. The Permanent Magnet (PM) generators have been researched for future all-electric destroyers [63] [64]. The generator (General Electric) for the gas turbine MT30 (Rolls Royce) is taken from IPS system research [65] [13].

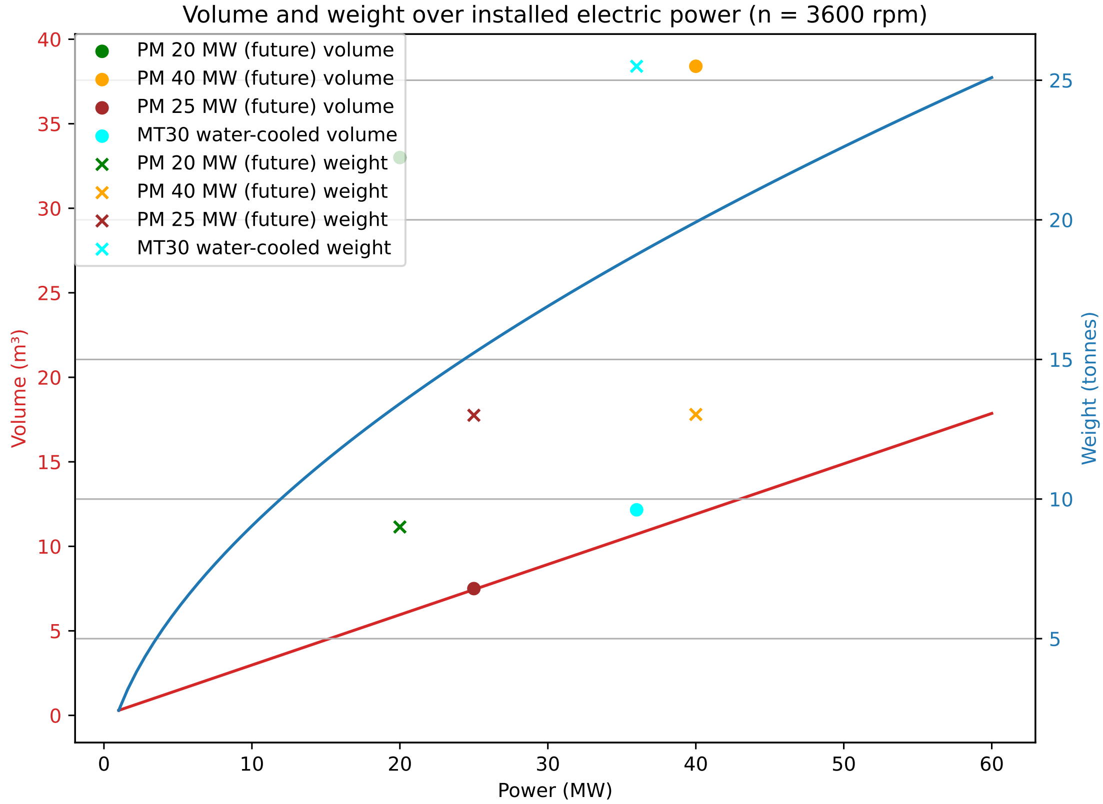


Figure 6.6: *Size and weight of naval generator with a shaft speed of 3600 RPM*

In figure 6.6, it can be seen that the specific weight of naval generators decreases over increasing power. The only existing naval generator with a rotational speed of 3600 RPM, the alternator for the MT30, is heavier than the model. The skid frame, required for shock resistance, is expected to be a significant part of this increased weight and is hard to estimate without extensive analysis. The data from PM generators tend to be lighter than the model. Overall, the model estimates the weight of a future EPM in line with other research studying future applications. Adding more data points for verification is challenging because these specific naval generators are not widely used due to the lack of large electrical power demand in conventional combatants.
When volume data is compared with the model, deviations are found. A volume margin should be kept to allow for the installation of the generator.

6.5. Conclusion

This chapter outlines the preliminary design of a power generation system for a fourth-generation SMR and vSMR. Power generation for the SMR is performed with the indirect closed Brayton cycle. An intermediate cycle with helium is employed while the power cycle uses a nitrogen working gas. The vSMR uses, due to its compactness, a direct cycle with helium.

A heat exchanger model using the LMTD method has been made to estimate the required volume and weight for cooling the (v)SMR power plant. Because a closed Brayton cycle is used, the size becomes significant. PCHE and plate heat exchangers are used to obtain a compact design.

The preliminary design of a naval helium closed-cycle turbine has been used in the heat exchanger model and for the specific weight and volume. The chapter concludes with electrical machines under which generators, including an analytical model for estimating their size and weight based on power output and rotational speed. The results could be verified with corresponding research despite deviating from the current generator data.

In conclusion, this chapter provides a comprehensive overview of the reactor compartment and power generation system for SMR and vSMR applications in combatants, including the necessary engineering considerations.

7

Power distribution & conversion

Power needs to be distributed throughout the combatant. Ultimately, energy is converted into propulsion or SEWACO and hotel load. Coloured red in figure 7.1, power generation components are covered in chapter 6. In green, the power distribution includes switchboards, circuit breakers, converters and ESS. Power conversion is required for propulsion and involves EPMs. Figure 7.1 shows that regardless of conventional or nuclear power, power distribution and conversion remain the same when chosen for an IPS.

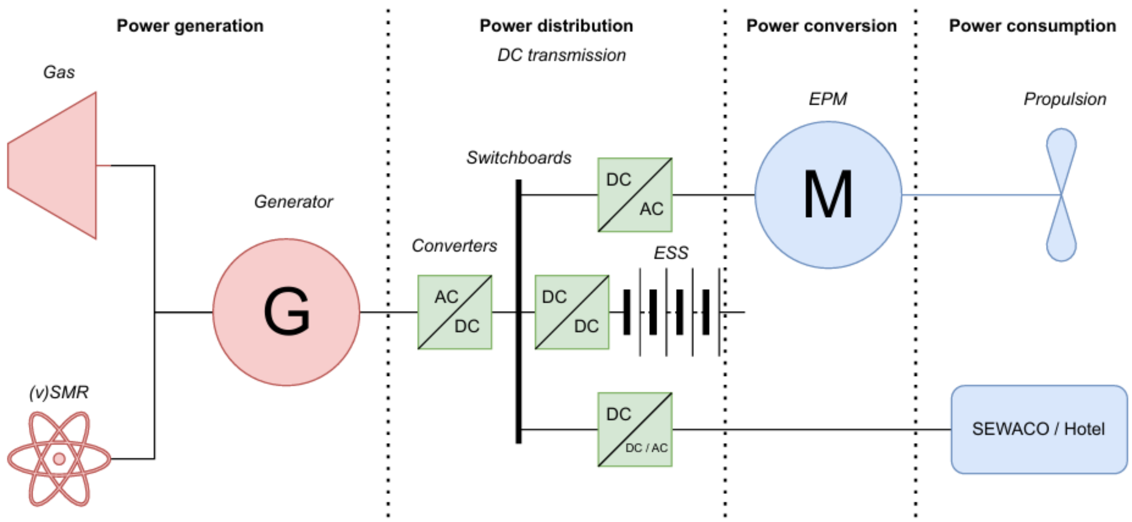


Figure 7.1: *Schematic power train for conventional (gas) or nuclear (SMR) technology*

Using internal combustion, conventional power generation on a surface combatant is done with Gas Turbine Systems (GTS). Combatants using (v)SMR technology have closed-cycle turbines to convert the nuclear heat to power. Regardless of a GTS or (v)SMR-powered combatant, the power train in this report is unaffected, as shown in figure 7.1.

7.1. Power distribution

The IPS power distribution configuration has been introduced in chapter 4.3. The high expected power and pulse loads present a significant challenge for the power distribution design. Due to the high power capacity, the electric power distribution system needs to comply with:

- High voltage ($V > 1kV$ for marine applications), meaning low current ($P = V \cdot I$), resulting in:
  - lower power losses ($P_{loss} = I^2 \cdot R$)
  - reduction in the size of generators, motors and circuit breakers
  - higher insulation requirements and the necessity for strict adherence to stringent safety procedures
- Supplying high levels of DC for SEWACO systems and ESS

A zonal distribution network with a ring-bus architecture could improve the system survivability from single-point failure [66] [67]. A simplified block diagram of the distribution system is shown in figure 7.2. The zonal distribution network is the baseline for the future surface combatant and does not change when alternative power generation or transmission systems are included.

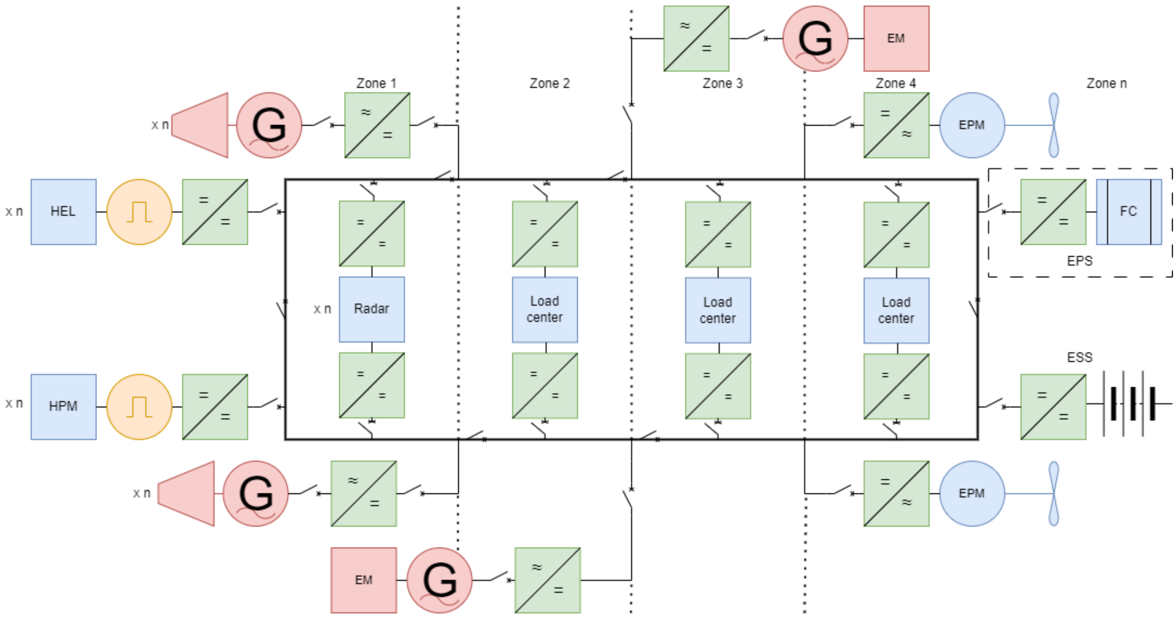


Figure 7.2: *Main power distribution system for a future surface combatant using IPS*

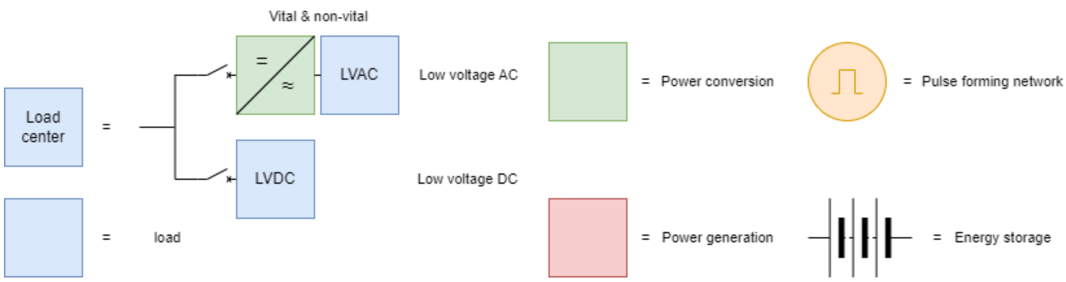


Figure 7.3: *Legenda for figure 7.2*

Regardless of being part of a closed Brayton cycle or conventional combustion design, gas turbines deliver power to a generator G. Emergency power is delivered with diesel generators, EM. The load centre delivers AC or DC to auxiliary equipment. Pulse-forming networks are outside the scope of this thesis. Energy Production Systems (EPS) can be connected to the grid. In further research, fuel cells or battolysers, as mentioned in the literature, could be implemented [1]. Depending on the combatant and using one SMR or multiple vSMRs, the number of zones, turbines, and NDE weapons can be differentiated and addressed with n. The ring-bus architecture only functions when at least one turbine and emergency generator (EM) are connected to the port and starboard of the bus.

Traditionally, a radial distribution with AC power systems is used. It is expected that a considerable amount of energy storage buffering is required to ensure the power system remains both statically and dynamically stable [68]. Therefore, the given requirements make DC power systems attractive for future applications. A Medium Voltage DC (MVDC) system, $V > 1kV$, is proposed to increase the power density of the electric distribution [67] [69] [70]. DC systems have many practical, operational and safety advantages over those based on AC:

- Using an active rectifier combined with proper control systems, the speed of the turbine is independent of the power quality delivered to the bus. This allows the generator to be tailored for optimal performance without integrating either reduction gears or speed-increasing gears [68].
- Efficient integration of energy storage systems because the need for conversion systems is reduced.
- As many NDE weapons and propulsion technologies fundamentally operate on DC, using a DC system reduces the need for AC-DC conversion, minimising power losses and improving integrability.
- DC systems can be simpler and more compact due to operation at higher frequencies, needing fewer components required for power conversion and the lack of frequency synchronisation. According to manufacturer ABB, a weight and volume reduction up to 30% compared to AC systems can be realised [71].
- The DC system can recover faster since generators and motors might not require synchronisation.

Detailed analysis of DC systems is not performed but found in literature [68] [72]. MVDC voltage levels greater than $6kV$ are proposed to minimise the cabling size for future combatants.

A significant drawback of MVDC (Medium Voltage Direct Current) systems is the lack of available components. In the maritime sector, components such as breakers, DC-DC converters, AC-DC converters, and DC-AC inverters are available up to a maximum of 1.5 kV as with the German F126 frigates [71]. Consequently, the demand for MVDC components is too limited to justify development and estimate system size [73].

7.1.1. Switchboard

Electric power distribution is managed through a switchboard, connecting multiple electrical power courses and users. In a ring-bus configuration, the switchboards are strategically placed throughout the surface combatant to form a ring. Each switchboard is connected to neighbouring switchboards through electrical cables or busbars, creating multiple paths for power distribution.
Each source or user connected to the switchboard is called a field, n_f, each equipped with its switch to direct electric power. Only main switchboards, as presented in figure 7.2, are considered. Additionally, the analysis includes the low-voltage distribution within load centres. The dimensions in meters and weight in kilogram of AC switchboards can be estimated with formulas 7.1 and 7.2 [61].

$$\text{For } V < 1 \text{ kV:} \quad \begin{cases} \text{Width} & = 0.65 \cdot (n_{f,in} + \frac{1}{4} \cdot n_{f,out}) \\ \text{Depth} & = 1 \\ \text{Height} & = 2.2 \\ \text{Weight} & = 500 \cdot n_{f,in} + 450 \cdot \frac{1}{4} \cdot n_{f,out} \end{cases} \tag{7.1}$$

$$\text{For } V > 1 \text{ kV:} \quad \begin{cases} \text{Width} & = 0.65 \cdot n_f \\ \text{Depth} & = 1.7 \\ \text{Height} & = 2.6 \\ \text{Weight} & = 1000 \cdot n_f \end{cases} \tag{7.2}$$

The size and weight of the low and high-voltage switchboards are estimated by determining n_f, $n_{f,in}$ and $n_{f,out}$ with figure 7.2. DC switchboards are generally smaller, lighter, and more straightforward in component architecture than AC switchboards. The equations 7.1 and 7.2 serve as a conservative estimation because DC switchboards will become more compact [71].

7.1.2. Converter

Power conversion elements contribute substantially to the size and weight of electric power distribution systems when designing a surface combatant. From figure 7.2 can be shown that the following converters are required:

- Rectification of power generation for DC distribution
- DC-DC converters to step down the primary distribution voltage into the zones
- DC-DC converters for large loads as SEWACO and ESS
- Variable speed drives for the EPM
- Inverters for in-zone AC loads

No manufacturer data for converters in an MVDC distribution system exists. A preliminary estimation regarding the size and weight of these converters has been based on previous work and given in appendix M [13].

7.1.3. ESS model

Requirements regarding ESS have been explained in chapter 4.2.2. The load P_{pulse} will be taken from the operational profile from appendix F. The pulse load, defined in equation 7.3, can be considered as the total power demand P_{tot} or by only implementing the SEWACO load from appendix A. The ESS capacity will be sized based on equation 7.3.

$$P_{pulse} = P_{SEWACO} \vee P_{tot} \tag{7.3}$$

The ESS model loads the operational profile. The provided power by the (v)SMR power plant is calculated with the ramp rate for ESS given in equation 7.4.

$$a_{ramp,ESS} = \frac{P_{th} \cdot \eta}{f_{ESS}} \cdot f_{ramp} \tag{7.4}$$

Where:

$a_{ramp,ESS}$: ramp rate $[MW/min]$
P_{th}: thermal reactor power $[MW]$
η: reactor efficiency $[-]$
f_{ESS}: available power factor for ESS $[-]$, assumed 0.1 for SEWACO and 1 for P_{tot}
f_{ramp}: ramp rate factor $[\frac{\%}{min}]$, 5 for SMR and 10 for vSMR according table 2.1

For every timestep, the provided power is given with equation 7.4 for each reactor type by providing thermal power, the ramp rate and the fraction of available power for ESS. The required energy storage is calculated with formulas 4.6 and 4.7. Finally, after integrating the power surplus or deficit, the ESS capacity is determined with equation 7.5.

$$ESS = \frac{\max(E)}{\eta_b \cdot EoL} \tag{7.5}$$

Where:

ESS: energy capacity $[MWh]$
η_b: battery efficiency $[-]$, assumed 0.99 [21]
EoL: end of lifetime factor $[-]$, assumed 0.8

Result

The pulse load equal to SEWACO, P_{SEWACO}, and the delivered power are visualised in figure 7.4 when analysing the given operational profile from appendix N. By integrating the surplus or deficit, the required ESS capacity over time is shown in figure 7.5.

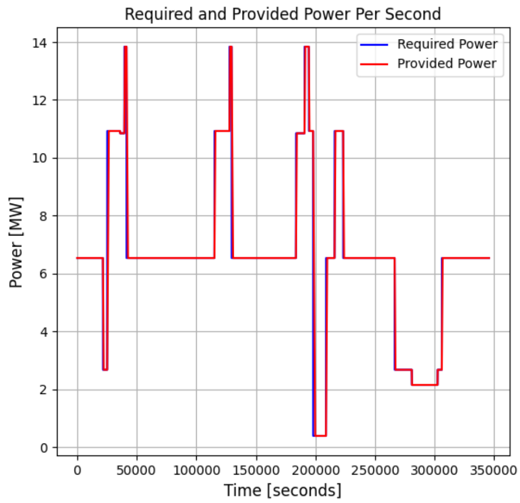


Figure 7.4: *Required and provided power ($P_{th} = 230MW$, $f_{ramp} = 5$ and $f_{ESS} = 0.1$)*

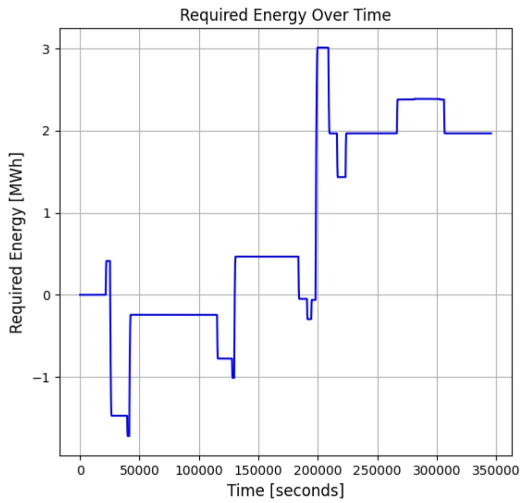


Figure 7.5: *Required ESS capacity ($P_{th} = 230MW$, $f_{ramp} = 5$ and $f_{ESS} = 0.1$)*

Depending on the absolute difference in power, a high C-rate is required, influencing the size and weight of the battery compartment seen in table 4.1. The SMR power plant modelled for figures 7.4 and 7.5 with a C-rate of 3 would require $28.3\ m^3$ and 29.1 tonnes. ESS capacity's required volume and weight heavily depend on the operational profile and reactor settings.

When the pulse load is equal to the total load, P_{tot}, the required ESS capacity for two examples of (v)SMR technology is given in figure 7.6 and 7.7.

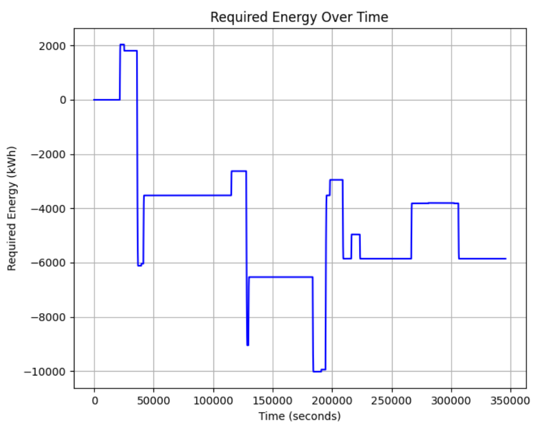


Figure 7.6: *Required and provided power for P_{tot} ($P_{th} = 230MW$ and $f_{ramp} = 5$)*

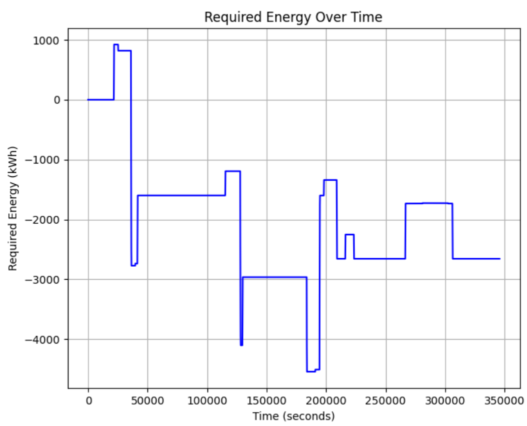


Figure 7.7: *Required ESS capacity for P_{tot} ($8 \cdot P_e = 10MW$ and $f_{ramp} = 10$)*

For the operational profile in appendix N, including the propulsion load per mission state, the example SMR requires 10 MWh and 8 vSMRs 4.5 MWh. It could be argued that when mobility performance, expressed in acceleration, needs to be improved, the vSMR offers a lighter ESS system. However, figure 7.9 needs to be evaluated first after implementing the required power for the total power demand in figure 7.8.

Figure 7.8: *Required and provided power for P_{tot} ($8 \cdot P_e = 10MW$ and $f_{ramp} = 10$)*

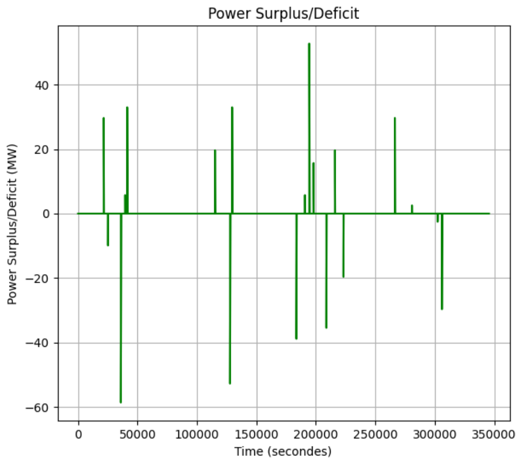


Figure 7.9: *Power surplus/deficit for P_{tot} ($8 \cdot P_e = 10MW$ and $f_{ramp} = 10$)*

The power peaks for SEWACO load are within the capabilities of the defined ESS. When including the propulsion load for ESS sizing, enormous power surplus/deficit peaks are observed in figure 7.9. The required calculated capacity considers the needed energy over time, independent of the observed peaks in power shortage. The vSMR power plant requires a C-rate of 12 to maintain the peaks with a capacity of 4.8 MW. An ESS with a higher C-rate than proposed in table 4.1 is required, or the capacity needs to increase. When sizing the ESS capacity using P_{tot}, the power surplus/deficit peaks are dominated by the propulsion load, resulting in the ESS sizing being independent of the ramp rates of SMR or vSMR power plants.

By evaluating the impact of including the propulsion load on the ESS capacity and the SEWACO load from appendix A, it is concluded that power peaks induced by the propulsion power demand, for example figure 7.9, dominate the ESS capacity. Technology with higher C-rates, such as supercapacitors, could also be a solution but is not covered in this thesis.
Therefore, when scaling ESS capacity for future surface combatants in this thesis, the SEWACO load will be prioritised over the propulsion load.

7.2. Power conversion

Electrical machines can convert power. The Electrical Propulsion Motor (EPM) is modelled in section 6.4. The EPM differs in rotational speed from a generator. For large surface combatants, the propeller's diameter is proportional to the efficiency. However, a larger diameter equates to a higher drag. Increasing the diameter increases thrust and torque load, indicating a low rotational speed [74]. Since large surface combatants tend to operate between 100 and 200 RPM, this analysis assumes a shaft speed of 150 RPM for future EPMs [75]. This shaft speed must be obtained regardless of geared or gearless transmission.

Transmission

As shown in figure 7.10, power transmission in SMR propulsion systems can be geared or gearless for electric configurations. A hybrid configuration, which is possible with SMR propulsion systems, allows for other transmission options, given in appendix C. Only electric propulsion is practical when considering a vSMR powerplant because of the low power output of $10\ MW_e$.

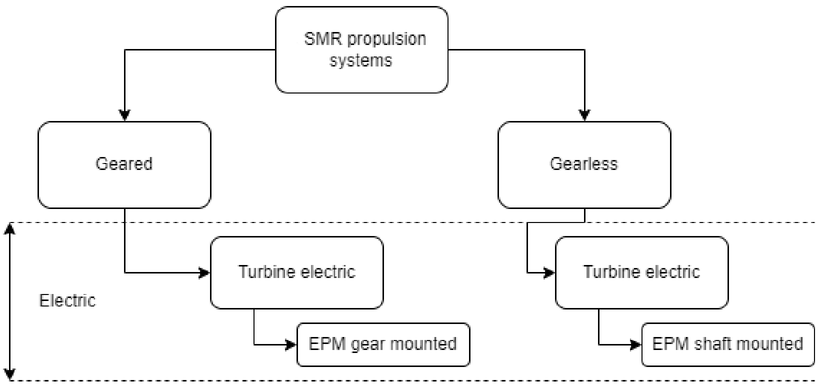


Figure 7.10: *Classification of (v)SMR power distribution layouts using IPS*

Gear-mounted EPMs are smaller and lighter because of the increased rotational speed. However, adding a gearbox increases the susceptibility of the combatant by influencing its acoustic signature. When ASW capabilities are required, a shaft-mounted EPM is often proposed to reduce the propulsion plant noise signature of the combatant. Future requirements are not available. However, since SMR technology is considered silent, shaft-mounted EPM technology might benefit a future surface combatant. Concerning ship design implications, this design choice leads to a conservative estimation of the EPM in terms of increased size and weight visualised in figure 7.11. To calculate if a combination of a gearbox and EPM is lighter, previous work can be used to estimate the size and weight of complex gearboxes [61].

Result

The size and weight of an EPM with a shaft speed of 150 RPM are given in figure 7.11. Data of large existing EPMs have been added to the plot [76] [63].

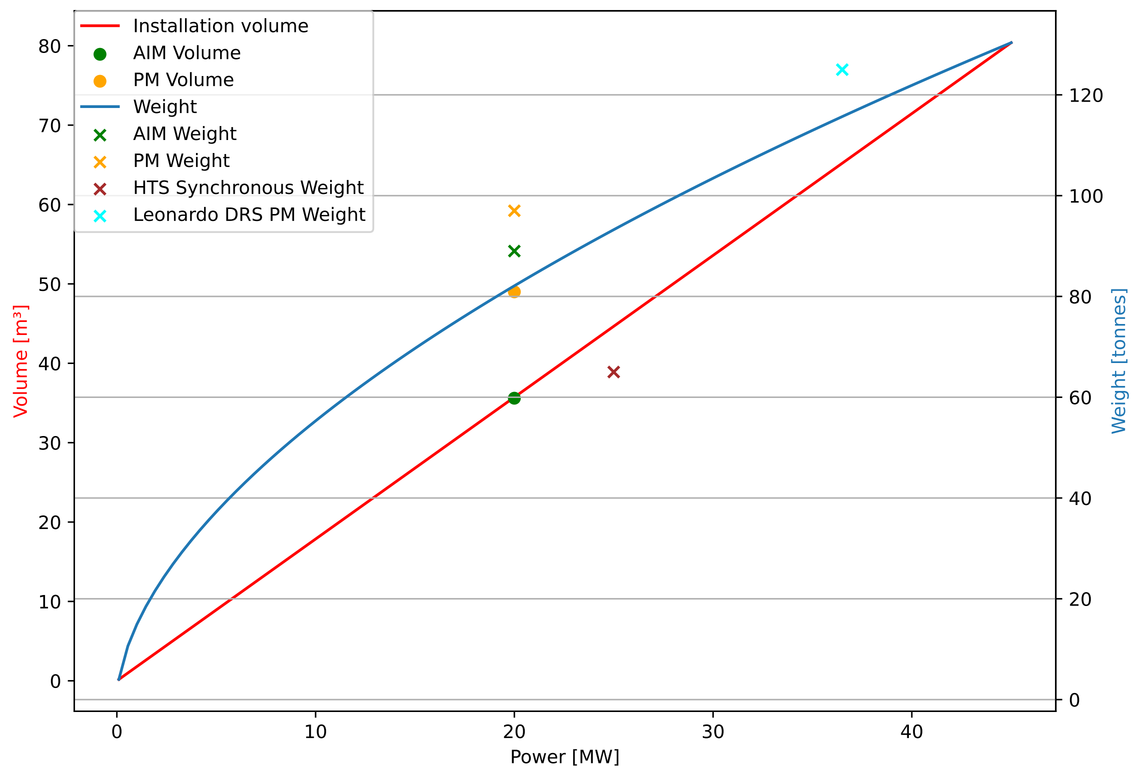


Figure 7.11: *Size and weight of naval EPMs with a shaft speed of* 150 *RPM*

More data points for verification are desired. However, due to the lack of all-electric surface combatants, not many large EPMs have been manufactured. It is concluded that up to an output power of 50 MW, this model can estimate the size and weight of future EPMs suitable when used in a preliminary surface combatant design.

7.3. Conclusion

This chapter discusses how the power and energy are distributed and converted throughout the future surface combatant.
Power distribution in combatants equipped with an IPS faces the challenge of handling high power and pulse loads, necessitating a transition to high voltage systems for efficiency and compactness. The recommendation of a zonal distribution network with a ring-bus architecture ensures resilience against single-point failures. The shift towards MVDC systems is highlighted for their potential to enhance power density and integration flexibility despite the current limitations in component availability.
Further, switchboards and converters are considered for the distribution of power. Because of the lack of data regarding MVDC components, conservative estimates for their size and weight are proposed based on existing technologies and theoretical models.
ESS is recognised for its role in buffering pulse loads from SEWACO systems. Lithium-ion battery technology has been modelled by integrating the SEWACO load from the operational profile of the combatant over time. Sizing the ESS capacity is dominated by the required energy over time, which depends on the ramp rate of the (v)SMR when considering the SEWACO load. When sizing ESS capacity, the propulsion load dominates power surplus/deficit peaks. This results in ESS sizing being independent of the ramp rates of SMR or vSMR power plants. Instead, the operational profile dominates the ESS sizing of the total power demand. For concept evaluation, ESS sizing will be based on complying with the SEWACO load.
The conversion of electrical power to mechanical power for propulsion is done with EPMs. Considering operational silence and acoustic signature, a gearless transmission is assumed for future surface combatants. The weight and volume of EPMs are verified with current systems. This result of the model results in a conservative estimation of the size and weight of the EPM.

8 Combatant sizing model

Evaluating various concepts with (v)SMR technology is necessary to find the impact on the design of a future surface combatant. The most critical parameters for a combatant are displacement and volume. With the right amount, all propulsion, power generation, SEWACO, auxiliary and accommodation systems can be fit in the combatant. This can be found in the design structure in figure 3.1. The design structure has been translated into a parametric model iterating the displacement for combatant concepts, presented in section 8.1. The outcome of the sizing model results in a recommendation for a more detailed case study performed in chapter 9.

8.1. Method overview

The concept of combatants is examined in terms of the following:

- Power $[MW]$
- Weight $[tonnes]$
- Volume $[m^3]$
- Energy storage $[MWh]$

A methodology was developed to conduct this analysis through a sequence of computational steps. The design flow visualised in figure 3.3 leads to the sizing model which is divided into four parts:

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

The method is implemented using the *Python* programming language. An overview of the process is provided in figure 8.1. Here, the red blocks represent not modelled design drivers. Green blocks are data files from calculations, literature, or manufacturers. Straightforward calculations have been executed in orange blocks. Complicated models relying on multiple calculations or data files are coloured blue.

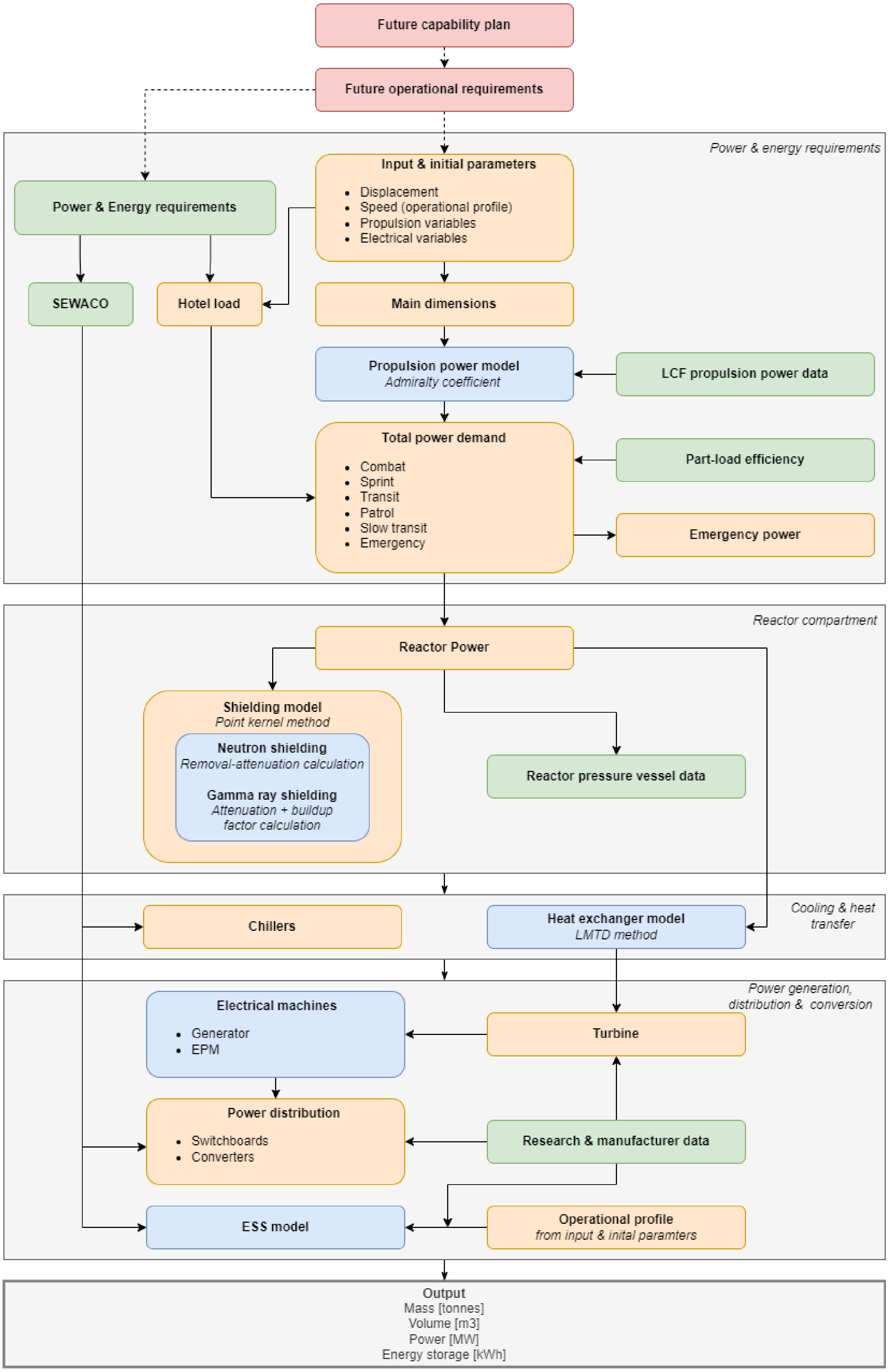


Figure 8.1: *Overview of the model*

8.1.1. Model details

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

Power & energy requirements

The performance requirement of table 3.1 is input for the sailing speeds. Propulsion variables such as the number of shafts, turbines and emergency generators are considered.
The power and energy requirement table from A is input for the SEWACO load. The larger the combatant, the larger the crew size, for example, increasing the HVAC requirements. The hotel load is corrected with f_{hotel} to take combatant size into account.
At lower sailing speeds (< 12 knots), most EPM technology becomes less efficient. The power demand in part-load conditions is corrected with a general efficiency curve for EPMs determined in previous work [61].

Reactor compartment

Reactor pressure vessel data was taken from literature [1].

Cooling & heat transfer

The heat exchangers required for the (v)SMR power plant are described in section 6.2. However, designing a future surface combatant involves integrating advanced radars and NDE weapons. Due to their poor efficiency, high heat is generated, as seen in appendix A. Therefore, a thermal management system is essential.

The thermal management system is a closed loop to prevent corrosion, fouling and heat load variability. The system is cooled with chillers which offer precise temperature control. This is crucial for sensitive electronics and weapons systems that require specific operating temperatures [61]. The chilled water plant produces water with additives of around $7°C$ for cooling SEWACO- and HVAC systems. A chilled water plant consumes significant space, for the LCF a volume of $26.88m^3/MW_{th}$ and a mass of 12 tonnes$/MW_{th}$.

NDE weapons produce enormous amounts of heat in a limited time, requiring many chillers. The HEL and HPM weapons are assumed to be cooled with heat batteries evaluated in previous work [17]. This results in radar and HVAC systems driving the required number of chillers, which will still be significant for future surface combatants presented in chapter 9.

Power generation, distribution & conversion

These components are covered in chapter 6 and 7.

8.1.2. Baseline model

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

- a fourth-generation (v)SMR powered combatant nor concept design exist 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 from figure 7.2. The model can choose between the two largest commercial naval turbines, the MT30 from Rolls Royce (RR) and the marine LM6000 from General Electric (GE) [77] [78]. 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. The layout is visualised in figure C.2.

8.2. Results

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

8.2.1. Power & energy

The required power and energy for the concept combatant are given in figures 8.2 and 8.3.

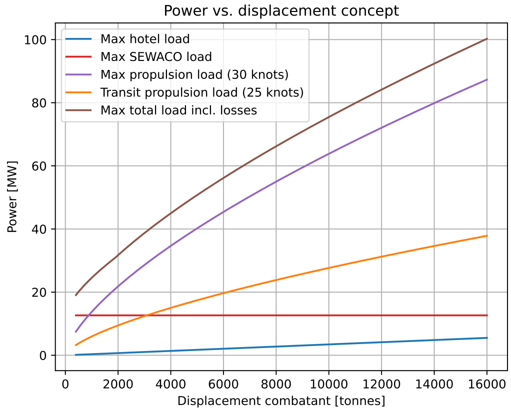


Figure 8.2: *Power required for hotel, SEWACO and propulsion*

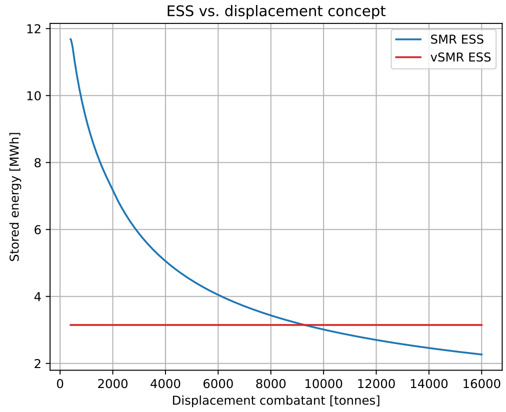


Figure 8.3: *Required ESS for (v)SMR technology ($10MW_e$ vSMR)*

In figure 8.2, the maximal loads for the concept combatant are shown. The hotel load increases over displacement, accomplished with equation 4.5. The maximal SEWACO load is constant from appendix A and found in combat mode. The propulsion load for the maximum sailing speed of 30 knots is by far the highest load for the combatant. To demonstrate the impact of a high sailing speed, the required power for 25 knots is given. Regardless of assuming a future SEWACO load, from figure 8.2 it is seen that the propulsion load dominates the total maximum power demand for all combatant sizes.

Figure 8.3 shows the required energy storage to accommodate the SEWACO systems for the given operational profile from appendix N. Because the vSMR power plant operates with multiple reactors of the same power output, the ESS capacity does not change. The ESS capacity required for an SMR power plant decreases over displacement. The ramp rate of the SMR is coupled with the total installed power in equation 7.4. A more significant combatant needs more power, which requires a larger SMR. 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.

8.2.2. Weight

The displacement is iterated over the power plant weight of the specific power configuration divided in an MSR (blue), number n of vSMRs (red) and number n of Gas Turbine Systems (GTS) (purple) in figure 8.4. 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 the literature. The red dotted line represents this practical limit.

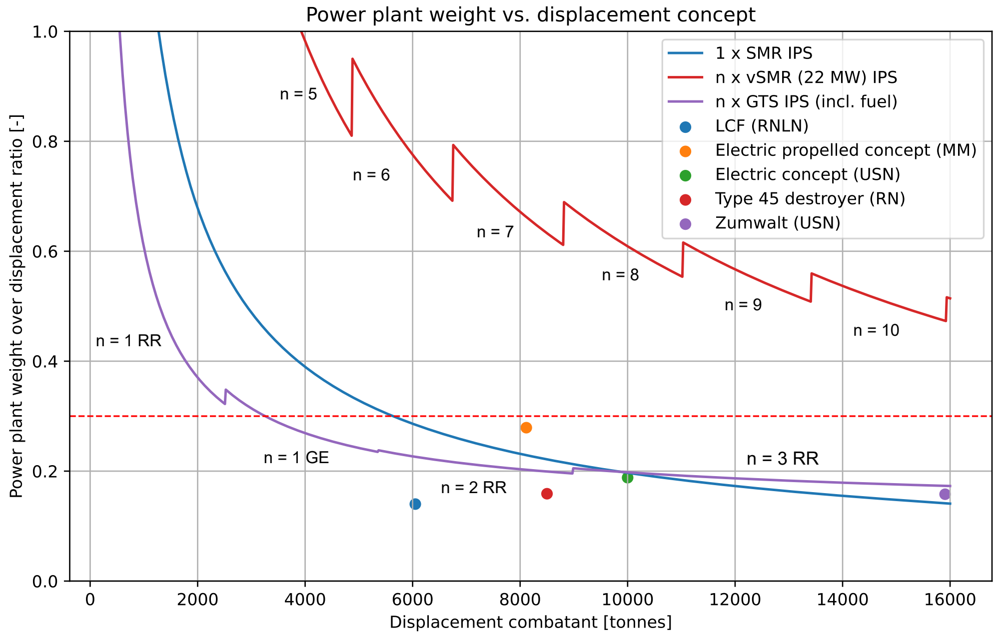


Figure 8.4: *The weight impact of the power plant on the displacement of the combatant*

The baseline (purple) in this research, the GTS IPS configuration, shows a differentiating preference for the gas turbine manufacturer. It can be seen that over increasing displacement, the baseline is lower than the upper limit of 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. 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 can be seen in figure 8.5.

The SMR, represented by the MSR, is for smaller combatants weighty. Equilibrium with the baseline has been found around a displacement of $9,860$ tonnes. Previous work evaluating PWR technology stated that a displacement of $7,500$ tonnes was the lowest viable combatant concept, considering financial costs [79].

The vSMR power plant, using the number n of individual Holos-Quads, is not near the traditional power plant ratio. Each step in the red line represents the addition of an extra vSMR 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.

8.2.3. Volume

Figure 8.5 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 evaluate if the turbine fits. Therefore, the volume in figure 8.5 is seen as a minimum.

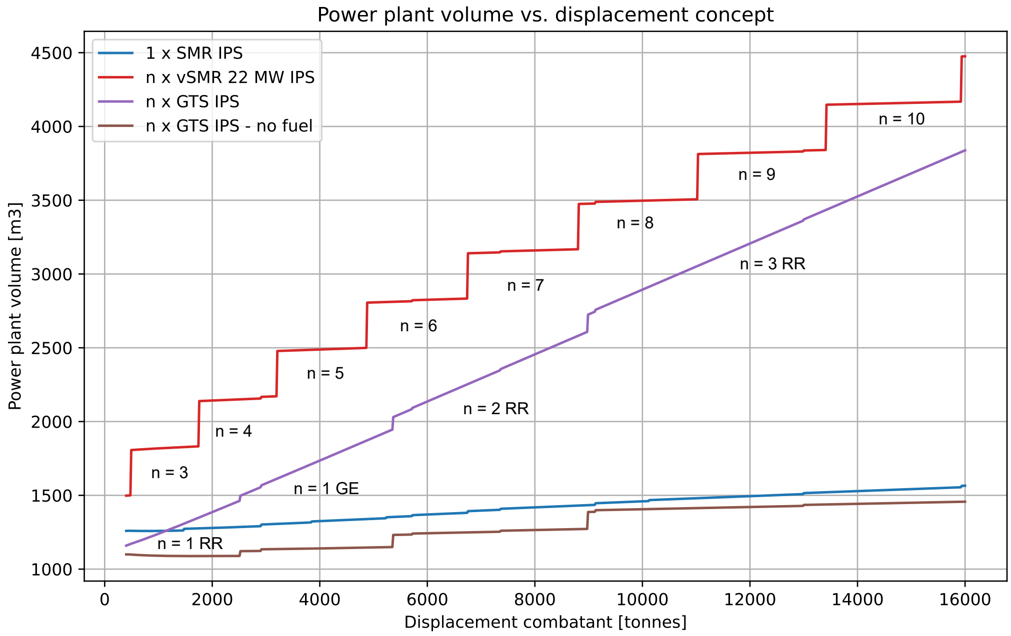


Figure 8.5: *The volume impact of the power plant on the displacement of the combatant excluding cables, pipes and exhausts*

The main steps caused by n vSMRs and gas turbines are visible. Smaller steps are also seen due to 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 combatants' hull. Volume saved does not directly result in usable space for payload or ESS. Only by evaluating the design of a combatant can we conclude if the reduction in fuel storage benefits the (v) SMR-powered combatant.

8.3. Discussion

Dominating propulsion power

When observing figure 8.2, 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. If propulsion power will dominate the required power for future surface combatants, an IPS becomes less attractive when hybrid systems prove cheaper, more reliable or more compact. An SMR power plant with a hybrid propulsion configuration has been modelled with a schematic visible in appendix C. The impact of a hybrid configuration strengthens this statement by looking at figure 8.6.

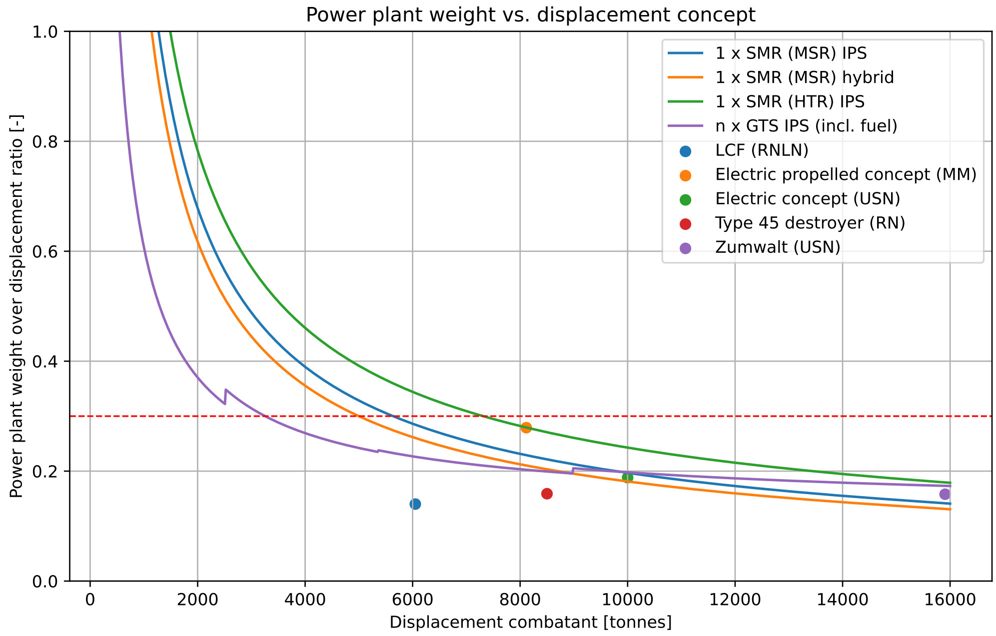


Figure 8.6: *The weight impact of the power plant on the displacement of the combatant with a hybrid and HTR configuration. For n, see figure 8.4*

The SMR power plant with a relatively simple hybrid power configuration (yellow) reduces the power plant weight mainly due to reduced required converters and smaller EPM suitable for patrol speed of 12 knots.
Also, the impact of choosing one HTR instead of an MSR is shown in figure 8.6. More shielding is required because HTRs have a lower core density than MSR reactors, resulting in a higher power plant weight.

SEWACO sensitivity analysis

For future applications, it is important to understand what behaviour regarding the weight ratio is observed when the SEWACO load differs from the current estimation. Appendix O shows the impact on weight and the required ESS capacity when the SEWACO load is doubled (to a maximum of $28MW_e$). It is observed that more vSMRs are needed for the same combatant, leading to an upward shift of the weight ratio curve to the right for vSMR technology, as shown in figure O.1. The weight ratio curve for SMR-powered combatants shifts to the left, moving the equilibrium with the baseline from $9,860$ tonnes to $10,400$ tonnes. Overall, an increase in SEWACO load leads to an increase in the weight of the (v)SMR power plant.

Heavy and large vSMR power plant

Looking at figures 8.4 and 8.5, 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, as shown in figure 8.8. Multiple smaller vSMRs are required to achieve the necessary power while increasing the amount of shielding, as compared to the SMRs shown in figure 8.7.

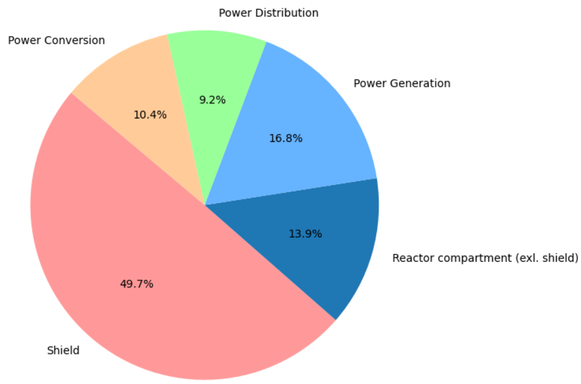


Figure 8.7: *Weight distribution of the modelled SMR power plant for a* $10,000$ *tonnes combatant*

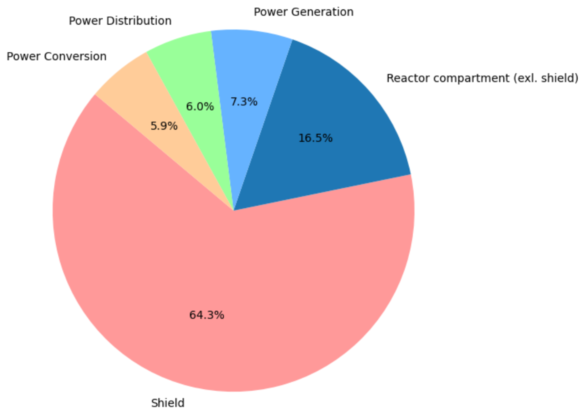


Figure 8.8: *Weight distribution of the modelled vSMR power plant for a* $10,000$ *tonnes combatant*

For a combatant of $10,000$ tonnes, 8 vSMRs are required. This affects the proposed benefit of vSMR, promising zoning, increased redundancy and easy refuelling while 60% of the combatant is needed for the power plant. Also, a high number of separate reactors increases its vulnerability. Every possible hit by an enemy can be a *nuclear* hit. Details concerning vulnerability regarding (v)SMR technology are addressed in section 9.2.1.

8.3.1. Recommendation

SMR technology for future surface combatants where the propulsion load dominates the operational profile requires extensive research.

Placing multiple smaller reactors on a combatant while making it not too heavy is challenging. Three suggestions are made to reduce the shielding weight by:

1. increasing the power output per vSMR (exceeding the literature definition of a vSMR where $P_e < 10MW_e$)
2. assuming a weight reduction of 30% based on previous optimisation [38]
3. placing vSMRs together in such a way they *share* shielding, resulting in less needed material

The impact of solution 1 is obtained by increasing the output power of the modelled vSMR. An output power of $55MW_{th}$ or $25MW_e$ considering an HTR is assumed in figure 8.9.

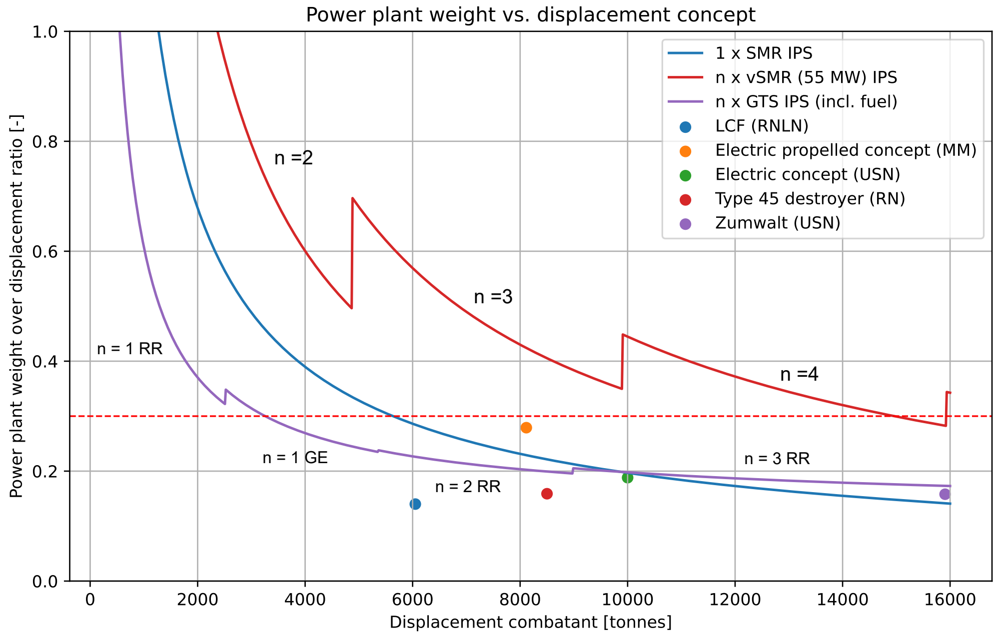


Figure 8.9: *Solution 1, the weight impact of the power plant on the displacement of the combatant including a more powerful vSMR*

By installing $25MW_e$ per vSMR, the power plant becomes closer to feasible ratios.

When more complex optimisation algorithms are used, the calculated weight by the Point kernel method could be reduced in line with solution 2.

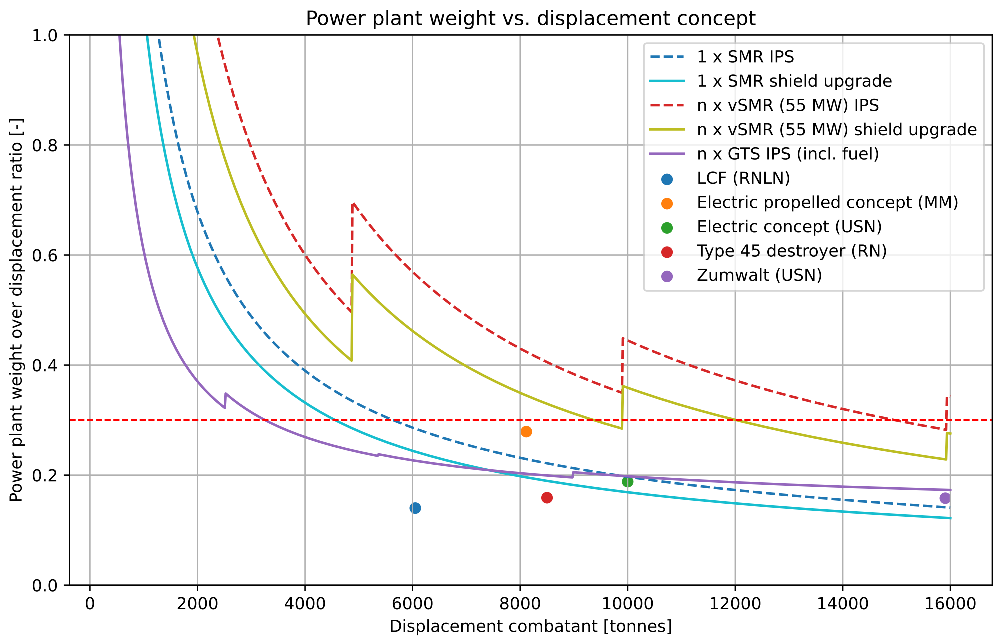


Figure 8.10: *Soution 2, the weight impact of the power plant on the displacement of the combatant with an accomplished shield reduction of* 30%

As shown in figure 8.10, a decrease of 30% obtained with optimisation could bring the ratio down to feasible levels. However, this is only valid for the vSMR with a power output of $25MW_e$. Still, apart from a hybrid electric concept of the Italian Navy (MM), multiple (v)SMRs lead to high propulsion plant ratios. The solution, in practice, would be obtained by combining shield optimisation and shields of the vSMRs.

Solution 3 reduces the overall amount of shielding such that the material required for multiple vSMRs can be reduced compared to if each vSMR had its shielding. The impact of solution 3 is not easily obtained and requires extensive research. Combining shields by placing vSMRs together has been done with Russian submarines and icebreakers. However, no data is available. Regarding the complexity of modelling two radiation sources in a compartment, further work or a different method has to be applied. Assuming constants by estimating the amount of shield shared is not considered accurate and is unfortunately not verifiable. Moreover, a severe weight reduction is found using a mathematical reduction factor by observing the shared volume when at least 3 to 4 vSMRs are placed together. This makes using vSMRs unpractical by increasing system complexity and reducing system redundancy.

The impact of solution 1, increasing the power output per vSMR, is further researched in chapter 9. Alternatively, vSMR could be a solution to provide the future SEWACO load in combination with a traditional GTS, which provides propulsion power. An introduction to such a system is given in section 9.3.

8.4. Conclusion

This chapter has presented a model 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 despite its potential benefits in terms of redundancy and modularity. The analysis indicates that for the defined future combatants 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 ($P_e < 10MW_e$) concludes that small SMRs, for example, with a power output of $25MW_e$, are more suitable than multiple vSMRs for the defined future surface combatant. A specific design is required to evaluate the volume needed for the (v)SMR power plant. A case study is required.

9 Case study

This chapter will contain a case study presenting details of a future surface combatant with a specific displacement of $9,800$ tonnes. The case study will compare a conventional, SMR and vSMR-powered combatant. Regarding required volume and weight feasibility, the vSMR will have a higher output power than $10MW_e$. These preliminary concept designs will show the required power plant volume to determine if the power plant is feasible. The effectiveness of the concept design is addressed in terms of survivability, mobility, range and endurance.

9.1. Preliminary design

From chapter 8, it is concluded a design is needed to evaluate the power plant concerning available volume. After analysing figure 8.9, it is decided to observe a future surface combatant with a displacement of $9,800$ tonnes. It is interesting to evaluate this displacement in detail because the SMR and the conventional GTS powerplant 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 according to section 8.3.1, the impact of multiple smaller reactors installed on the concept is assessed with 3 vSMRs with a power output of $25\ MW_e$ which result in a weight ratio of 0.35.

9.1.1. Main characteristics

The model from chapter 8 defines the dimensions with common size ratios for combatants [80]. The future surface combatant is presented in table 9.1.

Table 9.1: *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. The Type 055 destroyer is a class of stealth-guided missile destroyers constructed for the Chinese People's Liberation Army Navy (PLAN), comparable with the Ticonderoga and the Sejongdaewang class destroyers. During the design of the Type 055, the possibility of integrating IPS is used as a reference point [81]. 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 and a preliminary general arrangement are available [82] [83]. After scaling to the required displacement Δ, Lwl, B and T from table 9.1, the conventional baseline is visualised in figure 9.1.

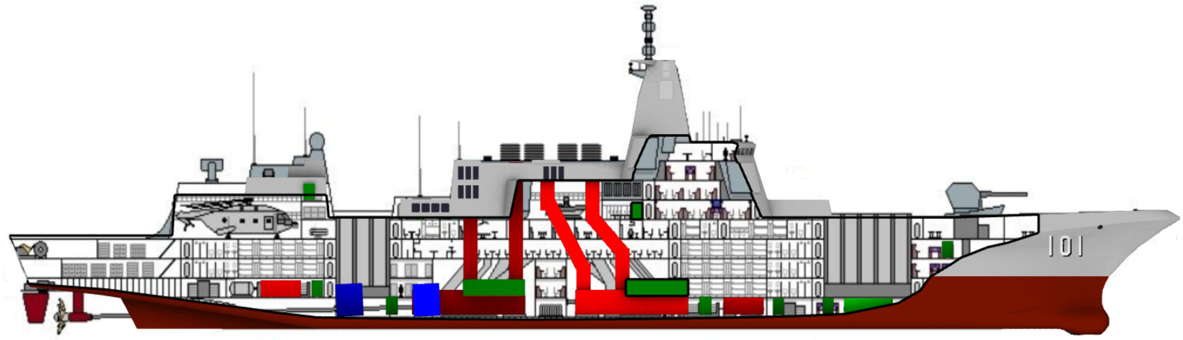
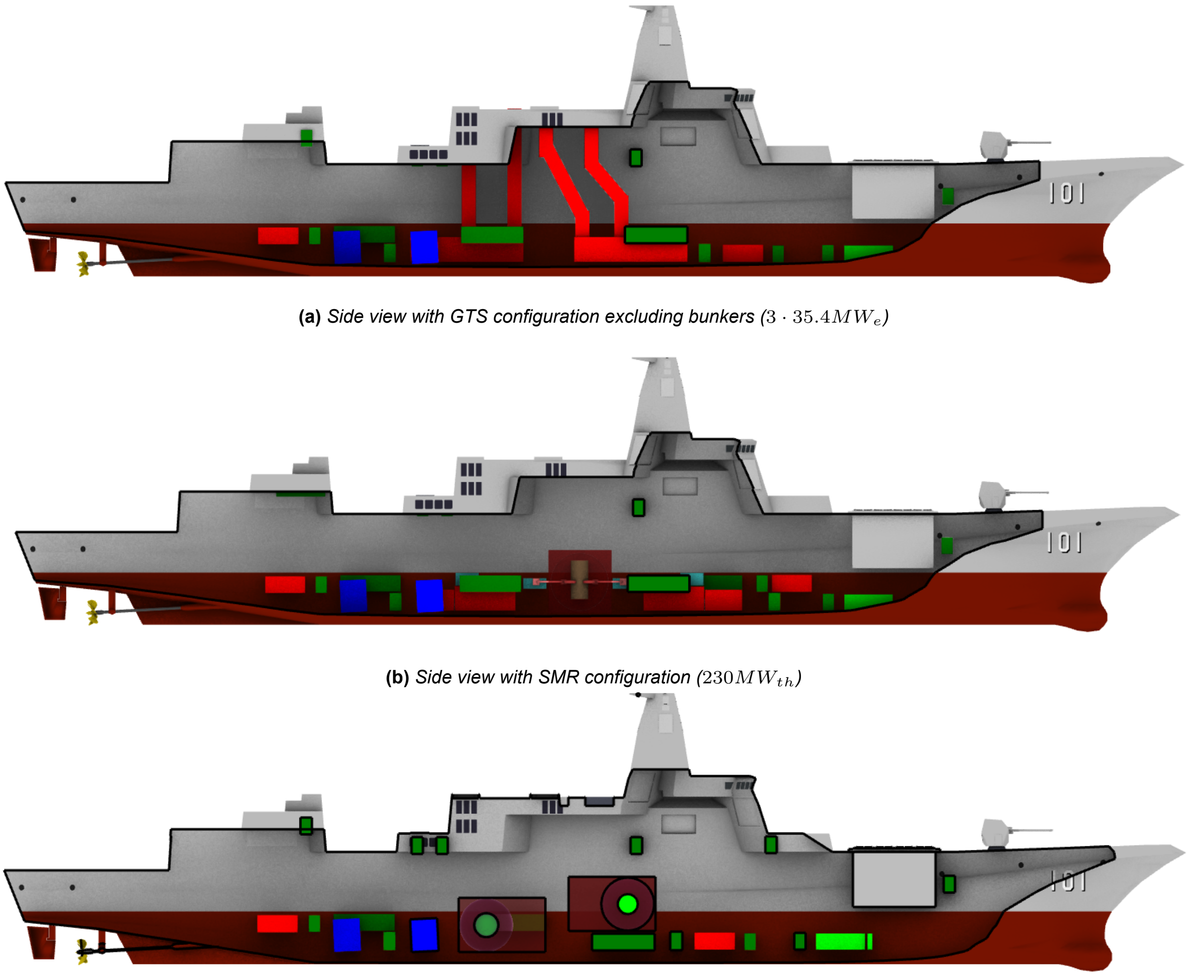


Figure 9.1: *Side view of the conventional baseline visualising the GTS with IPS, including the preliminary general arrangement. Power generation; red, power distribution; green, ESS; bright green and power conversion; blue.*

9.1.2. Result

The preliminary power plants with a GTS, SMR and vSMR configuration are shown in figure 9.2. 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 9.2: *Preliminary design viewing power generation, distribution and conversion components. Power generation; red, power distribution; green, ESS; bright green and power conversion; blue.*

The weight of individual components for each configuration is shown in table P.1. While fuel bunkers and chillers require significant space and weight reservation, the specific location depends on the preferences of the concerned navy. More details regarding the power generation of the configurations can be seen in figures P.1, P.2 and P.3. The preliminary design viewing all components without the hull is shown in figure P.5.

Considerable differences can be observed in figure 9.2. 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 preliminary design is visualised with *Rhino* in appendix P.
The SMR configuration is of comparable size to the GTS configuration, confirming the observed trend in figure 8.5. A detailed layout of the SMR power plant is given in appendix B. The SMR is located near the LCG 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 9.1. The SMR is not easily removed from its location, reducing modularity. While gas turbines are hard to remove from conventional surface combatants, they are more standalone power generators. An integrated nuclear power plant is heavier, has severe safety risks and requires a specialised crew.
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 for the reactor compartment is necessary because of the lower power density of the (V)HTR core. While the SMR is fuelled for extensive periods, the core needs to be swapped each $5 - 8$ years for a vSMR. 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 [1]. Therefore, it is believed the benefit of the possibility of modular vSMRs is reduced when used to comply with the total power demand.

9.2. Effectiveness

A conventional baseline concept will be compared to evaluate the effectiveness of a (v)SMR-powered future surface combatant. The effectiveness of a surface combatant can be expressed with the following characteristics [1]:

- Mission capabilities
- Survivability
- Mobility
- Range & endurance
- Automation

Mission capabilities are covered in section 3.2 and will be kept constant for all concepts. Automation is essential but considered outside the scope. The SMR and conventional powered concepts will be evaluated by comparing survivability, mobility and range & endurance.

9.2.1. Survivability

Survivability is a function of susceptibility, vulnerability and recoverability [1]. Many models which express survivability have been covered in literature [66]. To evaluate survivability properly, extensive analysis is required, especially vulnerability reduction, which is significant for ships with an IPS concept. This falls outside the scope of this thesis.
However, using the following COMMIT design standards [66], a part of survivability can be taken into account for a preliminary design:

- avoid single points of failure in vital distribution systems
- separate redundant sources
- generally, ring-shaped systems are a preferred solution

To avoid single points of failure, a zonal distribution network with a ring-bus architecture has been proposed in chapter 7.1. For the preliminary power plant designs, in figure 9.2, it can be seen that power sources and critical users are separated. The emergency generators, EPMs and turbines are mostly separated into different compartments when possible.

As explained in detail, it is seen that fourth-generation SMR technology could improve susceptibility to a great extent, reducing the possibility of visual detection and noise emission [1]. Using the closed Brayton cycle, the thermal signature profile can be improved significantly by removing the exhaust gases from the ship to decrease the likelihood of detection.
Compared with a GTS configuration, (v)SMR technology is more vulnerable for the combatant when hit by a critical target. When hit by a missile on the (v)SMR compartment directly, the possibility of radioactive contamination cannot be ruled out. The more nuclear sources, the higher the chance of contamination after direct critical damage. When (v)SMR technology is affected indirectly, no extra risk is attained because of the inherent safety properties. However, increasing the number of independent power sources ensures that the failure or loss of one reactor does not compromise the overall power supply, enhancing the combatant's operational reliability and survivability in combat situations. Recoverability is hard to estimate because it relies on the crew's skill level. However, radioactive contamination has occurred, and the movement of the crew is somewhat limited, which reduces the ability to recover from damage.

Figure 9.3 gives an illustrative example of how survivability is defined for a surface combatant and how it differs from a (v)SMR-powered combatant. While the susceptibility might improve, as shown in figure 9.3, a direct hit results in a higher vulnerability, which is harder to recover after radioactive contamination. The impact on survivability is demonstrated with the black arrow in figure 9.3 for both surface combatants.

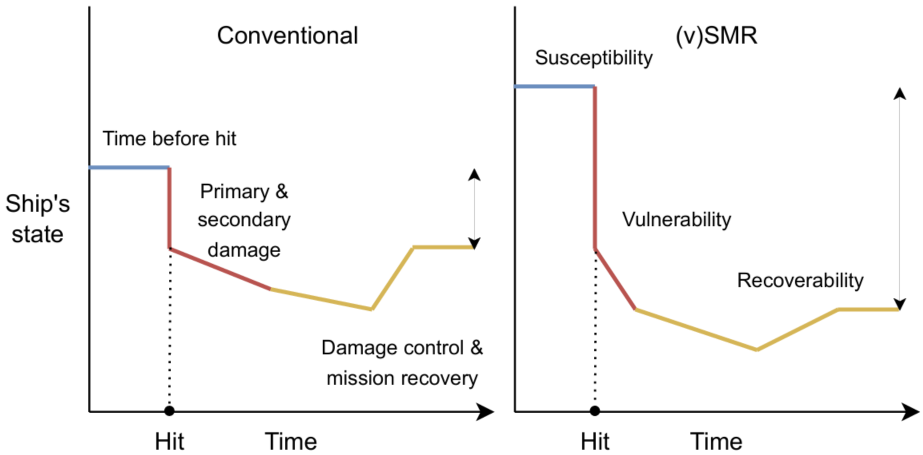


Figure 9.3: *Survivability for a conventional (left) and (v)SMR powered (right) surface combatant for illustrative purposes, inspired from [66]*

It can be argued that the shielding of (v)SMR technology might prevent radioactive contamination within the surface combatant after a direct hit. Ship survivability studies need to verify the impact on survivability in practice. The impact of susceptibility, vulnerability and recoverability on the concepts are given in table 9.3. It is estimated that a conventional GTS configuration and the SMR or multiple vSMRs have the same survivability impact despite being more vulnerable and lower recoverability.

9.2.2. Mobility

Mobility is defined as follows [1]:

- top speed
- manoeuvrability
- acceleration and deceleration

This report has limited the propulsion chain to brake power covered in section 4.1.1. This means the propulsion system will provide sufficient brake power to achieve the desired speed, but further analysis is required on how this power is delivered into the propulsion chain. All concepts have a design top speed of 30 knots.

Manoeuvrability is limited in this thesis on the ability to scale down power to low levels, for example, required to enter a port. In chapter 6, SMR technology requires HRS to dump heat generated from the lowest load possible by the power plant. Other high-energy consumers like electrolysers or resistors could support or replace an HRS system. Multiple vSMRs based on the Holos-Quad have implemented load follow strategies to scale to 0% in the load range.

A combatant needs to accelerate and decelerate while the power plant sizing is dominated by propulsion power resulting from top speed. The ramp rate of GTS in an IPS configuration is found to identify the impact on the acceleration of using (v)SMR technology. An MT30 gas turbine coupled to a generator has roughly a linear ramp rate, which reaches maximum electrical power at a stable level in 12 seconds [18]. The response of each configuration for the concept surface combatant is shown in figure 9.4.

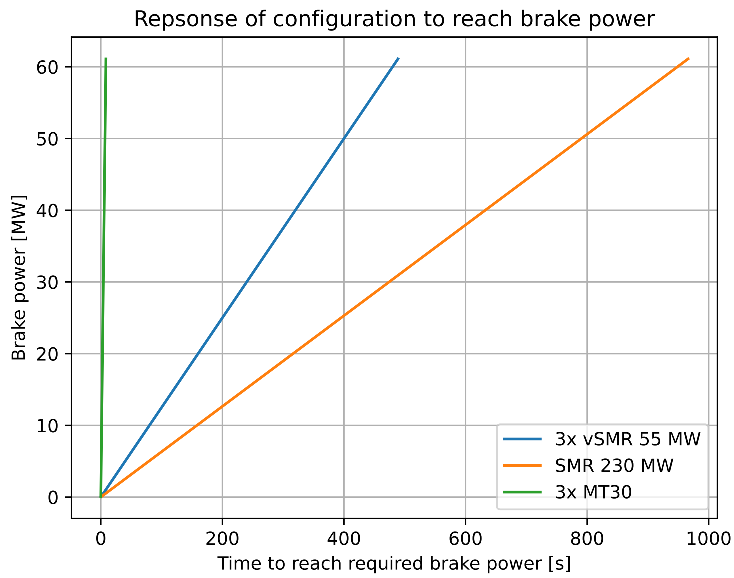


Figure 9.4: *The response time to reach a brake power level for the GTS and (v)SMR configuration of the future surface combatant*

The preference for GTS in conventional surface combatants is demonstrated in figure 9.4. The brake power necessary to reach the top sailing speed is reached in seconds regardless of the number of gas turbines. To brake power required for 30 knots is reached in 8 minutes for vsMRs and in 15 minutes for an SMR powerplant.
As explained in section 7.1.3, the ESS capacity required to improve the response time of (v)SMR technology is dominated by power peaks found in the operational profile and are independent of the reactor power plant choice. Considering ESS with a C-rate of 3 results in a capacity of 19.5 MWh, which would weigh 230 tonnes if chosen for the Corvus Orca from table 4.1.

9.2.3. Range & endurance

Depending on the reactor design, the range and endurance of a (v)SMR-powered combatant can be years. It must be addressed that the dynamic loading of the reactor decreases the length of the fuel cycle. SMR technology is superior in endurance compared to conventional and vSMR-powered combatants because of the long fuel cycle. Endurance of (v)SMR-powered future surface combatants is mainly limited by the need for ammunition and food supplies. Fuel burn-up is needed to evaluate the range of the combatant, which relies on the reactor manufacture. Hence, no further in-depth analysis has been performed.

9.2.4. Prioritisation

The defined characteristics that indicate effectiveness must be prioritised because not all capabilities are equally important. By combining the combatant's mission profile and mission capability requirements, the importance of any capability or technical characteristic can be determined [84]. Based on previous work for the LCF, capability prioritisation for the notional future surface combatant is found in table 9.2.

Table 9.2: *LCF capability prioritisation based on [84]*

Attribute	LCF
Susceptibility	-+
Vulnerability	+
Recoverability	+
Range	-+
Endurance	-+
Top speed	+
Acceleration	-
Maneuverability	-

Table 9.2 might change if future requirements differ from the current capability plan of the RNLN.

9.2.5. Result

The effectiveness is determined by interpreting the benefits and drawbacks of each capability and adjusted with the prioritisation table 9.2. This resulted in an effectiveness per concept compared in table 9.3.

Table 9.3: *Effectiveness comparison of conventional GTS, SMR and vSMRs concepts*

	Conventional	SMR	vSMR
Survivability			
Susceptibility	- -	++	++
Vulnerability	-+	-	-
Recoverability	+	-	- -
Total	-+	-+	-+
Mobility			
Top speed	+	+	+
Manoeuvrability	+	-	+
Acceleration	++	- -	-
Deceleration	++	- -	-
Total	++	-	-+
Range & endurance			
Total	- -	++	+
Effectiveness	-+	-+	-+

While the conventional surface combatant looks more promising after evaluating 9.3, capability prioritisation with table 9.2 eventually determines the final outcome of the effectiveness. After considering the capability prioritisation and evaluating survivability, mobility, range, and endurance, it is estimated that future surface combatants' effectiveness for conventional, SMR, or vSMR power plant configurations is equivalent, as shown in table 9.3.

9.3. Discussion

Nuclear hybrid

While it is concluded in chapter 8 that vSMRs with a power output of $10MW_e$ are not feasible for the total power generation of the future surface combatant, the possibility of powering future mission equipment must be considered. Figure 9.5 shows a hybrid configuration consisting of a $10MW_ev$ vSMR and a GTS.

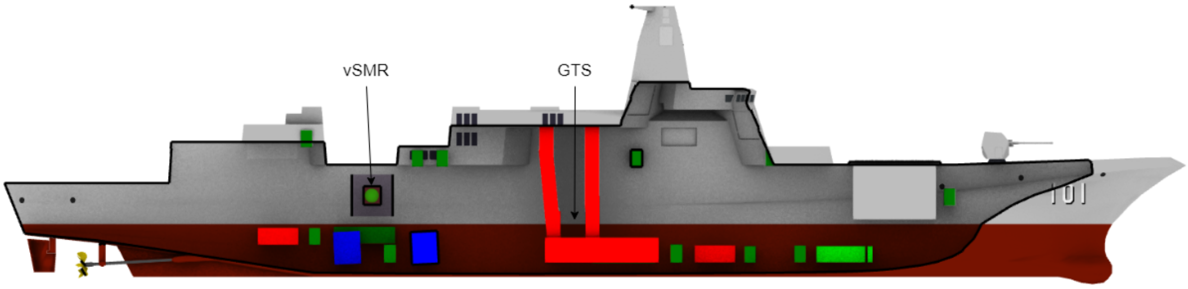


Figure 9.5: *Side view of a hybrid configuration containing a vSMR for future SEWACO load and a conventional GTS*

The GTS delivers power propulsion and conventional hotel and SEWACO systems. The vSMR will be installed when the power demand for future mission equipment increases. The vSMR is located near a possible entrance, making it modular enough to be replaced for refuelling. Placing vSMRs on the deck of a surface combatant is considered because of shielding difficulties, vulnerability considerations and legislation challenges. The shielding is pre-installed under the deck and integrated into the future surface combatant. With this method, vSMRs can be swapped without the heavy shielding.
The degree of modularity and easy access to the vSMR is determined by the system's weight, significantly affecting transverse and longitudinal stability at the location depicted in figure 9.5. Supporting structures need to be added as well after a strength analysis.

Increased stiffness

When installing (v)SMR technology, most of the power plant is located in the middle of the combatant as shown in figure 9.2 to reduce the impact of motions, accelerations and vibrations affecting the (v)SMR or the stability of the combatant. Vibration and shock resistance are identified as principal vulnerabilities of (v)SMR technology, though hardly covered in the literature.
The combatant's strength analysis will differ significantly from the GTS configuration. GTS systems have a low density and specific weight, meaning that the supporting structure does not immensely influence the combatant's strength. While supporting structures for (v)SMR technology are not considered, it can be imagined that the influence on the combatant's strength is affected when 50% of the power plant weight is located in the middle of the combatant. When the hull structure needs to be reinforced to carry the reactor with its shielding, the overall structure can increase stiffness.
In modern naval architecture, a certain level of flexibility in the structure is applied in the longitudinal direction for absorbing and dissipating the energy from impacts, such as missiles or torpedoes. The explosive gas expands after the shock wave, creating a low-pressure area under the hull. This downward force can lead to hull breach, deformation, and fracturing of the combatant's keel. This effect is exacerbated when a combatant is longitudinally too rigid and transfers more shock energy, potentially leading to additional stress, especially in sections that are not directly impacted.
Therefore, surface combatants require compartments which can take the damage. This results in the need for a redundant power generation system.

Dynamic behaviour

The introduction of ramping up and down the nuclear power plant in terms of mobility is introduced. To evaluate the mobility of the surface combatant, the dynamic capabilities of the nuclear power plant need to be explored further. This thesis demonstrated the response time of (v)SMR technology and

compared it with a conventional GTS. Improvement in ramp rate is necessary to achieve performance as a GTS configuration. This can be obtained by increasing the ESS capacity or implementing ESS with higher C rates.
The ramp-down rate (v)SMR technology is not comparable with GTS propulsion. This could be improved with increased ESS capacity, electrolysers producing hydrogen or resistors wasting energy.
A study has been initiated to compare the power behaviour of a nuclear power plant installation with other conventional sources to determine if the nuclear power plant alone can provide the required power specifications [85]. The study will assess if additional energy storage is needed for peak shaving in more detail.

Effectiveness

An introduction to determine the effectiveness of the future surface combatant is given. It must be stated that table 9.3 becomes, in practice, more complicated as the selection process must carefully balance these benefits against the potential risks and vulnerabilities inherent in nuclear power generation. The outcome from table 9.3 may change if the future capability plan significantly differs from the RNLN's current vision.

9.4. Conclusion

This chapter presented a case study exploring a preliminary design of a future surface combatant with a displacement of $9,800$ tonnes. The concept is compared with conventional GTS, SMR and a vSMR power plant. The weight ratio for the GTS and SMR power plants is 0.2, while for the vSMR it is 0.35, meaning that GTS and SMR power plant configurations use less weight of the available displacement. The analysis determined the impact of system size in terms of volume requirements:

SMR size: The SMR power plant is comparable to the GTS configuration in size. Suitable for a lifetime fuel cycle, the modularity of the SMR is less critical.

vSMR size: The vSMR power plant requires more space than the GTS configuration. With short fuel cycles, reactor placement concerning modularity is essential but not obtained.

The effectiveness of the future surface combatant using (v)SMR technology is evaluated in terms of survivability, mobility, range, and endurance. The following conclusions can be drawn:

Survivability: Without extensive analysis, it is estimated that a GTS configuration and the SMR or vSMRs have an equivalent survivability impact.

Mobility: All designs aim for a top speed of 30 knots. SMR and vSMR-powered combatants' response time is significantly higher than GTS-powered surface combatants. Increasing ESS capacity or implementing ESS with higher C-rates could improve this aspect.

Range & endurance: SMR and vSMR technologies offer unparalleled range and endurance compared with GTS.

In conclusion, the transition from conventional GTS to (v)SMR power plants in future surface combatants represents a trade-off between mobility in terms of acceleration and enhanced range and endurance. Increasing ESS capacity can improve ramp rates but at added weight and volume costs. An SMR offers compactness and a long fuel cycle while a vSMR offers higher load response times but requires modularity for refuelling while less compact. The choice between SMR or vSMR power plants involves balancing compactness, weight, and modularity against response time to comply with the future surface combatant's operational profile.

10
Conclusion & recommendations

Conclusion

Part II defined the necessary design structure, given in figure 10.1, for achieving the objective of the follow-up research:

Develop a future surface combatant preliminary design powered with (v)SMR technology to find the implications on ship design.

The future surface combatant's mission type, payload, and performance are described. Two reactors have been modelled as SMR and vSMR. Power requirements were determined by determining the propulsion, SEWACO and hotel load for the defined future surface combatant. An energy storage system has been selected and sized according to the combatant's operation profile. The reactor compartment, emphasising shielding, has been modelled in terms of volume and weight. Systems necessary for generating, distributing and converting power are identified and represented. A combatant sizing model has evaluated the feasibility of integrating (v)SMR technology regarding power, energy, volume and weight requirements. From the sizing model, a case study assesses a specific future surface combatant's feasibility and effectiveness.

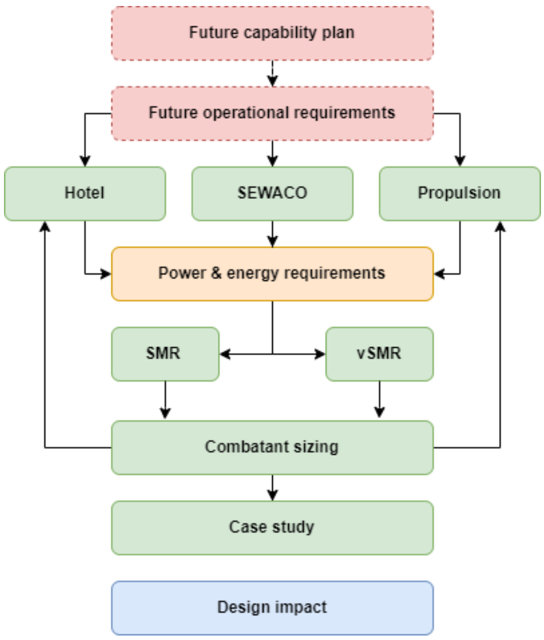


Figure 10.1: *Schematic design structure (duplicated from figure 3.1)*

Based on the conclusions found in the follow-up research, answers are given to the main research question of this thesis:

What are the implications of using IV generation (very) Small Modular Reactor technology for power generation on the design of a future surface combatant?

Chapter 4 estimated power and energy requirements for a future surface combatant considering propulsion, mission systems (SEWACO) and hotel loads. A generation IV (v)SMR affects how these loads are balanced, influencing Energy Storage System (ESS) capacity requirements to handle the dynamic power demand of the future surface combatant. It is found that the greater the allowable ramp rate of the (v)SMR and the lower the pulse load from the operational profile, the lower the energy storage capacity. A lithium-ion battery storage system is proposed, requiring significant space and weight. Given that (v)SMR has a low load response, an Integrated Power System (IPS) has been found essential to allow for dynamic power allocation in combination with ESS for peak demand management.

Chapter 5 outlines the preliminary design of the reactor compartment and power generation system for a fourth-generation SMR and vSMR. The necessity for substantial shielding to protect against radiation impacts the design's weight and volume. Water is unsuitable for the primary shield of (v)SMR naval applications regarding the risk of leakage and vaporisation. The Point Kernel method estimated that the lightest and most compact design was achieved with a borated polyethylene and lead shield, essential for reducing the overall mass.

Chapter 6 describes the required power generation systems. The SMR utilises a nitrogen-closed Brayton cycle with an intermediate helium cycle for safety, requiring a large machine room. A direct helium with higher efficiency is used for the vSMR. Using a closed Brayton cycle results in the need for heat exchangers. The load range of (v)SMR technology suggests that at low power levels, 20% of the installed thermal power needs to be cooled, introducing a Heat Removal System. Printed Circuit Heat Exchangers have been introduced because of their high efficiency and compactness. A two-stage plate-type heat exchanger is necessary to prevent coolant blockage using seawater. Therefore, the volume and weight reserved to accommodate all heat exchangers are significant. With a relatively low specific weight, turbine machinery for the closed Brayton cycle is compact. The weight and size of electrical machines are estimated based on power output and rotational speed.

Chapter 7 describes power distribution and conversion in future surface combatants with IPS, highlighting the transition to high-voltage, zonal distribution networks with ring-bus architecture for enhanced efficiency and resilience against failures. Sizing the capacity of the ESS using the SEWACO load is dominated by the energy required over time, which depends on the ramp rate of the (v)SMR and the SEWACO load. Propulsion load dominates with power peaks when sizing ESS capacity using total power demand. This results in ESS sizing being independent of the ramp rates of SMR or vSMR power plants. Instead, the operational profile dominates the ESS sizing of the total power, adding weight.

Chapter 8 presented a model to evaluate the sizing of future surface combatants when utilising generation IV (v)SMRs. It is found that the propulsion demand significantly dominates the power plant sizing, outweighing hotel and SEWACO loads. This underlines the need for power systems that efficiently meet high propulsion requirements where hybrid configurations become interesting to consider. ESS capacity is crucial for managing the variable power demand from SEWACO systems. For SMR implementations, ESS requirements decline with increasing displacement due to better load-following capabilities of larger SMRs.
For higher displacement combatants, SMR technology offers a more feasible solution than vSMR regarding weight due to the challenges related to extensive shielding needs. SMR power plants are viable for combatants with displacements above $8,000$ tonnes when connected to an Integrated Power System, balancing volume and weight constraints. The feasibility of $10\ MW_e$ vSMR is not viable for future surface combatants with up to $16,000$ tonnes displacement. This highlights the critical balance between the benefits of redundancy and modularity against the practical limitations of weight and space. It suggests that single, more powerful SMRs are preferable for future surface combatants rather than multiple vSMRs.

Chapter 9 provided a case study on a future surface combatant with a displacement of $9,800$ tonnes. A conventional gas turbine system is compared with an SMR of $230\ MW_{th}$ and a vSMR of $55\ MW_{th}$ power plant. The analysis highlighted 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, highlighting the importance of reactor placement for modularity due to their shorter fuel cycles.
The case study evaluated the effectiveness of the future surface combatant with (v)SMR technology in terms of survivability, mobility, range and endurance. While (v)SMR and GTS configurations offer equivalent impacts on survivability, the mobility of (v)SMR-powered combatants, particularly in acceleration, poses challenges that can be mitigated by increasing the Energy Storage System capacity or implementing ESS technologies with higher C-rates. A trade-off between SMR or vSMR power plants is found, balancing compactness, weight, and modularity against response time to comply with the future surface combatant's operational profile.

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. The implications highlight a trade-off between the benefits of enhanced endurance and range against the challenges of increased weight, volume requirements, and potentially reduced mobility. The choice between SMR and vSMR technologies further complicates this balance by choosing between compactness and load response. The essential conclusion is that the integration of generation IV (v)SMR technology is feasible without losing the effectiveness of the combatant while increasing autonomy and meeting future power loads.

Recommendation

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. Literature recommendations are found in the literature report [1]. Further research based on findings from the follow-up research is proposed as follows:

Reactor type
This thesis models the (V)HTR and MSR based on findings in the literature. However, noticing that weight is a critical design parameter, the Lead-cooled Fast Reactor (LFR) becomes interesting to implement in the sizing model. The LFR uses lead as a coolant, meaning that the coolant already covers most of the primary shielding. The required shielding weight for an LFR would be significantly reduced, making it an attractive reactor type for further research. Regarding non-investigated capabilities against motions and vibrations, heat-pipe reactors could be a solution.

Shielding
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 a background in nuclear engineering. The analytical calculation assumed an isotropic emission of neutron and gamma radiation with a distribution of 50%. A realistic radiation source must be evaluated to estimate the radiation field better, including the spatial distribution field of the reactor and the scattering of neutrons. Modelling the borated polyethene more accurately with a lamination of materials could reduce the required weight further. Also, implementing ALARA could refine the results to a higher level. 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 in shared shields to reduce the shielding weight is necessary for the feasibility of vSMR technology in surface combatants.

Thermal Management
The heat exchanger model is based on the LMTD method, which only considers the core without inlet ducts and other components. Pressure drop and several heat transfer losses should be considered for more accurate results regarding the initial size of a heat exchanger. Nodalisation

of the heat exchanger could increase the accuracy of the results. Piping is not considered and can be sized according to the required bulk velocities, influencing the needed system volume. Thermal stresses on the reactor vessel, shielding and other components have not been considered. Proper thermal shielding can add weight and volume to the system. While a closed Brayton Cycle does not emit heat into the air, it does use the sea for cooling. Further research should be conducted to determine if infrared sensors of potential enemies can see the thermal heat put in the sea.

Turbine technology
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 application. 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.

Energy storage system
An Energy Storage System must be integrated to increase the combatant's performance. While lithium-based battery technology is used in this thesis, further research should focus on implementing more advanced pulse-forming networks that can deal with dynamic loads of naval-directed energy weapons and propulsion power demand. Several peak shaving methods could optimise the ESS model and reduce the required capacity, influencing necessary volume and weight. Lastly, the results of the ESS model depend heavily on the operational profile. To determine the actual size of an ESS, it is important to analyse real-time and various operational profiles.

Reactor load response
While reactor control mechanisms, such as throttling valves, turbine bypass loops, inventory control circuits, and compressor shaft speed control, have been addressed in the literature, this thesis assumes a linear ramp rate. The dynamic response of (v)SMR has been modelled but with an operational profile of a surface combatant. Reactor loading near shutdown conditions should be modelled to determine the design specifications of the power generation system.

Hybrid configurations
Because the propulsion power dominates the power demand for future surface combatants, hybrid configurations become interesting to investigate. An introduction to a nuclear hybrid power plant was given, which indicated a slight reduction in weight and required volume. Also, the possibility of using vSMR for future SEWACO load is mentioned but not researched in detail on how it affects a surface combatant.

Structural impact
Both the SMR and vSMR power plants are relatively heavy compared with GTS. This increases the required strength of structures, which is not considered. It is not only expected that the lightship weight will increase but also that the required hull flexibility for absorbing and dissipating from energy impacts will be affected by increased stiffness.

Displacement impact
The impact of (v)SMR technology on the displacement of the future surface combatant has been evaluated thoroughly. However, navies employ larger ships like amphibious transport dock ships, which are not considered combatants. Further research should determine whether naval ships with higher block coefficients are more suitable for vSMR technology.

Effectiveness
An introduction to the determination of effectiveness for combatants is given. In practice, a more detailed model is necessary to evaluate the impacts of (v)SMR technology on the effectiveness of the future surface combatant.

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A
Hotel & SEWACO load

Table A.1: *Electrical Power Requirements by Mission Mode*

Mission Mode	**Combat (C)**	**Sprint (S)**	**Transit (T)**	**Patrol (P)**	**Slow Transit (ST)**	**Berth (B)**	**Emergency (EM)**
Bop (kW)	variable	variable	variable	variable	variable	variable	variable
Electric Plant (kW)	300	300	300	300	300	100	150
Aux+HVAC (kW)	800	800	1600	800	1600	1600	150
Outfit & Furnishings (kW)	100	300	300	100	300	200	0
P_{hotel} (MW)	1.20	1.40	2.20	1.20	2.20	1.90	0.30
Conv. Armament (kW)	125	62.5	62.5	125	62.5	0	0
HEL (kW)	1200	240	0	240	0	0	0
HPM (kW)	1820	364	0	364	0	0	0
UXV (kW)	0	0	200	200	0	0	0
VLS	850	500	0	500	0	0	0
Radar L Band	6000	6000	3000	6000	0	0	0
APARD X Band	600	600	300	600	100	0	50
Sonar	400	400	0	400	0	0	0
P_{SEWACO} (MW)	11.00	8.17	3.56	8.43	0.16	0.00	0.05
$P_{h,SEWACO}$ (MW)	12.20	9.57	5.76	9.63	2.36	1.90	0.35
Converter Efficiency	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Design Margin	1.1	1.1	1.1	1.1	1.1	1.1	1.1
$P_{e,tot}$ (MW)	13.84	10.85	6.54	10.93	2.68	2.16	0.40

SEWACO installation data

For all SEWACO, the nominal power and cooling requirements are given. This is the maximal required power fed to the specific system. In the case of naval-directed energy weapons, an un-considered pulse-forming network will bring the actual power output to higher levels. Heat batteries are used for weapons systems to reduce the required chillers. For the future surface combatant, a total of 11 MW of nominal power is necessary for SEWACO. This is comparable with other studies evaluating future SEWACO loads [13] [14].

- Sensors
  - **Long-range radar system (L-band)**
    Nominal power requirement: 6 MW
    Nominal cooling requirement: 4.2 MW, connected to chillers
  - **Active Phased Array Radar (X & S-band)**
    Nominal power requirement: 0.6 MW, based on [86]
    Nominal cooling requirement: 0.45 MW, connected to chillers
  - **Sonar**
    Nominal power requirement: 0.4 MW
    Nominal cooling requirement: 0.3 MW, partly cooled by sea and chillers
- Weapons
  - $2\cdot$ **High Energy Laser (HEL)**
    Nominal power requirement: 0.6 MW, in total 1.2 MW
    Nominal cooling requirement: 0.79 MW, connected to heat battery [17]
  - $4\cdot$ **High Power Microwave (HPM)**
    Nominal power requirement: 0.45 MW, in total 1.8 MW
    Nominal cooling requirement: 1.2 MW, 50% connected to heat battery [17]
  - **Verticle Launch System (VLS)**
    Nominal power requirement: 35 kW per module, 500 kW command control, totalling 0.85 MW [87]
    Nominal cooling requirement: -
  - **Conventional armament**
    Nominal power requirement: 0.125 MW
    Nominal cooling requirement: -
- Vehicles
  - **UXV's**
    Nominal power requirement: 0.2 MW
    Nominal cooling requirement: -

B
Reactor layout

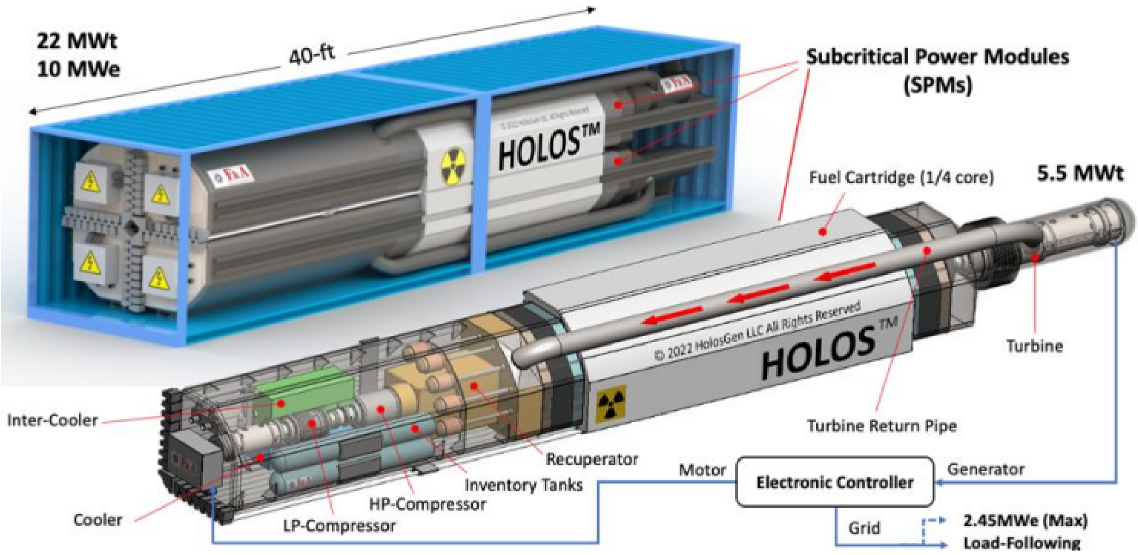


Figure B.1: *Detailed Holos-Quad layout with component labels* ($22MW_{th}$) *[8]*

Figure B.2: *Detailed CMSR layout* ($250MW_{th}$) *[4]*

C
Alternative propulsion architectures

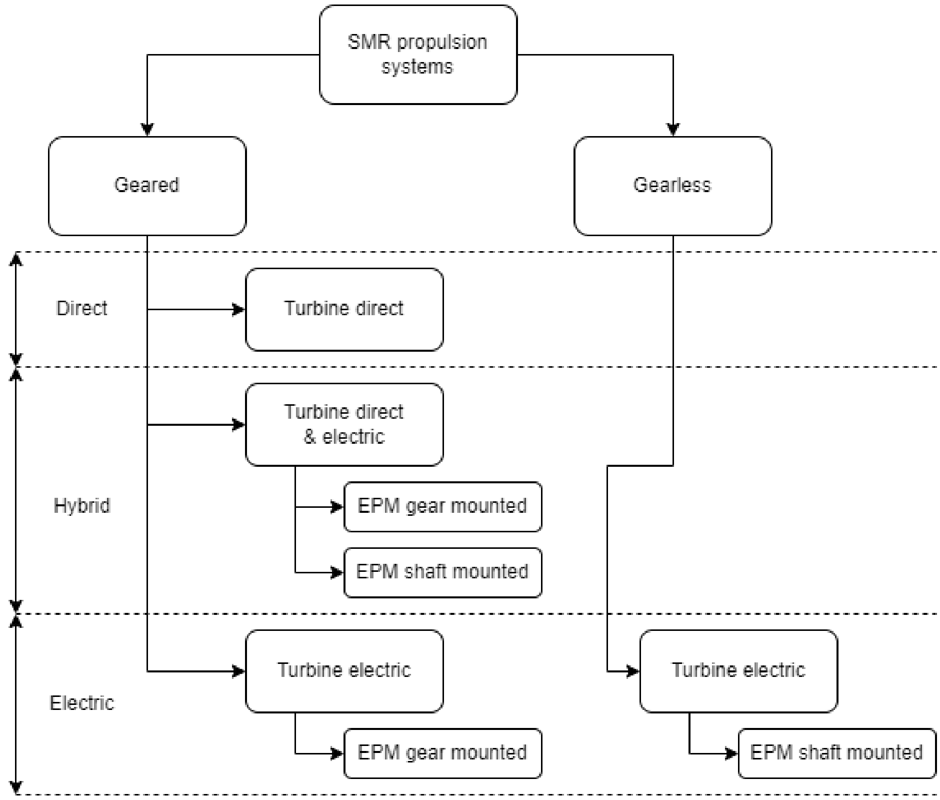


Figure C.1: *Classification of SMR propulsion configurations*

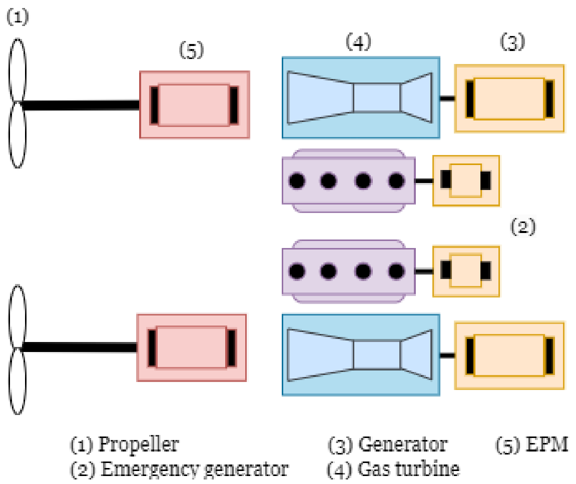


Figure C.2: *IPS propulsion configuration used with SMR, vSMR and conventional GTS*

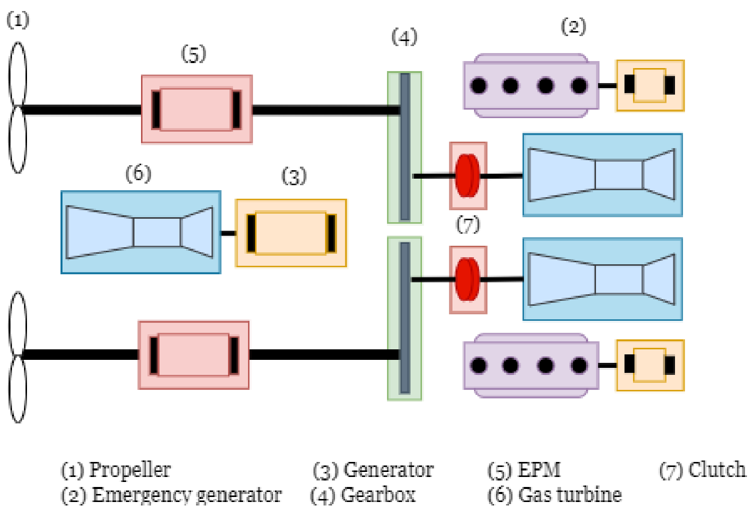


Figure C.3: *Hybrid propulsion configuration suggested for an SMR prime mover in chapter 8*

D
Radiation dose

The inverse square law dictates that the intensity of radiation exposure decreases with the square of the distance from the source seen in equation D.1.

$$I = \frac{I_0}{d^2} \tag{D.1}$$

Where:

I: radiation intensity at distance d
I_0: initial radiation intensity
d: distance from radiation source

The time spent near radiation sources is corrected with the occupancy factor in equation D.2.

$$f_O = \sum_{i=1}^{n} (T_i \times F_i) \tag{D.2}$$

Where:

T_i: fraction of the total time spent in the i^{th} area
F_i: dose rate factor for the i^{th} area, often normalized to the highest dose rate area
n: number of different areas or zones

The effect of the inverse square law in combination with the occupancy factor is given in an example for a machine room specialist.

Input variables:

- $r_{\text{max}} = 2$: maximum radius from the reactor
- $r_{r_{\text{work}}} = 5$: reference radius for the specialist executing maintenance
- $f_t = \frac{3}{4}$: fraction of the year specialist is on the combatant
- $t_{\text{spent}} = 4$: daily hours near the reactor
- t_{year}: annual hours near the reactor in a year, calculated as $t_{\text{spent}} \cdot f_t \cdot 365$ [hours]
- $t_{\text{year\_spent}}$: fraction of the year spent near the reactor, calculated as $\frac{t_{\text{year}}}{365 \cdot 24}$ [-]

The distance factor considers equation D.1, adjusting the exposure based on how distance affects radiation intensity. The specialist works at a distance of $r_{r_{\text{work}}}$ and sleeps at a distance of 20 meters away from the reactor compartment:

- $f_{d,work} = \left(\frac{r_{\text{max}}}{r_{r_{\text{work}}}}\right)^2$
- $f_{d,rest} = \left(\frac{r_{\text{max}}}{20}\right)^2$

The occupancy factor is then:

$$f_O = \frac{1}{f_t} \cdot \frac{1}{t_{\text{year\_spent}} \cdot f_{d,work+(1-t_{\text{year\_spent}})\cdot f_{d,rest}}} = 46.37 \quad \text{(D.3)}$$

The first fraction in equation D.3 considers the time present on the nuclear combatant. The second fraction in equation D.3 considers the time and distance spent near the reactor and the time and distance spent away from the reactor.

The conditions given to the specialist resulted in an adjusted exposure factor of 46. The maximum dose rate at the edge of the shield can be 46 times higher than the maximum allowed dose rate for a radiation worker under the following assumptions:

- Homogeneous radiation field: it is assumed that the radiation intensity only depends on the distance and not on angular distribution or obstacles that might affect the actual dose.
- Static Conditions: it is assumed that the conditions are static and do not change throughout the calculation. More specific occupancy factors and distance adjustments are crucial for realistic dose assessments in dynamic environments like ships, where personnel mobility and operational conditions vary.
- Simplified dose calculation: the simplified model ensures safety margins are in place. The actual calculation of radiation dose would require knowing the intensity of radiation at the source and applying these factors to calculate the dose received. This method calculates a factor to adjust the dose based on time spent and distance but doesn't incorporate specific radiation levels.

E

Principles of shielding

Reducing the radiation exposure to persons near radiation sources is called biological shielding [29]. Thermal shields are used inside the reactor to reduce the intensity of γ-rays, protect the reactor vessel from heating, and reduce radiation damage due to neutrons. As explained in chapter 5, it is necessary to shield against neutrons and γ-rays. The following radiation sources are to be considered [29]:

- **Prompt Fission Neutrons** are emitted from the core during operation, most important for designing the biological shield.
- **Delayed Fission Neutrons** are with few and have low energies. It is important to consider them in fuel-circulating reactors like the MSR, where they emit in the primary coolant loop.
- **Prompt Fission γ-rays**, are emitted in the core and easily reach the biological shield's end. Non-heavy metals are used in the shielding layers.
- **Fission Product Decay γ-rays** , continuously produced from the fuel, these γ-rays persist as a radiation source after the reactor has been shut down.
- **Inelastic γ-rays** are emitted due to inelastic neutron scattering and tend to be emitted from the reactor core and inner portions of the shield where the neutrons are the most energetic.
- **Capture γ-rays** are emitted each time a neutron is absorbed by a nucleus in a radiative capture reaction mostly occurring at thermal energies, resulting in capture γ-rays production in the shield.
- **Activation γ-rays** are emitted by radioactive nuclides formed from neutron absorption. In this manner, a significant portion of the reactor's internal structure, as well as the coolant and any additional atoms present in the coolant, becomes radioactive. This effect is necessary to evaluate when non-inert coolants are considered.

In practice, prompt fission neutrons are the hardest to shield [29]. Absorbing fast neutrons is impossible due to low absorption cross-sections of shield materials. Therefore, fast neutrons are slowed to thermal energies, followed by absorption. Hydrogen, which causes neutrons to lose 50% of their energy in elastic collisions, is mostly used in shields. Therefore, prompt fission neutrons are shielded with hydrogen-containing materials like water, concrete and polythene.
Radiation production in any operational reactor can be described as follows [26]:

- The fission process produces prompt fission neutrons and prompt fission γ-rays. Core materials mostly absorb the γ-rays.
- Some neutrons escape the reflector, thermal shield and reactor vessel. Dense hydrogenous materials are the most efficient neutron shields. Polythene is used extensively in the shielding of nuclear submarines.
- Fast neutrons are reduced to thermal energies and captured by iron and hydrogen constituents of the thermal shield, reactor vessel, primary shielding and compartment bulkheads. Capture γ-rays are produced according to:

  $$^{56}_{26}\text{Fe} + ^{1}_{0}n = \quad ^{57}_{26}\text{Fe} + \gamma$$

  . Boronated Polythene is used to reduce this effect. All γ-rays are most effectively shielded with high atomic number materials like lead.

- When non-inert coolant(s) are used, delayed fission neutrons and activation γ-rays in the primary coolant loop become important to consider.

The reactor needs primary shielding to reduce the neutron flux to levels that will ensure plant components are not activated [26]. The primary shield does not allow for safe exposure doses for the crew under full power operation. Secondary shielding must bring neutron flux and γ-ray production to safe levels.

Primary shield

The primary shield is designed on the dominant case. For example, the after-shutdown condition can determine the amount of gamma shielding to enter the reactor compartment for maintenance because of fission product decay γ-rays. The general design procedure is outlined [32].

- The intensities and distribution of the various sources arising in the core must be determined.
- The secondary sources that arise outside the core must be determined. Think of delayed fission neutrons in the primary coolant loop.
- After all existing materials in the reactor, reflector, and structure are considered, the additional shield material required outside the reactor proper must be chosen. Often expressed in required thickness, this conflicts with:
  - Both neutrons and γ - rays need to be captured
  - Weight and volume need to be minimised
  - The shield needs to be constructible in terms of production but also regarding personnel health when special but toxic materials are chosen.
- The listed steps must be considered for full power operation and after shutdown condition. This results in different boundary conditions for the secondary and primary shields as people might enter the reactor compartment after shutdown, which is forbidden during full power operation.

In practice, the reactor compartment is prohibited from entering during operation. This allows the primary shield to minimise neutron leakage in the reactor compartment and reduce the γ-ray production for safe shutdown conditions.
It is concluded that the design of the primary shield depends on full power operation and after-shutdown conditions.

Secondary shield

Commonly, the design of the secondary shield is done by assuming all radiation originating from the primary coolant because the core is covered with the primary shield. Lead, the most efficient material against γ radiation can be placed on the outside of the primary shield or in the secondary shield. The closer to the source, the more weight is saved when considering volume scaling. Often lead is found in the secondary shield due to savings in construction costs [32].
The secondary shield's weight and volume depend upon the reactor compartment's layout. General design considerations are outlined [32].

- The reactor should be placed in the centre. Asymmetric layouts, also with multiple primary loops, should be prevented.
- Equipment not activated by radiation should serve a dual purpose as shielding material. This should be placed near the secondary shield away from the reactor. This self-shielding can save in the primary neutron shield thickness.
- Use inert coolants.
- When using non-inert coolants like water within the Rankine cycle, minimise the primary loop length.
- Minimise the volume of the reactor compartment using space considerations for maintenance. Poor accessibility to equipment increases the exposure dose to personnel.
- Secondary shielding does not have to surround the entire reactor compartment. Radiation leaving the reactor compartment into unoccupied zones (ocean) is allowed. To avoid activation problems, a limit is imposed upon neutrons entering unoccupied zones.

It is concluded that secondary shield considerations affect the design of the surface combatant in terms of reactor placement, equipment protection, coolant requirements, maintenance requirements and activation problems.

Outside reactor compartment

The arrangement of working/sleeping areas determines the level of radiation allowed on the shield surface. Areas with limited access or less frequently used adjacent to the reactor compartment are advantageous. Weight and volume of the reactor compartment regarding shielding can be reduced by [32]:

1. Relocation of storerooms
2. Usage of water and/or fuel storage tanks
3. Include wire and pipe ways
4. Include power-load factors after analyses of the operational profile

F

Neutron Shielding

Given the simplified spherical reactor presented in figure F.1, the flux at point P can be calculated with formula F.1 assuming a small core and a thick shield. The detailed derivation can be found in literature [29].

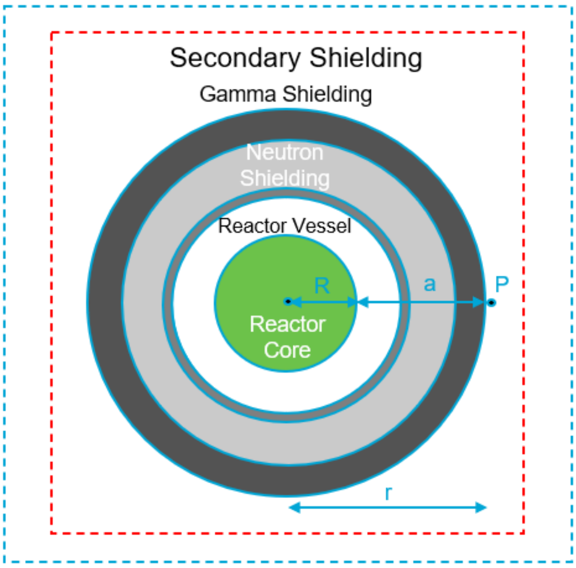


Figure F.1: *Spherical reactor core surrounded by a spherical shield with parameters*

In figure F.1, R is the core radius surrounded with shielding given a thickness a. The neutron leakage in point P is calculated with equation F.1.

$$\phi(P) = \frac{SA}{4\alpha}\left(\frac{R}{R+a}\right)^2 e^{-\Sigma_{Rs}a}\left(1-e^{-2\alpha R}\right)\cdot e^{-\Sigma_{RFe}t} \tag{F.1}$$

given

$$\alpha + \beta = \Sigma_{R_s} \tag{F.2}$$

where

$$\alpha = (1-f)\Sigma_{Rc} + f\Sigma_{Rm} \tag{F.3}$$

and

$$\beta = \Sigma_{Rs} - (1-f)\Sigma_{Rc} - f\Sigma_{Rm} \tag{F.4}$$

S is the fission density rate of neutrons produced uniformly expressed in $\frac{neutrons}{cm^3 \cdot s}$ calculated with equation F.5.

$$S = \nu \cdot \rho_Y \tag{F.5}$$

Assuming that the fissions occur in U-235, gives $\nu = 2.42$. The fission density can be calculated with equations F.6 and F.7.

$$Y = \frac{P_{th}}{Q} \tag{F.6}$$

With Y the fission rate ($\frac{fission}{s}$), P_{th} the installed rated power ($\frac{J}{s}$) and Q the recoverable energy per fission (J). For U-235, Q is around $200meV = 3.2e - 11J$. The fission density ρ_Y can be calculated with equation F.7.

$$\rho_Y = \frac{Y}{V} \tag{F.7}$$

With V, the core volume (cm^3) can be found by dividing P_{th} through the analysed reactor power density ($\frac{kW}{L}$). For the HOLOS-QUAD, f is estimated at 0.27 [8].

A is equal to 0.12 [29].

In equation F.3, the metal volume fraction in the reactor core equals f, which differs per reactor design. It can be estimated by summating the present volume of heavy metals divided by the coolant (water or gas). Σ_{Rc} is the summation of the macroscopic cross-sections, also called removal cross-sections, represented by the coolants. Σ_{Rm} represents the summation of the removal cross-section of present heavy metals. This is the summation consisting of the core material and the fuel.

In equation F.4, Σ_{Rs} is the summation of the removal cross-sections of the used shielding material (high-temperature resistant) concrete and polyethene, found in table F.1.

Table F.1: *Macroscopic (removal) cross-section of materials [29] [88]*

Material	Macroscopic cross section (cm^{-1})
Water	0.103
Concrete	0.089
Uranium	0.174
Iron	0.1681
5% Borated Polyethylene	0.1064

Σ_{RF} is representing the removal cross-section of the reactor (pressure) vessel. The thickness of the reactor vessel is notated with t and is not iterated in this calculation process.

According to the literature, a flux of 6.8 $\frac{neutrons_{fast}}{cm^2 \cdot s}$ gives a dose-equivalent rate of 0.01 mSv/hr [29], which allows for an estimation of the fast neutron dose rate at the surface in point P when assuming a spherical core with a reactor vessel and a shield.

G
Gamma Shielding

Gamma shielding is solved by adding lead to the neutron shield until the gamma-ray leakage in point P is considered safe. The gamma-ray leakage from a spherical core measured in point P is calculated with equation G.1 [29].

$$\phi_b = \frac{S}{4\pi \cdot R^2} \cdot B_p \cdot (\mu \cdot R) \cdot e^{-\mu R} \tag{G.1}$$

Where:

ϕ_b: gamma-ray buildup flux at the shield surface $[rays/(cm^2 \cdot s)]$
S: number of gamma-rays $[rays/s]$
R: radius to point P [cm]
B_p: buildup factor, determined with table [-]
μ: attenuation coefficient, determined with table [cm^-1]

Most gamma rays originate from the reactor by prompt fission gamma rays, gamma rays from fission product decay, and radiative capture and inelastic scattering. All gamma rays with their group exhibit energy spectra that are more or less continuous. These spectra are segmented into energy groups to facilitate attenuation calculations, and calculations are performed on a group-by-group basis [29]. This classification helps accurately estimate the shielding needs since gamma rays of different energies interact with shielding materials in varied ways. This thesis only considers prompt gamma rays.

The calculation of prompt gamma-ray emissions is performed for each energy interval group in table G.1.

Table G.1: *Numbers of prompt fission & product decay γ-rays emitted per fission [29]*

Group number	Energy interval, MeV	Prompt (χ_{pn})	Decay (χ_{dn})
1	$0-1$	5.2	3.2
2	$1-3$	1.8	1.5
3	$3-5$	0.22	0.18
4	$5-7$	0.025	0.021

With the fission rate from equation F.6, the number of prompt gamma-rays per energy group can be calculated with equation G.2.

$$S_i = \chi_{pn,i} \cdot Y \tag{G.2}$$

The calculation of the buildup factor is done with a look-up table. This differs for the material gamma rays travel through and their energy group. The buildup factor travelling through concrete is calculated with equation F.3.

$$B_{p,\text{concrete}} = A_1 e^{-\alpha_1 \mu R} + A_2 e^{-\alpha_2 \mu R} \quad \text{(G.3)}$$
$$A_1 = A$$
$$A_2 = 1 - A$$

All values for the different energy groups and the attenuation coefficient for concrete are in table G.2.

Table G.2: *Taylor expansion to determine buildup factor for concrete [29]*

Shield material	Energy (MeV)	A	$-\alpha_1$	α_2	$\mu_{concrete}$
Concrete	0.5	38.225	0.14824	-0.10579	0.0870
	2.0	18.089	0.04250	0.00849	0.0445
	4.0	11.460	0.02600	0.02450	0.0317
	6.0	10.781	0.01520	0.02925	0.0268

The build-up factor calculation with borated polyethylene as a neutron shield is more complicated. In the energy region $0.03 - 15MeV$, a geometric progression fitting expression for the build-up factor of polyethylene is given in equation G.4 [89].

$$B(E,x)_{poly} = \begin{cases} 1 + \frac{b-1}{K-1}\left(K^x - 1\right) & \text{for } K \neq 1, \\ 1 + (b-1)x & \text{for } K = 1, \end{cases} \quad \text{(G.4)}$$

where,

$$K(E,x) = cx^2 + d\frac{\tanh\left(\frac{x}{x_k} - 2\right) - \tanh(-2)}{1 - \tanh(-2)} \quad \text{(G.5)}$$

The fitting factors and the attenuation coefficient for borated polyethylene are found in table G.3. In equation G.4, $x = \mu_{poly} \cdot R$.

Table G.3: *Fitting expression to determine buildup factor for polyethylene, fitting factors from [89] and μ from [90]*

Shield material	Energy (MeV)	a	b	c	d	x_k	μ_{poly}
polyethylene	0.5	-0.086	2.301	1.490	0.022	16.198	0.0995
	2.0	-0.036	1.828	1.162	0.013	15.193	0.0506
	4.0	0.004	1.621	0.990	-0.007	19.326	0.0344
	6.0	0.026	1.503	0.917	-0.023	15.033	0.0276

With the build-up factor known per group and shielding material, the gamma-ray buildup flux at the shield is determined with the total intensity with the equation G.6.

$$I = \sum \phi_{b,i} \quad \text{(G.6)}$$

The intensity of gamma rays in point P can be transformed to dose rate with equation G.7.

$$\dot{X} = I \cdot E \cdot \left(\frac{\mu_a}{\rho}\right) \quad \text{(G.7)}$$

Where:

Table G.4: *Mass absorption coefficient in air [29]*

	Energy (MeV)	$\frac{\mu_a}{\rho}$
Air	0.5	0.0297
	2.0	0.0238
	4.0	0.0194
	6.0	0.0172

- $\dot{X}$: dose rate, when multiplied with 0.0659 measured in Sv/hr
- I: is the intensity of gamma radiation [$rays/(cm^2 \cdot s)$]
- E is the energy of the gamma rays [MeV]
- $\frac{\mu_a}{\rho}$ mass attenuation coefficient in air, measured in [cm^2/g]

The mass attenuation coefficient in the air is found in table G.4.

The half-value layer (HVL) is the thickness of a material required to reduce the gamma radiation intensity by half. An HVL of 1 cm is taken for lead [2]. The HVL for lead is used iteratively in the shielding calculations to ensure the total thickness reduces the gamma-ray dose to acceptable levels. Given the initial dose rate $\dot{X}$ and the desired maximum dose $\dot{X}_{\text{max}}$, the thickness (t) of lead required can be estimated using:

$$t = HVL \cdot \log_2 \left(\frac{I_0}{I_{\text{max}}} \right) \tag{G.8}$$

The iteration is stopped when 50% of the maximum exposure per year is reached.

H
Reactor shielding radius

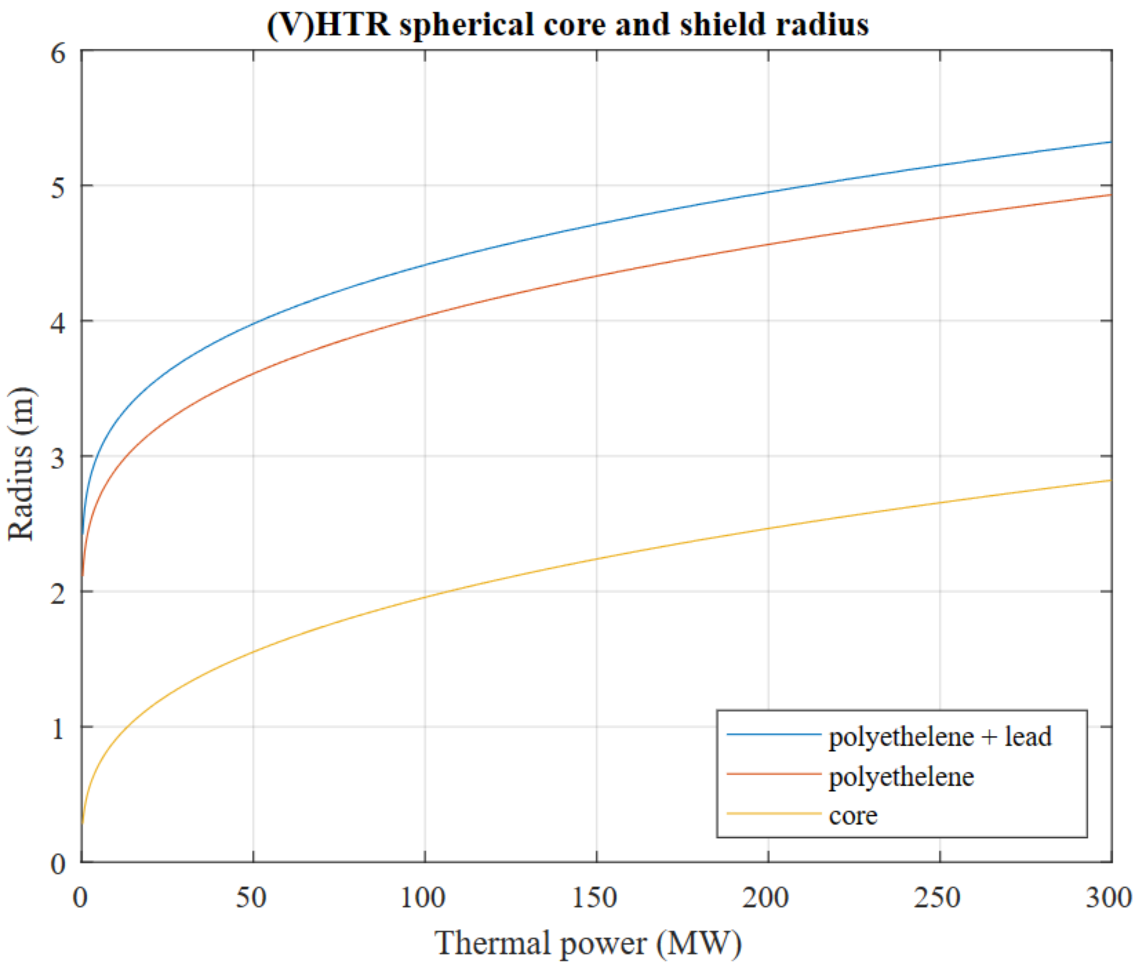


Figure H.1: *The radius of the core and different shielding materials over thermal power of the (v)HTR*

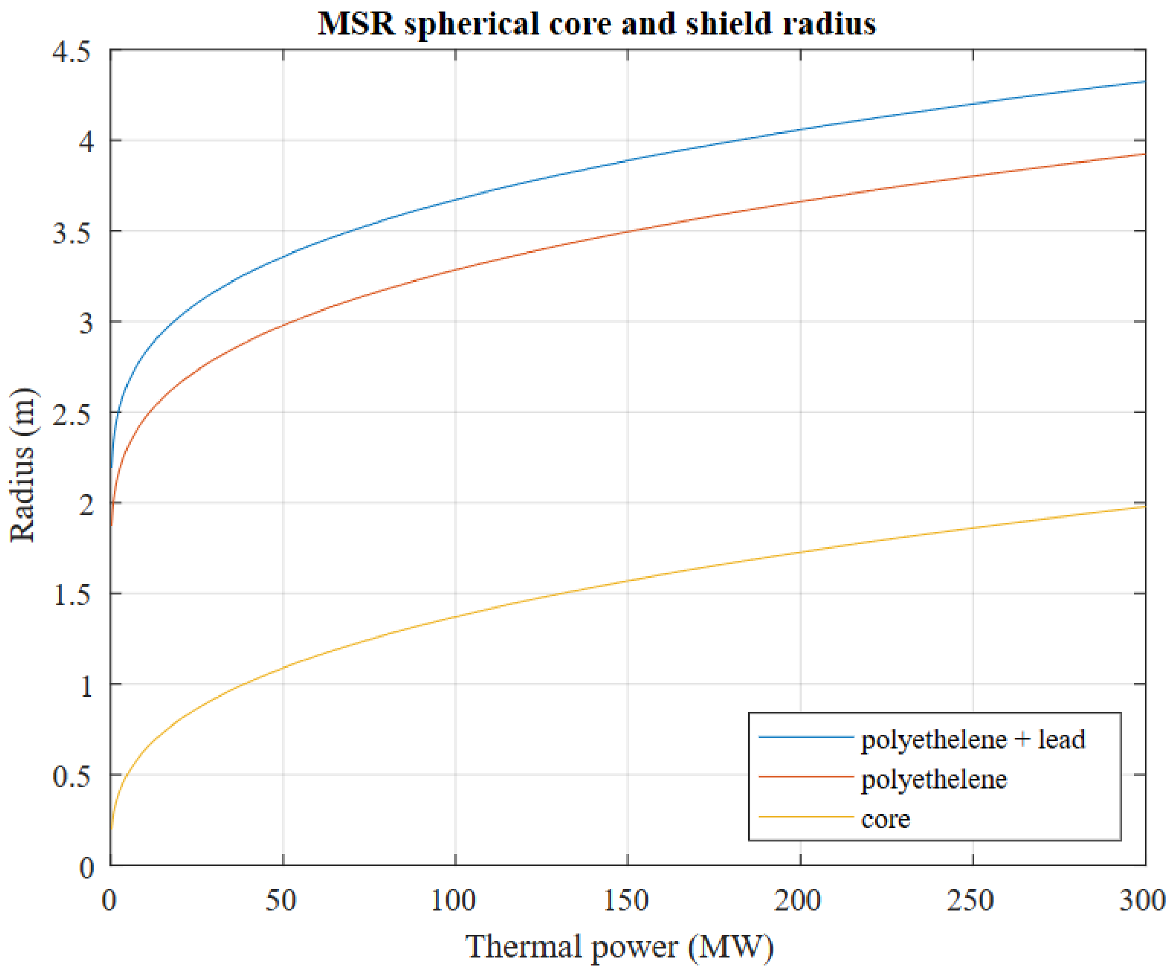


Figure H.2: *The radius of the core and different shielding materials over thermal power of the MSR*

I

Power cycle

Steam

As discussed in chapter 7, heat engines model a turbine converting heat into mechanical work. For simplicity and reliability reasons, a simple Rankine cycle without reheat is preferred in nuclear-powered naval combatants. Rankine technology is a proven and well-established technology with a globally established supply chain. Both in land and sea applications, experienced operators from around the world are available. The Rankine cycle achieves high efficiency due to low pumping power while the Brayton cycle achieves high efficiency due to high turbine inlet temperature [40]. However, using water as a coolant has several drawbacks which need to be considered when implemented in a naval combatant using fourth-generation reactor technology.

1. Size and weight of the steam cycle system are larger for the same power output
2. Maintaining acceptable water chemistry, increasing regular maintenance
3. Steam generators with their support system have corrosion issues over time, increasing maintenance
4. Neutron absorption by water, needing reactor monitoring systems
5. Water ingress possibility, leading to robust heat exchanger designs when used in the primary cycle
6. Potential for hydrogen generation by water-gas shift reaction, active safety monitoring systems needed
7. High-pressure operation which increases complexity and damage control while this varies for specific turbine designs (40-180 bar cycles have been observed)

It can be observed that all risks involved are related to the used coolant. While using water as a coolant is nowadays the preferable choice, it needs more manpower and extra systems to keep the power conversion safe and reliable. Using fourth-generation reactor technology allows for more independent autonomous operation while using a Rankine cycle might decrease this autonomy because of regular maintenance requirements. It is observed that with higher operational reactor temperatures ($600°C+$), gas coolants with the Brayton cycle are preferred over the Rankine cycle [4]. Still, MSRs operational between $500 - 700°C$ mainly use the superheated Rankine cycle [4].

Gas

The closed Brayton cycle initially lost its competitiveness to the open Brayton cycle in the $1970s$ due to the rapid development of commercial aeroplane gas turbines [40]. However, the closed Brayton cycle technology has resurfaced due to technology advancements in heat exchangers and turbomachinery manufacturing and operation capabilities. As explained in chapter 7, coolants in the form of gas can reach higher temperatures and increase efficiency. Also, a size reduction is observed in literature [1]. The following gases are considered as coolant on a surface combatant.

1. **Helium** has a high specific heat transfer coefficient (higher than air) and a good thermal conductivity. It is chemically inert and is, therefore, not susceptible to neutron absorption. It is highly resistant to corrosion and has high thermal efficiency. It can operate at extremely high temperatures and operational pressures not exceeding $10MPa$. Operational experience at different scales has been obtained, addressing issues with erosion of turbine blades but mostly warning about gas leakage. Also, helium needs purification before entering the reactor as impurities may cause direct corrosion at high temperatures [91]. Helium, unlike nitrogen, is a non-renewable resource on earth and in combination with increasing scarcity, many industries raise their concern on future availability and price [92].
2. **Supercritical-carbon-dioxide** (sCO_2) is officially not a gas but a highly dense supercritical fluid which has a comparable efficiency with the helium Brayton cycle at lower temperatures ($550°C$ instead of $850°C$) but at higher pressures (20 instead of 8 MPa) [93]. Nuclear reactors with core outlet temperatures above $500°C$ benefit in efficiency and size from a supercritical carbon-dioxide cycle. Furthermore, the system has advantages such as having high thermal efficiency, being small in size and being lightweight [94]. The gas is less chemically inert than helium and can be highly corrosive when exceeding $500°C$. There is limited operational experience at any scale with carbon-dioxide turbines and recuperators [95]. Turbomachinery needs special seals, bearings and high-temperature corrosion-resistant materials. Due to compact size, which results in a flow of a high-density fluid at very high velocities, erosion is a significant issue at the two existing $sCO2$ test facilities [95].
3. **Nitrogen** is virtually identical to atmospheric air. Therefore, with minor modifications, adapting machinery to N2 is less complicated as the machinery is similar to the current open Brayton air turbines. It is a semi-inert gas. However, nitrogen absorbs neutrons, which reduces fuel efficiency and produces the isotope carbon-14 (N-14, the most common nitrogen, produces the fission product C-14). Therefore, radioactivity control is needed. Nitrogen has a lower specific heat transfer coefficient than helium. However, it is shown that a nitrogen cycle delivers comparable thermodynamic cycle performance to that of a system using helium [96].

Further information to compare these suggested coolants can be found [41].

Supercritical-carbon-dioxide and helium

It is noted that using sCO_2 can increase the cycle efficiency and reduce the total plant size significantly. However, these high efficiencies are not obtained on a future surface combatant for the following reasons:

- There is no to limited operational experience with sCO_2 in the power cycle.
- Corrosive behaviour is observed in current prototypes [95].
- A high operating pressure of $20MPa$ results in safety concerns and maintenance challenges when installed on a combatant [95].
- Thermal stability problems at elevated temperatures have been mentioned, as the prospect of carbonaceous deposits on the turbine blades which increases maintenance[97].

The $sCO2$ closed Brayton cycle is believed to have promising benefits for combatants regarding compact turbomachinery and heat exchangers. However, surface combatants desire a reliable and robust power generation system. Considering system autonomy and the high operational pressures, $sCO2$ as a working medium is currently practical for land-based applications.

Nuclear reactor designers often suggest helium as a working medium because it is inert and has a high specific heat coefficient over increasing temperature and pressure ($5.1kJ/kgK$ at atmospheric pressure). However, from the experience of many test facilities, several considerations regarding the use of helium (He) compared to nitrogen ($N2$) are important to address:

- Helium turbomachinery has a lower TRL than nitrogen-based solutions [96]. Nitrogen has an increased thermal and physical similarity to air, meaning existing turbomachinery can be employed after relatively small changes rather than adapting towards helium-driven turbines. Rolls-Royce has presented a conceptual design featuring a nitrogen-helium mixture which U-battery is keen on integrating [98]. Experience with the nitrogen cycle can be found in France, CEA [99].

- The density of nitrogen makes the mass flux and bulk velocities comparable to steam-driven systems, benefitting from operational experience the TRL increases.
- Helium is a problematic working medium to contain. Experience from previously operated high-temperature helium power conversion systems shows leakage as inevitable [100]. Complicated seal designs have been introduced to minimise this problem. Nitrogen, with a molecular weight 7 times higher than helium, resulting in a better containable gas.
- Helium cycle turbomachinery must incorporate more compressor and turbine stages due to the combination of low molecular weight and a high specific heat ratio [101]. Both properties lead to an increase in compressor stages to obtain the desired pressure ratio for the turbine. Nitrogen, with a high molecular weight, requires fewer stages and reduces the system's length in axial turbine design.
- Helium turbines operate at high rational speeds $(18,000)$ RPM limited by the tip blade speed to maintain structural integrity [40]. In combination with many stages, a long slender rotor is required, which becomes dynamically unstable [100]. Therefore, using nitrogen can simplify the structural integrity of the rotor.

J
Turbine

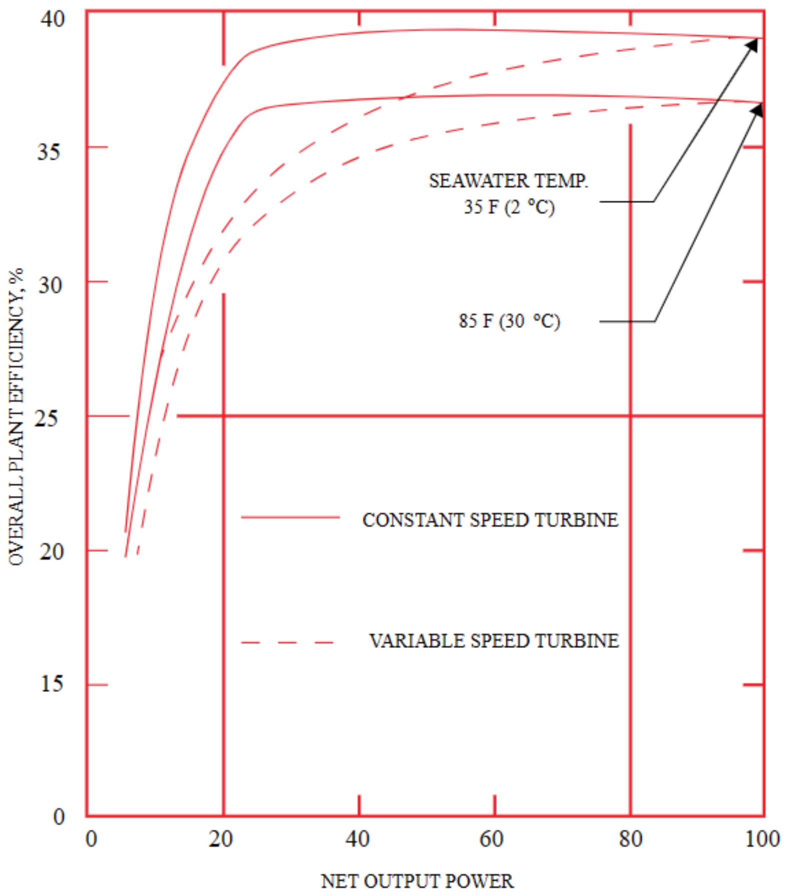


Figure J.1: *Plant efficiency vs output power in % of the installed turbine power [54]*

K
Heat Exchanger

Logarithmic mean temperature difference

$$\delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{K.1}$$

With,

$$\begin{aligned} \Delta T_1 &= (T_{\mathrm{h,i}} - T_{\mathrm{c,o}}) \\ \Delta T_2 &= (T_{\mathrm{h,o}} - T_{\mathrm{c,i}}) \end{aligned} \tag{K.2}$$

Overal heat transfer coefficient calculation
It must be noted that this thesis uses estimated overall heat transfer coefficients from literature; see table 6.1. When the layout of the heat exchanger is known, the overall heat transfer coefficient can be calculated with equation K.3.

$$\frac{1}{U} = \frac{1}{h_h} + \frac{t}{k} + \frac{1}{h_c} \tag{K.3}$$

Determining the overall heat transfer coefficient U in equation K.3 depends on the convective heat transfer coefficients h_h&h_c, which can be calculated with the Nusselt number, equation K.4.

$$\mathrm{Nu} = \frac{hD_h}{k} \tag{K.4}$$

The thermal conductivity k depends on the plate or tube material used. D_h is the hydraulic diameter. The Hesselgraves' recommendation for laminar flow and Gnielinski's correlation for turbulent flow can be used to estimate the Nusselt number. In literature, several relations can be found [45]. The correlation below is used for $N2$.

- Laminar flow $(Re \leqslant 2300)$

$$Nu = 4.089$$

- Turbulent flow $(Re \geqslant 5000)$

$$Nu = \frac{\frac{f}{8}(Re - 1000)Pr}{1 + 12.7\left(\mathrm{Pr}^{2/3} - 1\right)\sqrt{\frac{f}{8}}}$$

For turbulent flow conditions, use the Reynolds and the Prandtl numbers.

$$\mathrm{Re} = \frac{D_h v \rho}{\mu} \tag{K.5}$$

$$\mathrm{Pr} = \frac{c_{\mathrm{p}}\mu}{k} \tag{K.6}$$

The friction factor f can be obtained from the Moody chart or the Colebrook-White correlation.

$$\frac{1}{\sqrt{f}} = -2.0 \log \left(\frac{\varepsilon / D_h}{3.7} + \frac{2.51}{\text{Re} \sqrt{f}} \right) \tag{K.7}$$

Detailed intermediate cycle

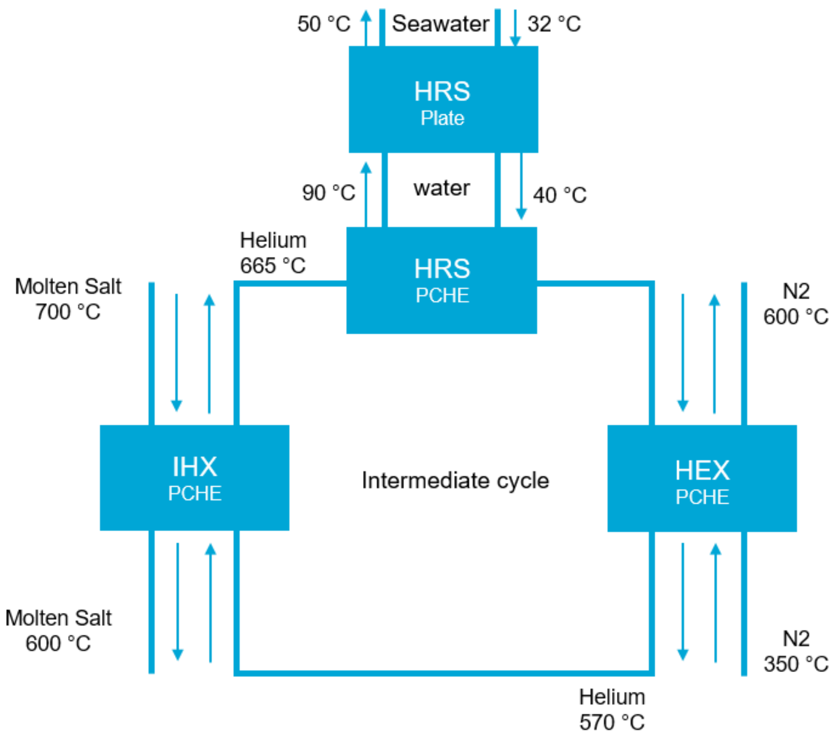


Figure K.1: *Intermediate cycle*

Detailed power cycle

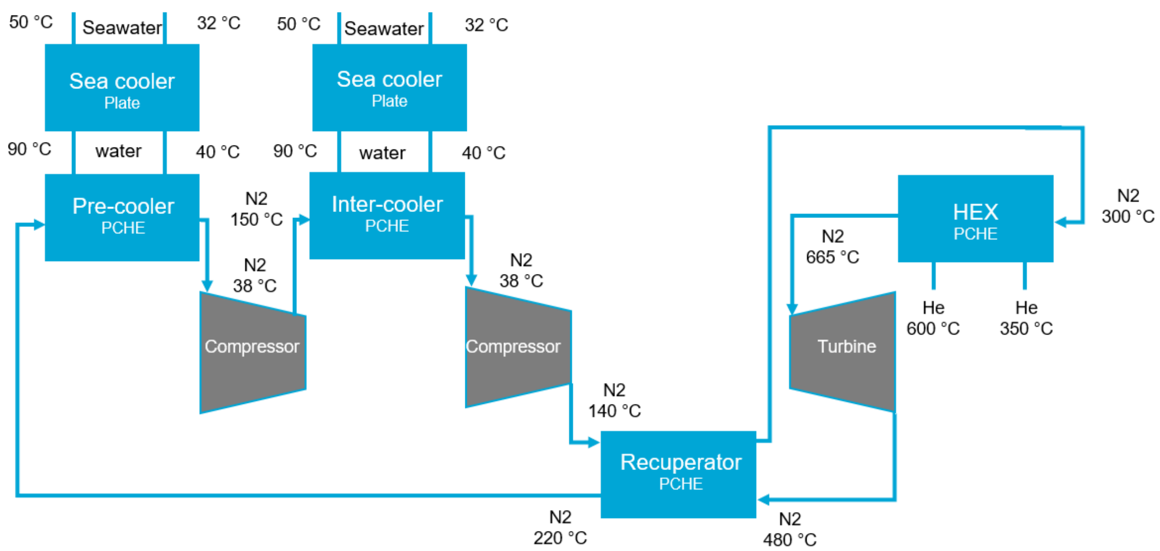


Figure K.2: *Power cycle*

L

Electrical machine

The sizing of an electrical machine [61].

$$\text{Width } = D_{\text{stator}} = \left(\frac{T}{TRV \cdot s^2 \cdot \frac{\pi}{4} \cdot L/D} \right)^{\frac{1}{3}} \tag{L.1}$$

$$\text{Length } = L_{\text{stator}} = L/D \cdot \left(\frac{T}{TRV \cdot s^2 \cdot \frac{\pi}{4} \cdot L/D} \right)^{\frac{1}{3}} \tag{L.2}$$

$$\text{Height } = \left(\frac{T}{TRV \cdot s^2} \right)^{\frac{1}{3}} \cdot CVF \cdot (L/D)^{-\frac{1}{3}} \cdot \left(\frac{\pi}{4} \right)^{\frac{2}{3}} \tag{L.3}$$

$$TRV = \frac{T}{V_{\text{rotor}}} = \frac{T}{\pi \cdot r_{\text{rotor}}^2 \cdot l_{\text{rotor}}} = 2 \cdot \sigma \tag{L.4}$$

Typical values for TRV, s, CVF and L/D are given in full detail in previous work [61].

M
Converter data

Dimensions and weights for conventional DC-AC power converter units are found in table M.1.

Table M.1: *DC - AC converters ($10kV$ DC - $6.6kV$ AC), higher than a power rating of 26 MW is extrapolated [13]*

Power Rating (MW)	Weight (kg)	Length (**m**)	Depth (**m**)	Height (**m**)
6	3720	4	1.6	2.36
8	3780	4	1.6	2.36
10	3900	4	1.6	2.36
12	3960	4	1.6	2.36
14	5610	5.5	1.6	2.36
18	5730	5.5	1.6	2.36
22	6438	6.4	1.6	2.36
24	6618	6.4	1.6	2.36
26	$*$	7.3	1.6	2.36
28	$*$	7.3	1.6	2.36
30	$*$	8.8	1.6	2.36
32	$*$	8.8	1.6	2.36
34	$*$	8.8	1.6	2.36

The used estimations for DC-DC converters are found in table M.2.

Table M.2: *DC - DC converters ($10kV$ DC - $1kV$ DC) [13]*

Converter	Primary Voltage (**kV**)	Secondary Voltage (**kV**)	Weight (**kg**)	Length (**m**)	Depth (**m**)	Height (**m**)
10 MW DCDC	10	1	10000	14	1.6	2.36
5 MW DCDC	10	1	5000	7	1.6	2.36

N

Operational profile

Event: Exercise week

Location: Naval Exercise Area, International Waters

Scenario: The future surface combatant participates in a joint ASW and AAW exercise with allied naval forces. The exercise tests the combatant's capabilities in defending against submarine and airborne threats. No historical data of current combatants have been analysed to model this scenario.

Table N.1: *Event Data, power is found in table A.1*

Timestamp	Event Type	Event Description	Power (MW)
Day 1 00:00	Transit	Sea	T
Day 1 06:00	Transit	Sea	T
Day 1 06:00	Slow Transit	Departure	ST
Day 1 07:00	Slow Transit	Departure	ST
Day 1 07:00	Patrol	Coastal Patrol	P
Day 1 10:00	Patrol	Coastal Patrol	P
Day 1 10:00	Combat	Engagement	C
Day 1 11:00	Combat	Engagement	C
Day 1 11:00	Transit	Next destination	T
Day 2 08:00	Transit	Open Sea Transit	T
Day 2 08:00	partol	Submarine Hunt	P
Day 2 10:00	partol	Submarine Hunt	P
Day 2 10:00	Combat	Anti-Air Defense	C
Day 2 12:00	Combat	Anti-Air Defense	C
Day 2 12:00	Transit	Coastal Waters	T
Day 2 15:00	Transit	Coastal Waters	T
Day 2 16:00	Transit	Coastal Waters	T
Day 3 03:00	Transit	Coastal Waters	T
Day 3 03:00	Combat	Surface Engagement	C
Day 3 06:00	Combat	Surface Engagement	C
Day 3 06:00	Slow Transit	Underway Replenishment	ST
Day 3 08:00	Slow Transit	Underway Replenishment	ST
Day 3 08:00	Transit	Coastal Waters	T

Continued on next page

Table N.1 – *Continued from previous page*

Timestamp	Event Type	Event Description	Power (MW)
Day 3 12:00	Transit	Coastal Waters	T
Day 3 12:00	Patrol	Coastal Patrol	P
Day 3 14:00	Patrol	Coastal Patrol	P
Day 3 14:00	Transit	Next destination	T
Day 3 16:00	Transit	Open Sea Transit	T
Day 4 02:00	Transit	Open Sea Transit	T
Day 4 06:00	Slow Transit	Harbor Entry	ST
Day 4 08:00	Berth	Port Visit	B
Day 4 12:00	Berth	Port Visit	B
Day 4 13:00	Slow Transit	Harbor Exit	ST
Day 4 15:00	Transit	Sea	T
Day 4 16:00	Transit	Sea	T
Day 5 00:00	Transit	Sea	T

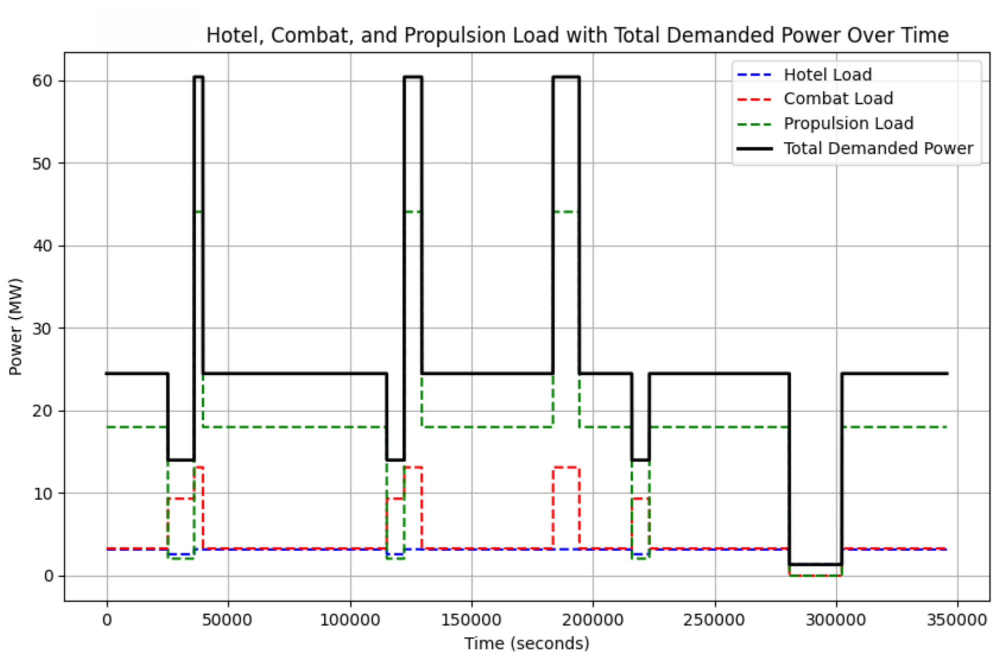


Figure N.1: *Example of operational profile from table N.1 used in Python*

O Double SEWACO load

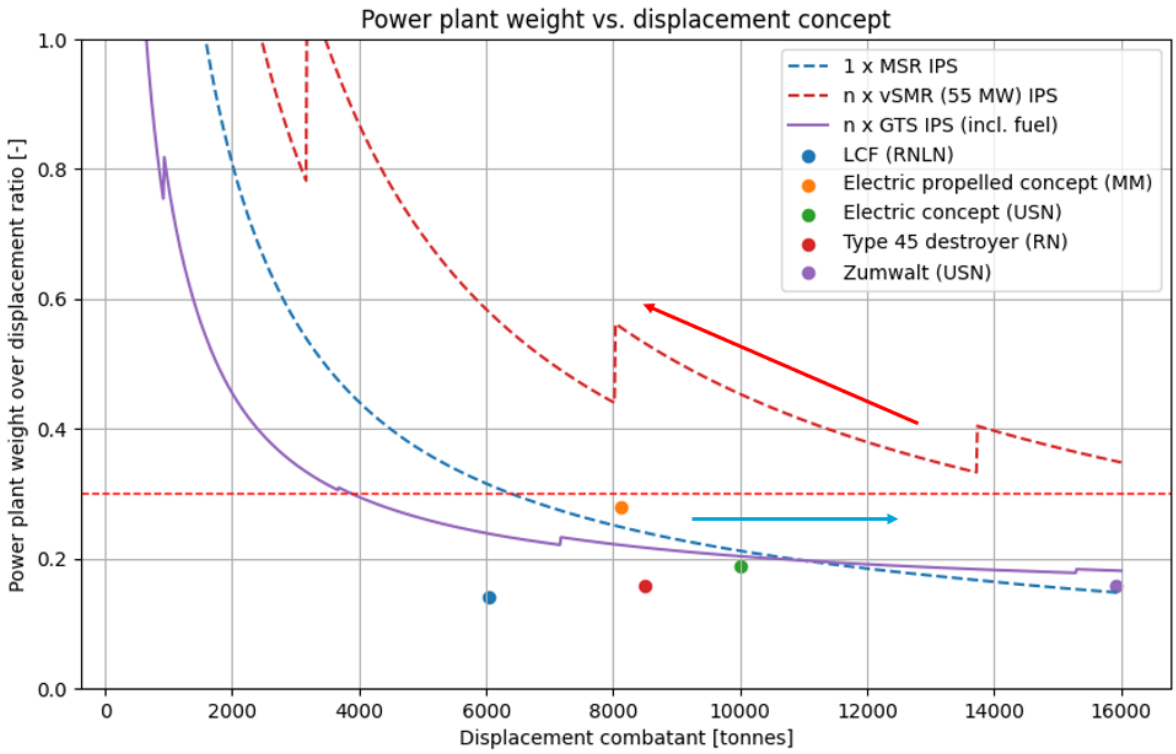


Figure O.1: *The weight impact of the power plant on the displacement of the combatant for a SEWACO load of* $28MW_e$ *(twice the initial load). The weight ratio of the SMR moves slightly to the left (blue arrow). After an increase in SEWACO load, the weight ratio of the vSMR moves to the right and upwards (red arrow).*

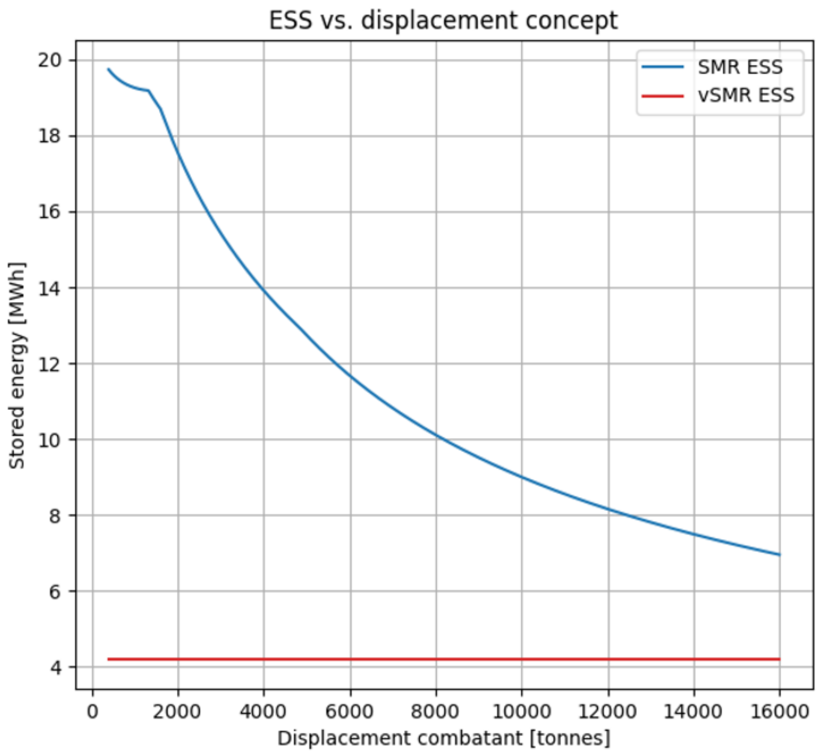


Figure O.2: *Required ESS for (v)SMR technology for a SEWACO load of* $28MW_e$ *(twice the initial load)*

P
Preliminary design

Table P.1: Weight [tonnes] data for surface combatant of $9,800$ tonnes

Parameter	**SMR**	**vSMR**	**GTS**
Shield(s)	1020	2345	-
Reactor pressure vessel(s)	126	315	-
Heat exchangers	161	120	-
Generators	38	46	77
Turbines	60	60	155
Emergency motors	85	85	85
Switchboards	33	37	35
Converters	127	140	135
Batteries	29	12	-
Electric propulsion motor	214	214	214
SEWACO	689	688	688
Chillers	91	91	91
Bunker	-	-	1225

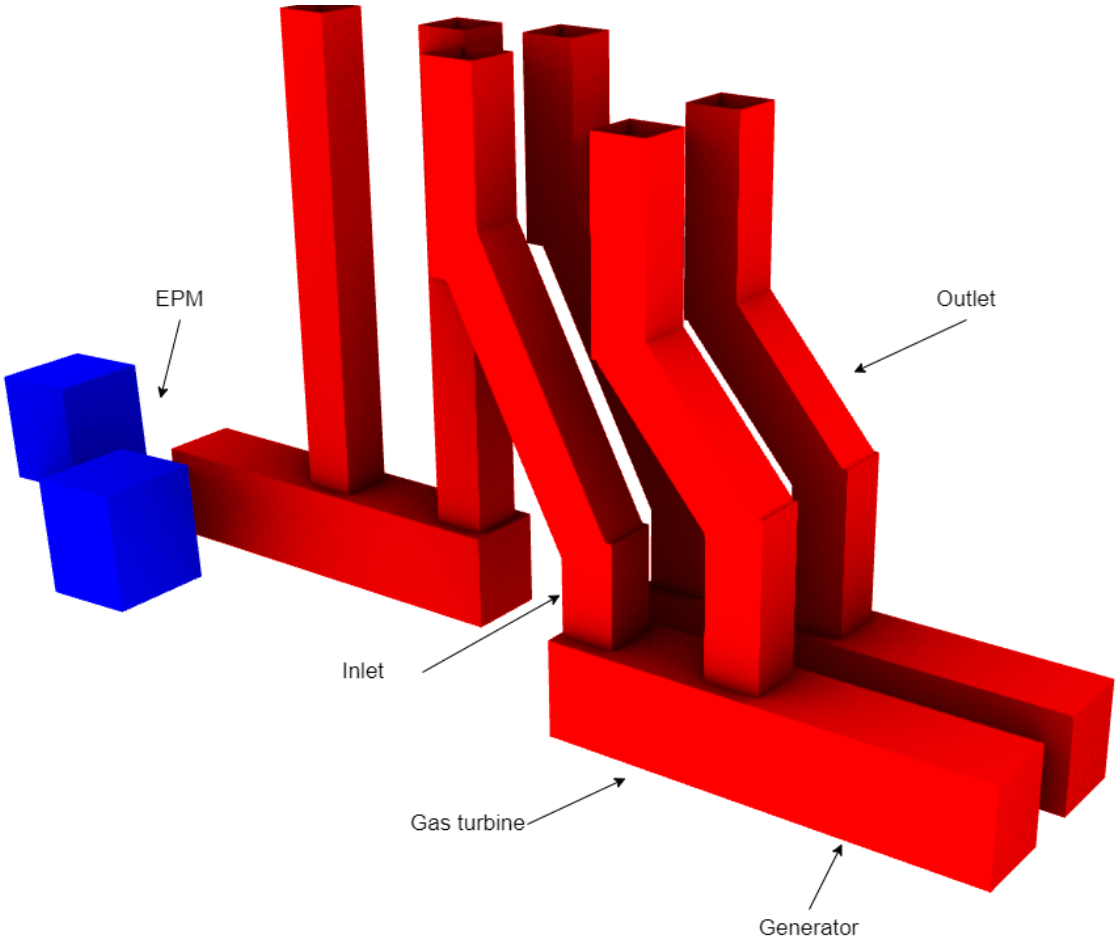


Figure P.1: *Conventional GTS layout with component labels* ($3 \cdot 35.4 MW_e$)

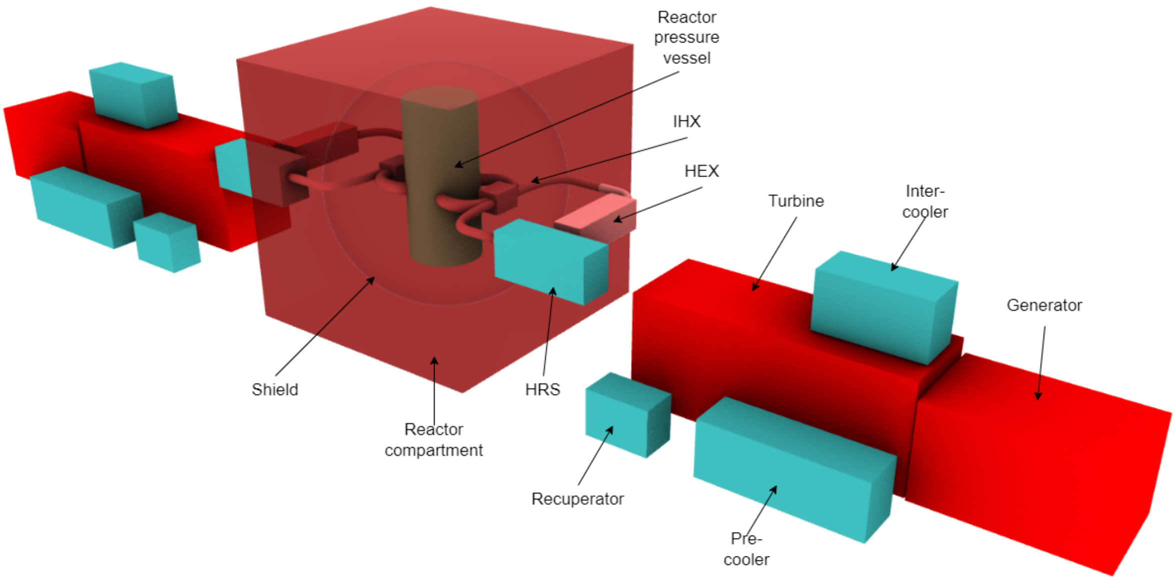


Figure P.2: *SMR layout with component labels* ($230 MW_{th}$)

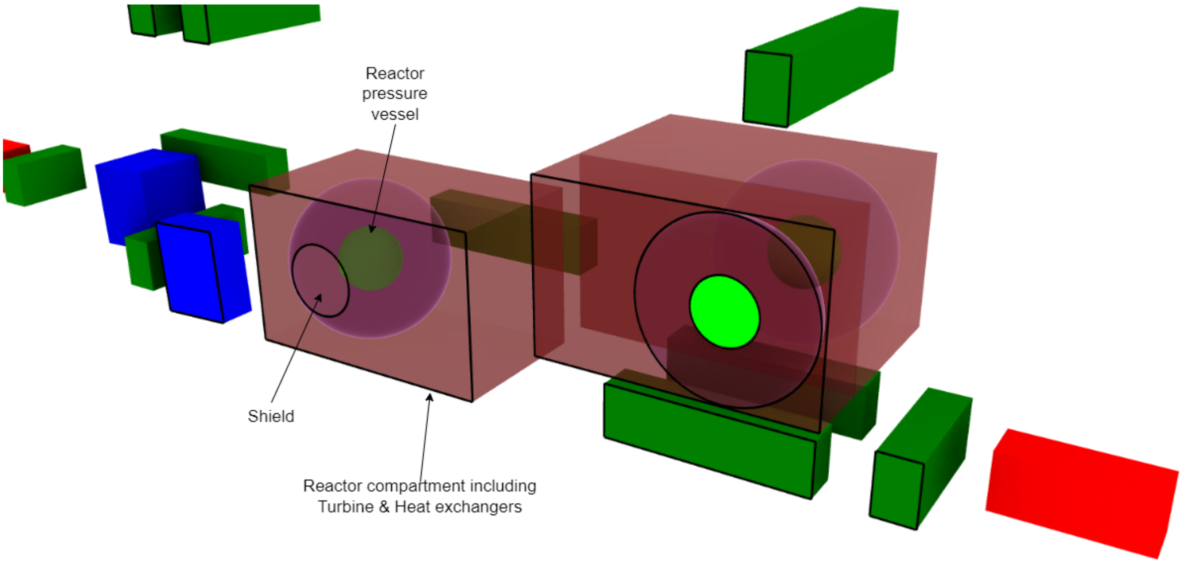
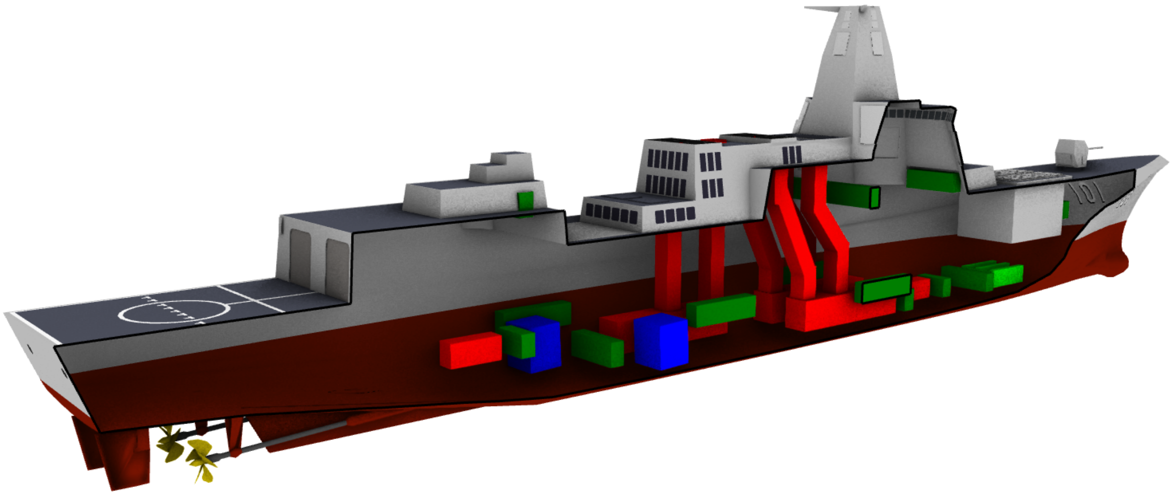
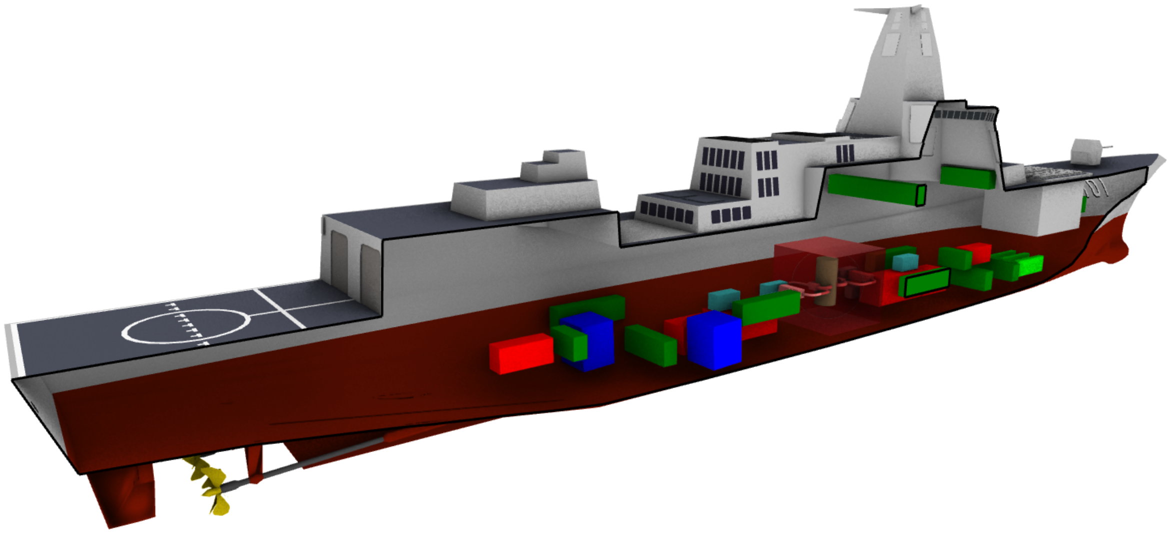


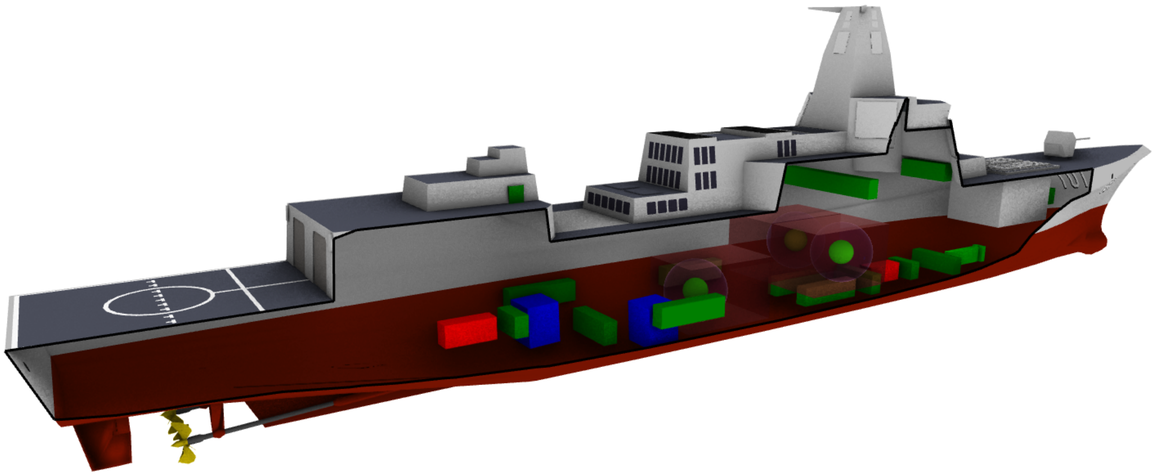
Figure P.3: *vSMR layout with component labels* ($3 \cdot 55MW_{th}$)



(a) *GTS configuration excluding bunkers* $(3 \cdot 35.4MW_e)$

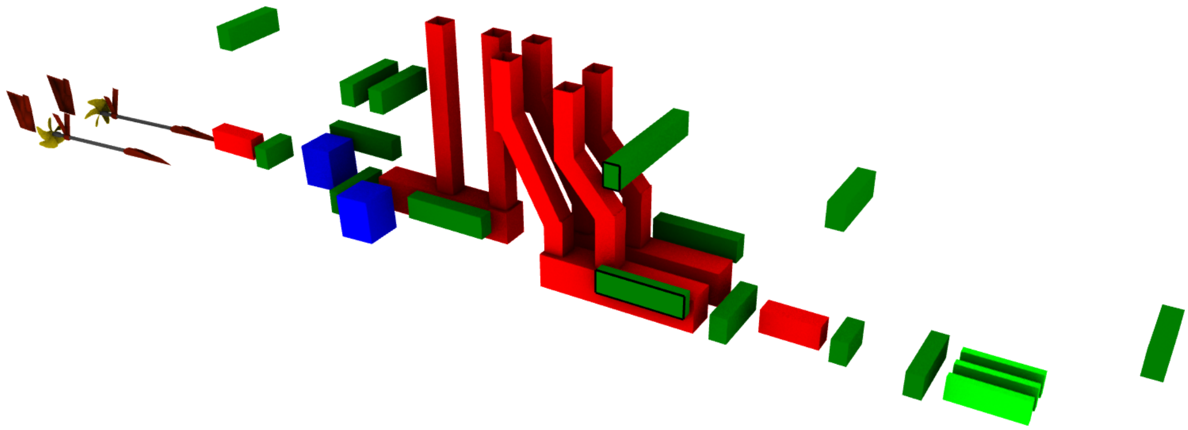


(b) *SMR configuration* $(230MW_{th})$

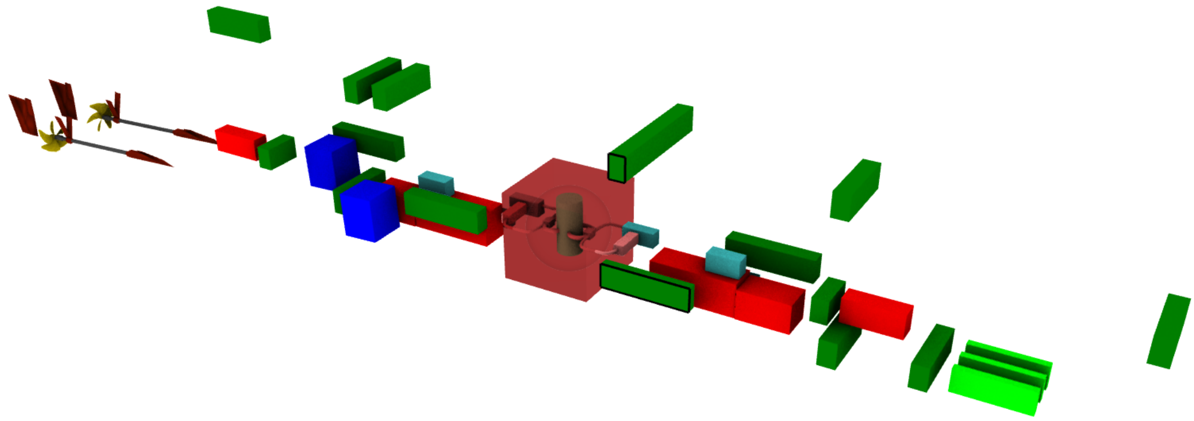


(c) *vSMR configuration* $(3 \cdot 55MW_{th})$

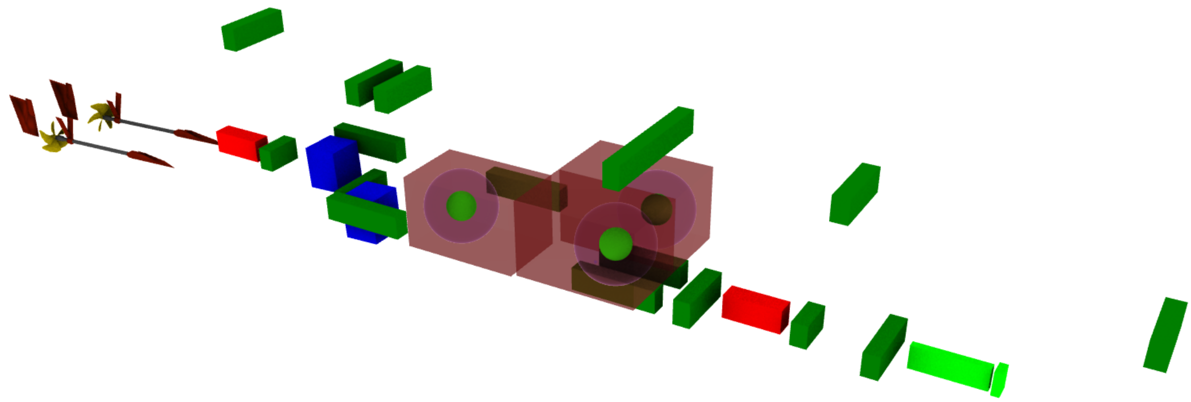
Figure P.4: *Preliminary design viewing power generation, distribution and conversion components with hull*



(a) *GTS configuration excluding bunkers* ($3 \cdot 35.4MW_e$)



(b) *SMR configuration* ($230MW_{th}$)



(c) *vSMR configuration* ($3 \cdot 55MW_{th}$)

Figure P.5: *Preliminary design viewing power generation, distribution and conversion components without hull. Power generation; red, power distribution; green, ESS; bright green and power conversion; blue.*

Nuclear energy has found widespread application in navies across the globe. This thesis explores the potential integration of generation IV (very) Small Modular Reactor (SMR) technology for future surface combatants, focusing on the Very High-Temperature Reactor modelled as vSMR and a Molten Salt Reactor as SMR. The impact of using generation IV (v)SMR technology for power generation on the design of future surface combatants was unexplored. An estimation of future power and energy requirements and a detailed investigation of reactor compartment design with a focus on shielding, power generation, distribution, and conversion systems are performed to find the implications on ship design. Emerging naval-directed energy weapons and advanced sensor technologies are implemented to position the combatant within the spectrum of future mission capabilities.
A sizing model evaluates the feasibility of (v)SMR integration in terms of power, energy, volume, and weight. An indication of the available weight for (v)SMR technology is searched by iterating over the displacement of future surface combatants. For the defined future surface combatant, naval SMR power plants are compatible in terms of weight with conventional all-electric gas turbine-driven combatants with displacements above $8,000$ tonnes. The model reveals that vSMR technology faces significant challenges related to weight despite its potential benefits in terms of redundancy and modularity. For combatants up to $16,000$ tonnes, naval vSMR power plants are not feasible due to their substantial weight and space requirements, primarily driven by the need for extensive shielding. Increasing the power output per vSMR reduces the required shielding and provides an alternative solution.
A case study explores a preliminary design of a future surface combatant with a displacement of $9,800$ tonnes. The study suggests that the propulsion demand significantly impacts the size of the power plant. This results in the need for energy storage systems that manage variable power demands, particularly for SMR technology integrated into large surface combatants.
The study assesses the effectiveness of the preliminary design in terms of survivability, mobility, range and endurance. It is estimated after capability prioritisation that (v)SMR technology and conventional gas turbine configurations have an equivalent survivability impact. A critical trade-off is highlighted between enhanced endurance and range against challenges, such as an increase in weight, volume requirements, and compromises in mobility compared to conventional gas turbine systems. The choice between SMR and vSMR technologies further complicates this balance by choosing between compactness and load response. A first indication is that generation IV (v)SMR technology can enhance a future surface combatant's autonomy and future power load capabilities without compromising its effectiveness.

This thesis is a graduation project on generation IV (v)SMR technology integrated into future surface combatants for power generation. Delft University of Technology (TU Delft) collaborates with the Material and IT Command (COMMIT) on this graduation project to contribute to the realisation of fourth-generation nuclear propulsion and power generation for the maritime sector.

TU Delft

Materiel and IT Command
Ministry of Defence