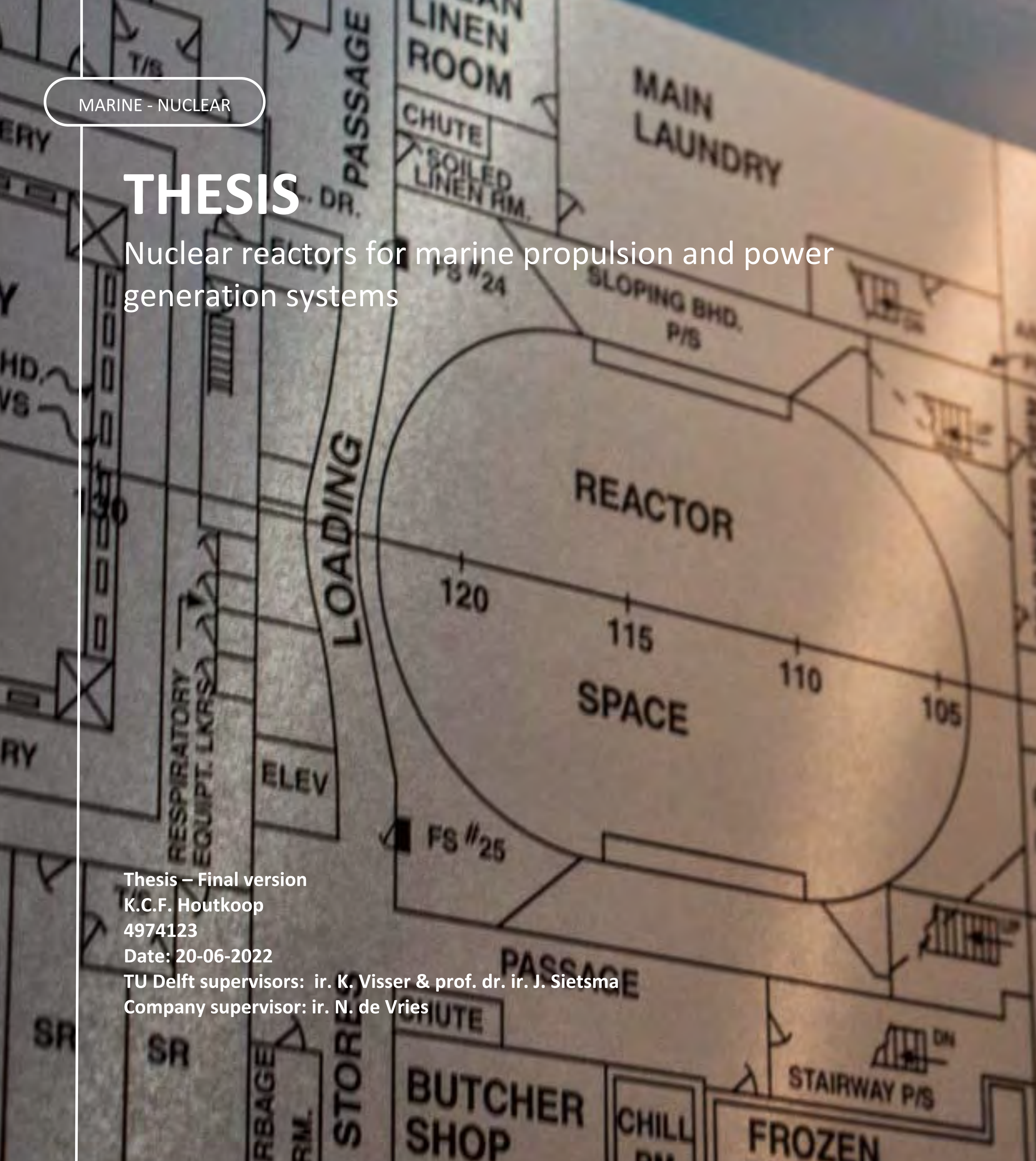
MARINE - NUCLEAR

THESIS

Nuclear reactors for marine propulsion and power generation systems



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C-JOB DEDICATED NAVAL ARCHITECTS

Figure on titlepage: photo of the NS savannah plan [1]

MARINE NUCLEAR

Thesis for the degree of MSc in Marine Technology in the specialization of *marine engineering*

Nuclear reactors for marine propulsion and power generation systems

By

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Performed at

C-Job Naval Architects

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SUMMARY

Nuclear power is currently not a commonly used option in commercial marine applications, despite its potential for significant emission reductions. This thesis is an overview of what has been done before, and what the potential is of modern marine nuclear power applications considering the long-term goals of harmful emission reduction in the maritime industry.

The concept of nuclear power is discussed, followed by the current state of nuclear power in both the shore-based, naval and the mostly historic marine application. The regulations for the marine application are noted to be outdated and require significant work for a successful application. Finally, the societal aspect of nuclear power is highlighted, as societal acceptance is not self-evident for nuclear power applications.

Different developments in the field of nuclear power are addressed, with specific interest in the SMR (Small Modular Reactor), concepts that are part of the "generation IV" family, and concepts that can operate using thorium as fuel. Multiple options are considered, from the well-established PWR (Pressurized Water Reactor) to the gen IV concepts: the HTR/VHTR (high/very high temperature reactor), fast reactors in both gas-cooled, liquid-metal and sodium cooled varieties (GFR, LFR, SFR) and finally the MSR (Molten Salt Reactor). Of these the HTR/VHTR and MSR in small modular reactor form are considered the most attractive option for the marine application, due to their passive safety, high burnup, high operating temperatures, and possibilities for thorium use in the future.

Criteria are established that are of importance to a marine propulsion and power generation system, establishing a framework for an implementation. Focusing on topics as: efficiency, transient loading capabilities, environmental impact, economic viability, size, and weight.

For power conversion (linking the heat generation to power/electricity for the vessel) the open-cycle Brayton turbine with a heat exchanger is selected as most suitable, despite the steam turbine being more developed and projecting a possible higher efficiency. The choice for the open-cycle Brayton turbine stems from the system size and weight reduction, along with a relatively easily implementable heat rejection system for enhanced load following capabilities. The selected heat exchanger is of the helical coil type, as this is significantly more developed and proven than the PCHE.

The most suitable layout is determined to be an all-electric layout, as this will greatly improve reliability (enhancing safety by redundant arrangements) and make the implementation easier applicable to a host of vessels. The electric layout allows for the combination of additional system such as batteries and emergency power. This layout is then combined with the open Brayton turbine and its heat rejection capabilities to ensure a system that is both compact as well as highly capable in performance.

Finally, four suitable concept vessels were established that allowed for a like-for-like replacement with a nuclear propulsion and power generation system. This allowed for a comparison to the conventional fuel-based systems where it is shown that the implementation of nuclear power can provide very large CO_{2eq} reductions (over 98%), while reducing size and weight if vessels of suitable size are selected. The trade-off to this reduction is the production of nuclear waste, alongside the increased upfront cost due to the high capital investment associated with nuclear power.

PREFACE

This thesis on the application of nuclear reactors for marine propulsion and power generation systems was written as graduation assignment for the master Marine Technology at the Delft University of Technology. The graduation assignment was carried out at C-Job Naval Architects in Hoofddorp.

First of all, I'd like to thank Niels de Vries of C-Job for first of all pitching the interesting graduation topic and following that the weekly progress meetings and critical feedback, which was of great help for the overall coherence and quality of the report.

Secondly, I'd like to thank both my university supervisors:
Klaas Visser for his time, enthusiasm for nuclear powers marine application and asking critical questions that brought in new perspectives.
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Finally, I'd like to thank those that helped me at parts of my research by providing clarity, new insights or simply pointing me in the right direction.
Thomas Steenberg, from Copenhagen atomics, for taking the time to explain some of the details and considerations for molten salt reactors alongside with pointing me in the right direction on some of the specifics of nuclear power.
Ginevra Delfini, for taking the time to discuss legislation issues, possible bottlenecks, and the direction in which legislation developments are going.
Everyone at C-Job for their interest and questions on a subject that is quite a departure from conventional propulsion and power generation systems.

Koen Houtkoop
Rotterdam, June 2022

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ABBREVIATIONS

ABWR	Advanced Boiling Water Reactor
BOP	Balance Of Plant
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium
CAPEX	Capital Expenditure
DBA	Design basis accident
DWT	Deadweight tonnage
ECCS	Emergency Core Cooling System
EEDI	Energy Efficiency Design Index
EPR	European Pressurised Reactor/Evolutionary Power Reactor
FliBe	Fluoride, Lithium & Beryllium based salt
FPSO	Floating Production, Storage and Offloading
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
GWd/tHM	Gigawatt days per ton of heavy metal (1 GWd = 24000 MWh)
He	Helium
HEU	High Enriched Uranium (>20% U235)
HTGR	High Temperature Gas-cooled Reactor
IAEA	International Atomic Energy Agency
ICE	Internal Combustion Engine
IMO	International Maritime Organisation
LASH	Lighter Aboard SHip (concept where a specialized vessel transports lighters/barges)
LEU	Low Enriched Uranium (up to 20% U235)
LFR	Lead-cooled Fast Reactor
LMTD	Logarithmic Mean Temperature Difference
LOA	Length Over All
LOCA	Loss Of Cooling Accident
LWR	Light Water Reactor (parent category of the PWR, BWR and SCWR)
MSR	Molten Salt Reactor
NRC	(United States) Nuclear Regulatory Commission
OPEX	Operational Expenditure
ORNL	Oak Ridge National Laboratory
Pa	Protactinium
PCHE	Printed Circuit Heat Exchanger
PEM	Polymer Electrolyte Membrane
PRIS	Power Reactor Information System
Pu	Plutonium
PWR	Pressurized Water Reactor
RBMK	Russian reactor design, translation: High power channel-type reactor
RoPax	Roll-on-roll-off & passenger ship
SCWR	Super-Critical Water Reactor
SFR	Sodium-cooled fast reactor
S-I	Sulphur-Iodine
Sm	Samarium
SMR	Small Modular Reactor
SOLAS	Safety Of Life At Sea
SWU	Separative Work Unit
Th	Thorium
U	Uranium
UNCLOS	United Nations Convention on the Law Of the Sea
VHTR	Very High Temperature Reactor
VVER	Russian reactor design, translation: water-water energetic reactor
Xe	Xenon

INTRODUCTION

Introduction

The maritime industry has to reduce harmful emissions[1] sharply to comply both with its own set goals for decarbonisation and the international goals set in light of climate change. To achieve these goals new power and propulsion system options have to be considered. Nuclear power is seen as an interesting option, especially with the developments of the past decades on more modern reactors.

The operational experience with commercial marine nuclear reactors is limited. This results in a lot of information being unknown, primarily in terms of technical feasibility, which comes associated with specific regulations, the lifecycle of the plant and the economic feasibility.

The goal of this thesis is to explore the potential of nuclear power for the commercial marine application, identifying the possibilities, considerations, and constraints for applying modern reactor technology in the maritime environment. Technical requirements and issues must be identified, as well as relevant regulations and economic considerations. This literature report is focussed on these questions.

Structure of the report

The main research question is:
What is the potential of nuclear reactor-based propulsion systems for the decarbonisation of shipping?

To answer this main research question, it is required to split the question into multiple sub questions. For the literature report these are the following sub questions:

1. **What is nuclear energy?**
2. **What is the current state of nuclear energy?**
3. **What are the developments in nuclear energy?**
4. **What are the defining conditions of a marine propulsion system?**
5. **What energy conversion and power plant systems are suitable for a nuclear based marine propulsion system?**
6. **What are the specific additional considerations for the application of the nuclear marine propulsion and power system?**

For the research addition to the thesis

7. **What are the most significant performance parameters for nuclear propulsion and power generation system components?**
8. **What are the overall characteristics of an implementation of a nuclear propulsion and power generation system?**
9. **How does a nuclear propulsion and power generation system compare to a conventional marine propulsion system?**

[1] Harmful emissions in this report refers to both greenhouse gasses (Carbon dioxide (CO_2), methane (CH_4), Nitrous oxide(N_2O), and others) as well as air pollution (SO_x ,NO_x ,Particulate matter)

1 NUCLEAR ENERGY

This section is an introduction into nuclear energy. This chapter covers the fundamentals to provide the basic understanding on the subject and answers sub question 1: What is nuclear energy?

1.1 Required terminology

Nucleus indicates the centre of the atom, where the protons and neutrons that form the bulk of the atomic mass are clustered together [2].
Radioactivity indicates that the element is unstable at its nucleus level and will change into a different nucleus, often while emitting some form of radiation [2].
Radiation is a form of energy that is released in the form of high-speed particles or electromagnetic waves. Alpha, Beta and Gamma radiation are all forms of radiation classified by their wavelength. Besides these forms of radiation nuclear fission is also an emitter of neutron radiation [2].

1.2 Fission

All currently operating nuclear power reactors rely on the basic principle of fission[2], which starts with a nucleus of a heavy element capturing a neutron. The neutron provides the nucleus with additional energy, exceeding its binding energy and causing it to fission: Fission meaning that it splits into multiple lighter fission products as well as releasing energy and multiple neutrons. This is shown in Figure 1.

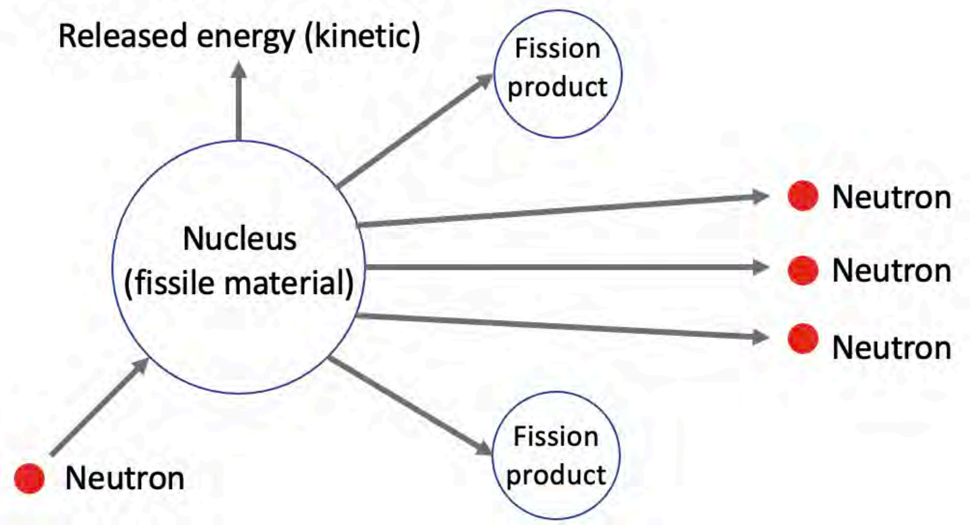

Figure 1 Fission reaction

If the released neutrons are then captured by another nucleus of fissile material this can undergo fission as well. The second nucleus that just absorbed the neutron then follows the same principle, eventually causing a chain reaction of fission reactions to occur. This chain reaction is the fundamental principle of nuclear power from fission [2].

1.2.1 Fissile isotopes

Not all materials can be used as fuel in a nuclear reactor, for it to be used as fuel it has to be fissile. The only naturally occurring fissile fuel material is $^{235}U_{92}$ (hereafter called U235)[3] which is an isotope of uranium. When a material is fissile it means that the nucleus of this material can undergo fission when

[2] Fission is not the only possibility, but the other options (mainly fusion) are still in development and not used in commercial power installations which is why they are not addressed in this report.
[3] U235 indicates that the sum of the protons and neutrons in this isotope of uranium is 235, 92 indicates the number of protons. Leaving 235 - 92 = 143 neutrons.

capturing a neutron and that the material can be used in a sustained fission chain reaction. U235 is however not the only material that can be used as fuel in a nuclear reactor, there is a selection of others. These are however non-naturally occurring: $^{233}U_{92}$, $^{239}Pu_{94}$ and $^{241}Pu_{94}$. These isotopes are man-made and formed almost exclusively in nuclear reactors [2].

1.2.2 Fertile materials

Fertile material indicates material that can become a fissile material after it has received and absorbed neutrons, followed by radioactively decaying into another material. This is the case with uranium (U238) which after absorbing a neutron, decays to neptunium (Np239) before decaying into fissile plutonium (Pu239).

Similarly thorium (Th232), which after capturing a neutron, decays into protactinium (Pa233), which decays into uranium (U233). This is shown in Figure 2 for two "breeding" reactions that can occur in the nuclear reactor. The breeding of material is the formation of fissile material from fertile material initiated by neutron absorption. The decay process is not instantaneous and as shown in Figure 2 can take substantial time.

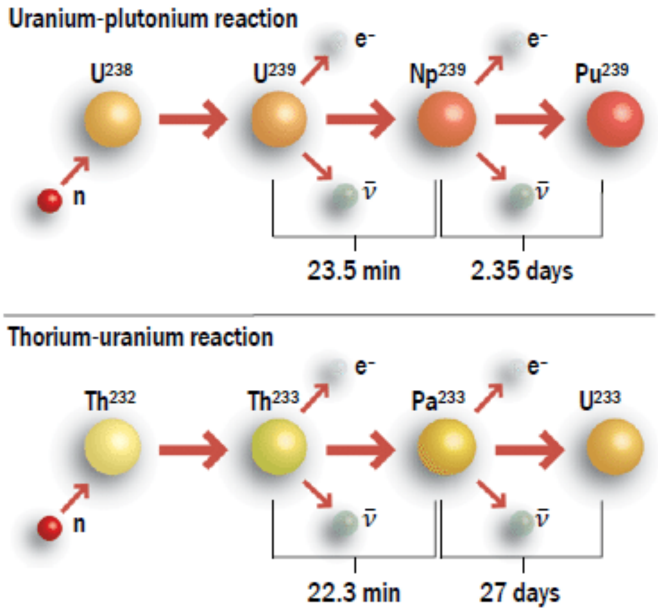

Figure 2 Common fissile to fertile reactions [3]

If a reactor turns more fertile material into fissile material than it consumes it is called a breeder reactor. If it consumes more material than it produces, it is called a converter or burner reactor.

1.3 Basic concept of a nuclear reactor

To better describe the selection of reactor concepts that will be discussed in further chapters, first the fundamental principles of nuclear reactors are covered.

1.3.1 Reactor core

The purpose of the core is to contain the material and serve as a vessel in which the fission reaction can be maintained. A basic cross-section representation of a nuclear reactor is shown in Figure 3, with each of its components discussed in further detail in the following subchapters.

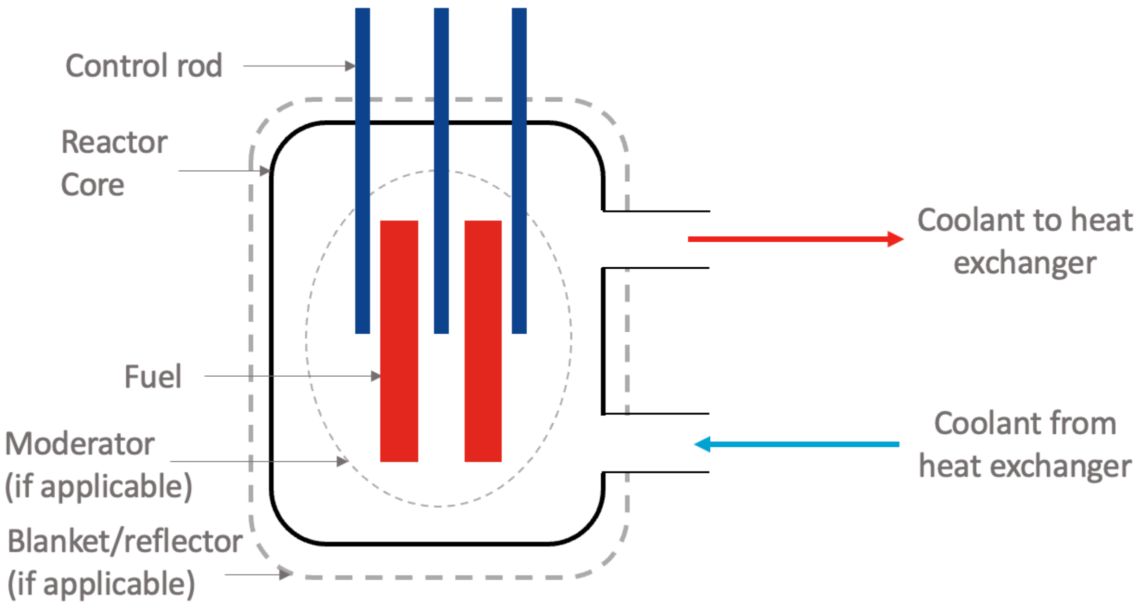

Figure 3 Basic representation of nuclear reactor, based on information from [4]

1.3.2 Reactivity and control

This fission reaction must occur in a tightly controlled environment, as otherwise the fission reaction would not start or cannot be controlled effectively: Without control the number of neutrons could in theory keep growing as the output of neutrons from the fission reaction is greater than the neutrons required to start new fission (as seen in Figure 1).

Not all the neutrons engage in new fission activities, some engage in breeding reactions with fertile material or are lost by leakage out of the reactor vessel or are absorbed by the control rods. For the reactor to function properly the fission reaction should sustain itself, but not increase or decrease the number of fissions strongly. This balance is defined as the reactivity of the reactor as seen in Equation 1, where *k* is the multiplication factor, with *F* being the number of fissions for each generation *n.* [4]

$$k = \frac{F_n}{F_{n-1}}$$

Equation 1 Reactivity [4]

- k lower than 1, reactor will decrease in power. The number of neutrons available from fission are less than the number of neutrons required to continue the fission reaction at the same rate. The fission chain reaction dies out, referred to as subcritical.
- k at exactly 1, reactor is exactly self-sustaining and maintains the same frequency of chain reactions for the duration. Referred to as unity, or critical.
- k above 1, reactor will increase in power as each successive fission chain reaction creates more fission reactions. Each fission reaction releases several more neutrons that are absorbed and start new fission reactions. Referred to as supercritical.

This reactivity is passively and actively controlled, as *k* at or close to 1 is the desired state in steady operation.

Active control is done by managing the number of neutrons that are free to engage in fission. The most common way is by raising and lowering control rods, which are neutron absorbing rods that can be lowered in the reactor (between the fuel) to absorb free neutrons and prevent them from engaging in new fissions reactions. In this case rod is a broad definition as it indicates a long object that is being lowered, that can either be round or another shape such as a cruciform. The most important part is the high neutron cross section, indicating that it has a high chance of interaction with the neutrons that are released by the fission reaction and moving inside the reactor. The high neutron cross section is realized by the choice of element (common choices are cadmium and boron), as neutron cross section is a material property that can vary greatly on a material-by-material basis. If the control rods are raised (and thus leave the core partly) fewer neutrons are absorbed, and thus more are free to engage in fission activities, increasing the reactivity. The control of the criticality is important for the reactor to provide power, as managing criticality is the primary measure to control and alter the heat generation of the reactor [4].

Besides the purpose of maintaining criticality the control rods can also be used to shut down the reactor in either a normal shutdown or in emergency, in emergency situations this is called scramming.

Another commonly used option is to use a chemical to control the reactivity, the principle is however the same and is used commonly on reactors that operate with water in their core: The element (commonly boron) is mixed in with the water that flows through the core, boron has a high neutron cross section and thus absorbs more free neutrons when more is mixed in with the water [4].

Besides controlling the reactor with the control rods or chemically, the reactivity is also controlled by the governing processes of reactor physics. These processes do not have to be actively controlled but are a reaction to the changes in the core, this reaction to change can either be positive or negative feedback. This feedback is referred to as a coefficient, which is then either negative or positive. If for example the core increases in temperature and the reactivity decreases as a result this is called a negative temperature coefficient. An important consideration (which is seen in nearly all reactor designs) is to have an overall (combination of all coefficients) negative coefficient for spontaneous power increases, as otherwise the reactor becomes difficult to control [2].

The reactor control is an ongoing process, as due to fluctuations in the variables, and in the power demand (in the form of heat extracted) the process must be regulated. To summarize the most common types of control are shown in Table 1, with novel reactor specific exceptions being possible but not mentioned here for simplicity's sake.

Active control	Passive control
• Neutron absorption through control rods • Neutron absorption through chemical in coolant/moderator	• Governing processes of reactor physics (feedback coefficients)

Table 1 Active and passive control of common power reactors

1.3.3 Fuel

The fuel of the reactor is a combination of fissile material and fertile material. For a reactor to be operated successfully it requires a critical mass of fuel, indicating the minimum density of fissile material to be present to obtain criticality. The fuel of a nuclear reactor can be contained in a variety of formfactors: It is processed and then either assembled as pellets inside cladded fuel rods/pins which can be mounted inside fuel assemblies (Figure 4),processed as particles/granules/pebbles (Figure 5) or in the case of molten salt reactors as part of the fuel salt [5].

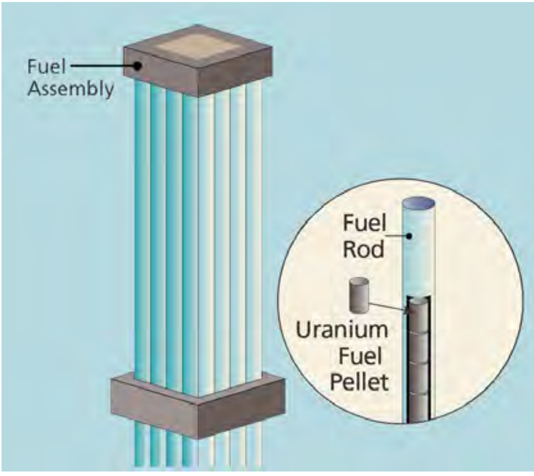

Figure 4 Uranium fuel pellet, in fuel rod, in fuel assembly [6]

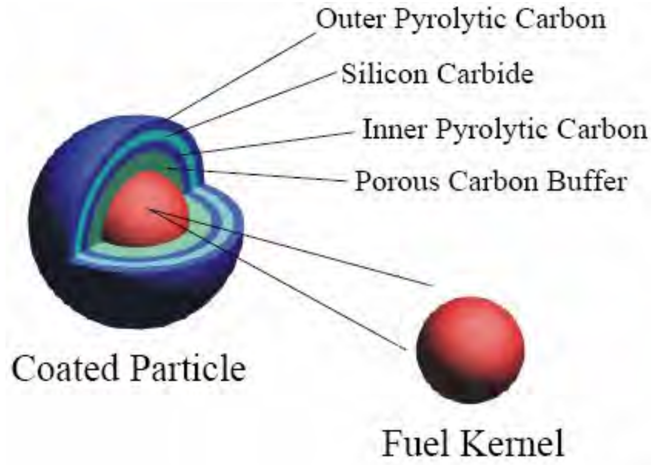

Figure 5 Coat particle/pebble/kernel [7]

The most common fuel is enriched uranium. Natural uranium is mined and consists of 99.275% fertile U238 and 0.720% fissile U235, however a higher percentage of fissile material is preferred for most reactors [2], [8]. This requires a process known as enrichment, which means that the percentage of U235 is increased relative to the percentage of U238. This is up to 20% for Low Enriched uranium (LEU), between 20-80% for High Enriched Uranium (HEU), above 80% is considered weapons grade uranium [2].

The enrichment is done in an enrichment facility, the obtaining of higher enriched uranium produces "tails" as waste product which is the leftover uranium from which most of the U235 is removed. These tails are a form of so called "low level waste" which means its radioactivity is limited but still requires consideration. The downside of higher enrichments is that they are more costly as they require more natural uranium, resulting in an increased tails production. Additionally, the increase in enrichment also increases the amount of work required to attain the enrichment. This amount of work is measured in "Separative Work Units" (SWU) [8]. Example values for enrichment can be seen in Table 2.

Enrichment	Feed factor (kg natural uranium per kg of enriched uranium)	Tails (kg tails per kg of enriched uranium)	Approximate SWU (Separative work units required)
LEU 5%	9.4	8.4	9
LEU 20%	38.8	37.8	46
HEU 93%[4]	181.6	180.6	236

Table 2 Uranium enrichment, calculation based on [8], with tails assay of 0.2%

Other fuel options are: MOX, which is a mix of plutonium and uranium, and has been used as a way of removing plutonium that was once part of nuclear weapons or weapons programmes [9]. Uranium U233, the other fissile isotope of uranium, not found in nature but can be formed in breeding reactors from thorium (Th232). The final option is a possible mix of earlier mentioned fissile materials and a

[4] Discussed further in chapter 2, used for naval submarines.

fertile material (such as thorium) [2].

Most land-based reactors use LEU, with enrichments of about 3-5% [2]. In general enrichments beyond 20% are not seen in power reactors, this can be attributed to the proliferation[5] risk associated with such fuels and the increased cost due to the increased work (in SWU) and base material required for the higher enrichment.

The fuel is removed from the core when it reaches the end of its useful lifetime, this can either be due to depletion of the fissile material or by material constraints of the fuel rod and associated materials [10]. Depending on the reactor this is done either completely, or in parts (called partial replacement). For the current nuclear power plants in operation this process is done approximately once every 1,5 to 2 years [8]. At the end of the lifecycle the spent fuel is either recycled by separating part of its constituents or stored permanently as "high-level waste" to decay in a long-lived waste repository. How quick the end of the lifecycle is reached depends on the type of fuel cycle employed in the nuclear reactor. There are two different options: The Once through fuel cycle and the Closed fuel cycle (Figure 6).

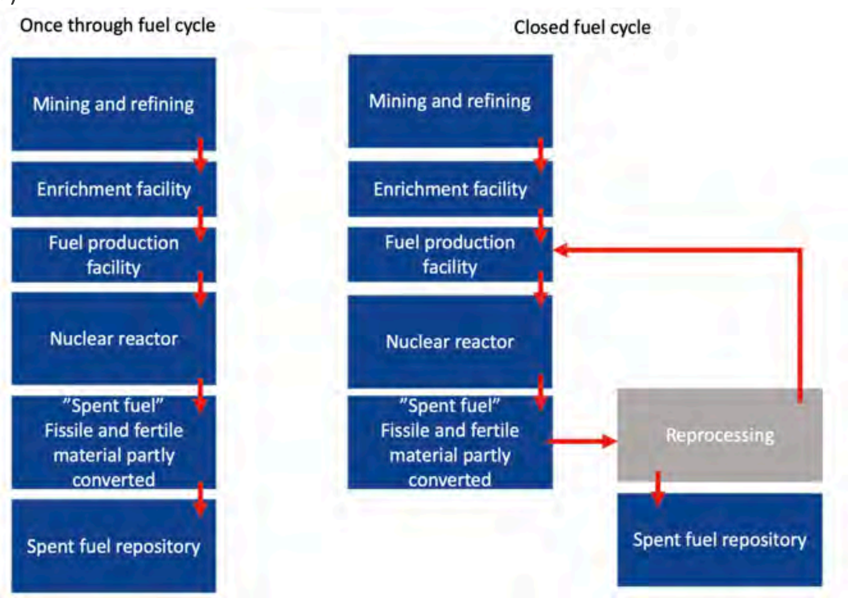

Figure 6 Open and closed fuel cycle, reproduced simplified version from [8]

The final relevant quantity related to the fuel is the amount of thermal power a reactor can "extract" from a given amount of fuel. This is measured in burnup; burnup is measured in GWd/tHM or gigawatt days per ton of heavy metal. Where heavy metal indicates not only the fissile material, but also the fertile material that is in the fuel [4].

1.3.4 Moderator

In most of the current reactors the core is equipped with a moderator, this moderator is in the core together with the fuel and the control rods. The moderator functions as a way of "slowing down" the free neutrons that are released from the fission reactions. This "slowing down" essentially means to shed some of their energy by collision with the moderator material constituents. This is more logical when it is considered that neutron spectrum is denoted in the measurement of eV, or electron volt, where 1 electron volt is equivalent to 1.602×10^{-19} Joule and is thus a form of energy [2]. The

[5] Nuclear non-proliferation indicates that nuclear material which could be used for the creation of nuclear weapons should not be spread to unauthorized countries, organizations, or persons.

moderator reduces the speed of the neutrons as they collide with its constituent nuclei and the neutrons lose part of their energy to the moderator, this process is referred to as scattering. The amount of scattering of a moderator material is similar to the earlier discussed control rods, a material property [4]. After shedding some of their speed to the moderator the chance of fission with a fissile nucleus increases, as a thermal neutron has a higher chance to cause a fission [2].

If a reactor has a moderator, it is very often a "thermal" reactor, where thermal is a term that indicates the energy spectrum of the neutrons (referring to Figure 7). Common moderators are light water (H_2O), heavy water (D_2O) and graphite (C). Thermal reactors comprise the vast majority (99.5%) of the power generating reactors currently in operation, according to the Power Reactor Information System (PRIS) that is maintained by the IAEA (the International Atomic Energy Agency) [11]. The other option is that there is no/very limited moderation, in this case the reactor is known as a fast reactor. This is also shown in Figure 7.

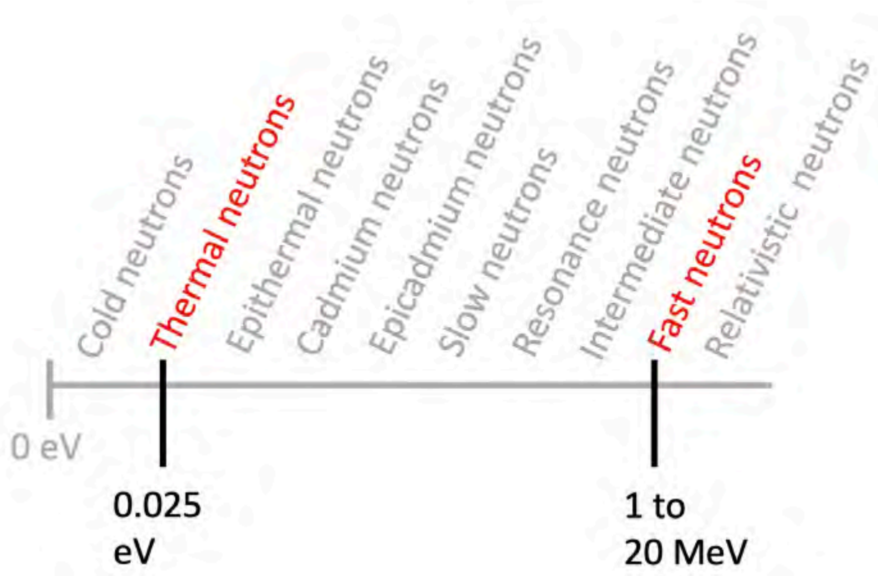

Figure 7 Neutron spectrum, data from [12]

In a fast reactor the chance of a successful fission is less likely, so the design of these reactors is different (increase in enrichment or critical mass) to make sure the fissile chain reaction remains possible [2], [13].

1.3.5 Reflector and/or blanket

The outer shell of the core can serve as neutron reflector for the core. Reflectors are generally made of moderator material in which the free neutrons can collide and change direction, increasing the number of neutrons that remain in the core by returning the neutrons back to the core. Another option that is seen mostly on breeder reactors is the use of a "blanket" where fertile material is placed in the outer regions of the core, where it is free to capture neutrons and become fissile material. If too many neutrons leak out this can be an issue, as this both means that the reactor operates less efficiently and thus requires a higher fuel load, as well as increasing the problem of dealing with the neutrons that are leaking out. The use of a reflector and or blanket reduces the leakage of neutrons and gamma radiation that subsequently has to be reduced by shielding. This shielding prevents the personnel from being exposed to excessive radiation, but also protects equipment and other materials from radiation related damage [4].

1.3.6 Coolant and heat extraction

As fission occurs in the reactor energy is released, this energy in the form of kinetic energy and radiation is converted into heat. This heat is either first transferred to the fuel assemblies or directly to the coolant. To prevent the reactor (specifically the fuel assemblies) from being damaged by the increasing heat and to make use of the energy this heat has to be extracted. Heat extraction is done by the coolant; the coolant is either a liquid or gas that flows through the core and moves the heat outside of the core. Water has been used as the coolant of choice for the past decades, with only a small percentage of reactors using different coolants (according to the earlier mentioned PRIS [14]). The use of different coolants such as helium, liquid metals, and liquid salt with more favourable properties and higher operating temperatures are widely researched for new reactor concepts. These will be discussed in further detail in chapter 3.

The amount of heat the reactor outputs is defined as its thermal power (indicated in MWth for megawatt thermal), this heat can be either used directly (for instance for desalination, hydrogen generation or other processes that require heat). Or as electrical power, for this it first must be converted from thermal to electrical power. The most common way to do this is via a steam generator followed by a steam turbine. The electric power generated (indicated in MWe, for megawatt electrical) is in general between 30 to 40% of the thermal power of the reactor. The other 60 to 70% is rejected as waste heat (shown in Figure 8) [2]. If there is an intended secondary purpose for the waste heat the plant is referred to as a cogeneration plant [15].

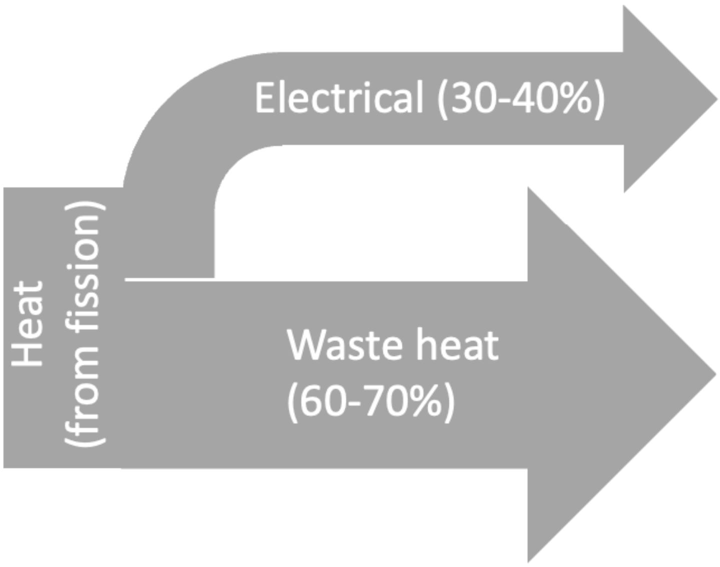

Figure 8 Simplified Sankey diagram for power generation from fission

The output temperature of the coolant has a large influence on the efficiency of the cycle, as well as the applicability of the reactor for other purposes. Higher temperatures are thus favoured for both high energy conversion efficiencies as well as heat demanding processes. A final important consideration with nuclear power in general is that the fission reaction does not only produce direct heat, but also decay heat. This decay heat is a concern when the reactor is stopped, as contrary to many other power sources this means that the reactor maintains a percentage of its power for a significant time after stopping (where stopping means in this case, stopping the fission reaction). This decay heat is in the order of 7% of the total heat output and exponentially decays over time [4].

1.4 Chapter conclusion

Nuclear energy as it is known and used at the present time for power generation is based on the principle of fission, where a fissile material (most commonly U235) is used as fuel for a nuclear reactor. The reactor serves as a vessel for containing and controlling this fission reaction and allowing the generated heat to be extracted, the extracted heat can then either be used directly or converted to mechanical energy at the cost of the conversion efficiency. Mechanical energy can either be used directly or converted to electrical energy as is common in nuclear power stations around the world. The working principle of the nuclear reactor remains the same independent of its intended purpose.

2 CURRENT STATE OF NUCLEAR ENERGY

This chapter answers sub question 2: What is the current state of nuclear energy? This is done by first providing insight in nuclear power for both shore and marine applications, detailing classification of reactors, the waste stream and giving a brief background on the societal aspect. Afterwards the important licensing and legislation of nuclear reactors in both land-based and marine applications is discussed.

2.1 Current state of nuclear power

This chapter gives a brief introduction on nuclear power and its current application, both on shore as well as on ships.

2.1.1 Nuclear power in shore-based applications

According to the IAEA in 2020, 442 nuclear generators were in operation across the world, delivering 390 GWe of power [11]. The main benefit of using nuclear power over fossil fuel-based options is the significant harmful emission reduction. Nuclear power produces no down-the-pipe emissions, and the only CO_2 emissions are caused by the production processes of the reactor and fuel [16].

Nuclear power is widely used to provide baseload electrical power, indicating that the reactor supplies a fixed power at most if not all times during the day. This is mostly an economically driven choice, as nuclear power is favourable for constant power applications due to its high capital but relatively low fuel cost. Load following is a capability, although due to the earlier mentioned economics not always applied or designed for in nuclear plants. According to a recent report by the IAEA: Most recent plants are designed for load following that can be up to +-5%/min of the rated thermal power, in the operating range between 50-100% of the rated thermal power [17]. Similar figures of +-5% where given for land-based plants in Germany in a publication by Kosowski & Diercks [18]. If a reactor is utilized in this purpose, it allows the plant to follow the daily energy demand of the country, as this generally varies over the day. For reference: the difference in load between day and night is in the order of between 60 to 80% of the load of the day [17]. The load following capability can be higher for certain reactor designs, although this is reactor specific and generally comes associated with a maximum number of allowed cycles. This is covered in the publication by the Nuclear Energy Agency on the topic of load following [19]. For the same economic reasons nuclear reactors are often active for almost the full year, only being stopped for maintenance and refuelling. The actual yearly downtime of a reactor (including plant systems) varies, a study by the IAEA defines four periods for specific downtimes: Refuelling – 7 to 10 days, Refuelling and standard maintenance – 2 to 3 weeks, Refuelling and extended maintenance – up to 1-month, Specific outages/ major backfitting – longer than 1 month [20]. A different study by the IAEA shows the outage times of two PWR plants in operation in Finland over the past 16 years. Average downtime was 14 days per year for plant 1 and 15 days per year for plant 2. Longest downtimes were just over three weeks, shortest just over 1 week [21]. Using this downtime information, it can be determined that there was an average downtime of below 5% per year.

Besides being used as electrical power plants there are also nuclear reactors in other applications, most notable in: desalination and regional heating networks. Besides these applications that are in active use, the idea of using nuclear power plants to generate hydrogen on a large scale (or hydrogen derived fuels) is also actively investigated [22].

2.1.2 Classification of nuclear reactors

A variety of nuclear reactor concepts have been in use or are in development. Between these reactors there are distinct variations.

As further on more types of nuclear reactors are discussed, it is important to address the classification systems that divide the nuclear reactors by the following metrics:

- The neutron spectrum of the reactor (thermal or fast)
- The coolant used in the reactor (water, gas, liquid metal, liquid salt)
- Breeding reactor or a converter reactor

A final distinction can be made for their parent group, which is the defined "generation" of the reactor. The "generation" groups of reactors based on safety features, efficiency, and age. These range from generation I to IV and are shown in further detail in Table 3. A full breakdown of reactor types belonging to the mentioned categories is added in the appendix, with further information on the relevant designs given in chapter 3.

Generation	I	II	III	III+	IV
Generation name	Early prototype reactors	Commercial power reactors	Advanced LWR's	Evolutionary designs	Revolutionary designs
Neutron spectrum	Thermal and fast	Thermal	Thermal		Thermal and fast
Converter/breeder	Converter and breeder	Converter	Converter		Converter and breeder
In operation	No	Yes	Yes, but limited		No/ test reactors only
Examples	Fermi 1 Magnox Shippingport Dresden	PWR* BWR CANDU VVER RBMK	ABWR EPR		VHTR* MSR* SCWR GFR* SFR* LFR*

*Table 3 Generations of nuclear reactors, data from [23] & [2] * indicates that these will be covered in detail further on with the others added in Appendix A: Nuclear power plant generations*

2.1.3 Nuclear power in naval applications

Nuclear powered propulsion is a staple in some of the largest navies in the world. The benefits of nuclear power, such as the very long endurance on a single fuelling and reduced thermal signature (due to not having exhaust gasses) makes it very attractive for naval purposes. This is paired with the general favourable characteristic of not having any harmful down the pipe emissions. Nuclear submarines and surface ships such as aircraft carriers have been in use since the 1950's, most prominently in the United States and the former Soviet Union/current Russia. The application has been very successful in submarines, due to its independency of air and being very compact along with the earlier mentioned long endurance. The application is often mentioned in literature, as specifically the submarine is one of the first applications of nuclear power. Available literature in this field is rather limited, specifically on the technical application and its intricacies. The most comprehensive publication on application and technical specifics is given in the publication "Naval Nuclear Propulsion" by Ragheb [24], which covers mostly the developments in the United States and some coverage on the technology used in the former Soviet Union. Reliable other information on former Soviet Union/current Russia is sparse, with available articles often referring to non-digitally available sources or sources in Russian. Information in literature is focussed heavily on design considerations and rarely mentions operation specific details such as load profiles.

In the naval applications the PWR (Pressurized Water Reactor) is the most common type, the reactors used on board of naval surface vessels and submarines are purpose designed for their naval application. The PWR is an older generation (generation II) reactor but proven in use by its many reactor hours of experience. This reactor type operates in the thermal neutron spectrum with water as coolant and a steam turbine system for energy conversion. The use of highly enriched uranium allows the reactor to be made more compact (93% U235 and higher enrichments are used). Besides this the highly enriched uranium increases the amount of available fissile material per total weight. It also gives distinct benefits of higher reserve reactivity and the associated possible negation of reactor poisoning. This poisoning, where at lower and transient loads xenon and samarium build-up in the fuel rods, is an important issue to address in any mobile application[6]. The build-up of Xe and Sm is caused by the decay of the fission products: iodine and tellurium. Both Xe and Sm have high neutron cross sections which can lead to the possible stalling/stoppage of the reactor due to decreased reactivity, as the neutrons are being absorbed by the Xe and Sm instead of the fissile material. If the reactor is stopped when there is a significant build-up of fission products it can cause enough negative reactivity that the reactor cannot be restarted for several hours, as it does not have enough reserve reactivity anymore to surpass the negative reactivity until the Xe and Sm have decayed. This condition is called deadtime and shown in Figure 9 for a reactor with a reserve reactivity of 20% (depicted as 0.2 in the figure) [4].

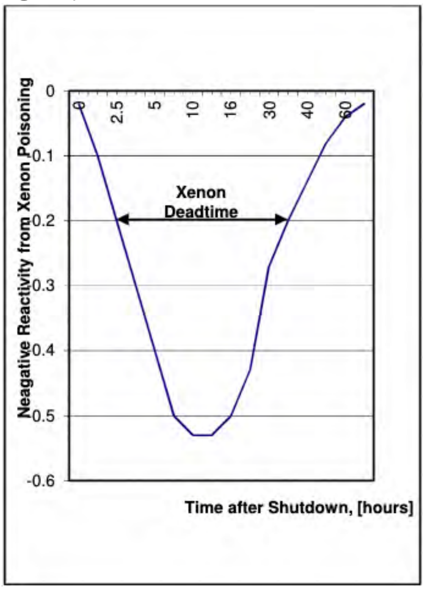

Figure 9 Deadtime due to reactor poisoning by xenon, shown for a reactor with a reactivity reserve of 20% [24]

Negation of deadtime is especially important for mobile applications as not being able to restart for hours/days after a scram/stop can create serious issues [24].

A few submarines have used fast reactors, notably the Soviet “Alfa” class which used a lead-bismuth cooled fast reactor [25]. These fast reactors had the benefit of being significantly smaller than a PWR for the same power output. They did however suffer from many problems, most prominently the corrosion of the reactor components, the requirement of maintaining temperature when the reactor was stopped, and the build-up of poisonous polonium in the coolant [24], [26].

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[6] This problem does not occur in all nuclear reactors but happens in most, as the fuel rods are a closed container the fission products do not leave and can only be removed by decay.

The installed power of the submarines and surface vessels depends on the reactor used and the number of reactors installed (surface vessels sometimes used more than one reactor, up to as many as four on some aircraft carriers) [24]. A short list is shown in Table 4 indicating either the thermal power (MWth) or shaft power of the submarine/surface ship that used the reactor, which as can be seen is not always given together.

Reactor designation	Application	Type	Development country	Thermal power (MWth)	Shaft power (MW)
A2W	Submarine	PWR	United States	None stated	26.1
A4W/A1G	Aircraft carrier	PWR	United States	None stated	104.4
S5W	Submarine	PWR	United States	78	11.2
S6G	Submarine	PWR	United States	148	26.1
D2W	Submarine	PWR	United States	165	26.1
OK650	Submarine	PWR	Soviet Union	150	None stated
OK550	Submarine	LFR*	Soviet Union	155	None stated

*Table 4 Thermal and shaft power of selected naval reactors, data from [24] & [26], * LFR = Lead-cooled Fast Reactor*

2.1.4 Nuclear power in commercial marine applications

Nuclear power has been applied in commercial marine applications, although in significantly fewer ships than for the naval application. Most notable examples are the Savannah and the Otto Hahn, both commercial cargo vessels originating early in the development cycle of nuclear power. Currently the only commercial vessels using nuclear propulsion are the cargo ship Sevmorput and a small fleet of Russian flagged icebreakers. All commercial vessels used or are using PWR based reactors, with a steam cycle for power conversion [27]. It should be noted that these reactors are different from their naval counterparts, as the commercial application (for non-proliferation reasons mentioned in section 1.3.3) does not make use of highly enriched fuels. An overview of ships is shown in Table 5.

<table>
<tr><th>Ship</th><th>Type of ship</th><th>Type of reactor</th><th>Installed power (MWth)</th><th>Shaft power (MW)</th><th>Years in service</th></tr>
<tr><td>Lenin</td><td>Icebreaker</td><td rowspan="14">PWR (Pressurized Water Reactor)</td><td>3 * 90 (270)</td><td>32.8</td><td>1959-1989</td></tr>
<tr><td>Savannah</td><td>General cargo</td><td>74</td><td>16.2</td><td>1962-1972</td></tr>
<tr><td>Otto Hahn</td><td>General cargo</td><td>38</td><td>7.3</td><td>1968-1979</td></tr>
<tr><td>Mutsu</td><td>General cargo</td><td>36</td><td>7.3</td><td>1974-1992</td></tr>
<tr><td>Arktika</td><td rowspan="3">Icebreaker</td><td>2 * 171 (342)</td><td>55.9</td><td>1975-2008</td></tr>
<tr><td>Sibir</td><td>2 * 171 (342)</td><td>55.9</td><td>1978-1992</td></tr>
<tr><td>Rossiya</td><td>2 * 135 (342)</td><td>55.9</td><td>1985-2013</td></tr>
<tr><td>Sevmorput</td><td>Cargo (LASH/container)</td><td>135</td><td>29.8</td><td>1988-2007,
2016-present</td></tr>
<tr><td>Taimyr</td><td rowspan="6">Icebreaker</td><td>171</td><td>37.3</td><td>1989-present</td></tr>
<tr><td>Sovetskiy Soyuz</td><td>2 * 171 (342)</td><td>55.9</td><td>1989-2014</td></tr>
<tr><td>Vaygach</td><td>171</td><td>37.3</td><td>1990-present</td></tr>
<tr><td>Yamal</td><td>2 * 171 (342)</td><td>55.9</td><td>1992-present</td></tr>
<tr><td>50 Let Pobedy</td><td>2 * 171 (342)</td><td>55.9</td><td>2007-present</td></tr>
<tr><td>Arktika</td><td>2 * 171 (342)</td><td>55.9</td><td>2020-present</td></tr>
</table>

Table 5 Commercial nuclear-powered ships, data from [24], [28], [26], [29]

From the total number of ships in Table 5 it can be concluded that the widescale adoption of nuclear power for commercial marine application did not happen, with only the icebreakers seeing use beyond what can be considered a “prototype/first of a kind” vessel phase. An important aspect to take into consideration was the time, as exploitation of the cargo vessels was done in the 1950’s to 1990’s when global warming was less at the heart of the public debate. To put it into perspective: Exploitation of the Savannah was also before the first oil crisis which happened in 1973. Besides this it was the first generation of vessels with nuclear propulsion, the vessels faced the problem of being first of a kind, which resulted in higher maintenance and operational costs as facilities could not be effectively shared with other similar vessels. This is especially apparent for the Savannah, of which the financials and information on the exploitation are publicly published due to the vessel’s construction being US government funded [30]. Despite some of these problems and the different times they operated in these ships brought significant subject knowledge and information in the field of commercial marine nuclear power. The study by Schøyen & Steger-Jensen [31] covers this and mentions that these ships paved the way for new developments: Identifying issues such as governmental policy, regulatory framework and economic/lifecycle concerns that have to be addressed for nuclear ships to be a successful alternative to fossil fuels.

Although no recent commercial nuclear powered cargo ships were constructed the idea was not abandoned. Research has been done over the past decades both on the general application of nuclear power for marine propulsion as well as in more detailed works on conceptual vessel design.

In the general application: the two-part publication by Carlton, Smart & Jenkins [32], [33] offers an overview and some exploratory considerations of the subject. One part [32] discusses the technical matters and focusses on the fundamentals such as fuel cycle and size, although limited to only the use of the PWR. In this paper no direct technical issues are found, as most developments are built upon proven technologies. This study roughly identifies a couple vessels for which the application can be used (tankers and bulkers, containerships, cruise ships, all of varying sizes), although these concepts are not refined further. The other part [33] discusses the economical, regulatory, and societal concerns. With the most interesting parts being the comparison of current standards in the maritime industry and how these would relate to the implementation of nuclear power, as well as the recognition that the regulations are outdated for a current implementation. This coverage of the regulations is especially important considering the affiliation of the authors with classification society Lloyds Register, showing that the topic is on the radar of classification societies.

For the more detailed conceptual vessel designs three are of note: The study by Hirdaris et al. [34] on a Suezmax tanker concept with nuclear propulsion, as this is both quite recent (2014) and ties in closely to the research into new reactor developments being done in this research. The most significant contribution by the study is the focus on the legislation and the involvement of a classification society (again Lloyds Register) in the study. The eventual implementation proposed in the research is discussed further in section 6.1, after relevant matters have been discussed.

Secondly the report by Jacobs [35]: While being a little more dated (2007), it predates some of the more recent developments in the field of nuclear power. This study focusses in detail on a difficult application in the form of a small nuclear powered container feeder vessel, discussed in further detail in section 6.1.

Finally, the nuclear fast ship by Vergara & McKesson [36], a high-speed container vessel with a high power and modern reactor concept installed. This study is of interest because of its detailed economic breakdown, despite its parent vessel concept being an outlier in installed power and size. Again, discussed in further detail in section 6.1.

2.1.5 Waste production from nuclear power

When discussing nuclear power in its current form, it is important to discuss the waste stream as well. As mentioned earlier in section 1.3.3: there are two main types of waste, high-level waste, and low-level waste. Low-level waste is waste that has been radioactively contaminated but is only mildly radioactive. Examples of low-level waste are items and equipment used in maintenance such as shoe covers and cleaning cloths [2]. The high-level waste is highly radioactive and often comes associated with long half-life times. This waste both requires shielded storage as well as cooling, with the main contributor to the high-level waste being the spent nuclear fuel of a reactor [2].

The amount of high-level waste produced depends both on the reactor power output, type of fuel, type of fuel cycle and the burnup (as burnup is an efficiency measure, where higher indicates more power produced per kg of fuel). Indicating that the total high-level waste stream is very much dependent on the required input fuel material. The waste stream of nuclear power is often discussed, with special focus on the high-level waste and its long-lived character. It should be noted that a large part of the spent nuclear fuel remains unchanged over its period spent in the reactor. Only a part of the fuel (depending on the height of the burnup) is used over its period in the reactor. This is best shown in Figure 10 for a conventional reactor used in power generation.

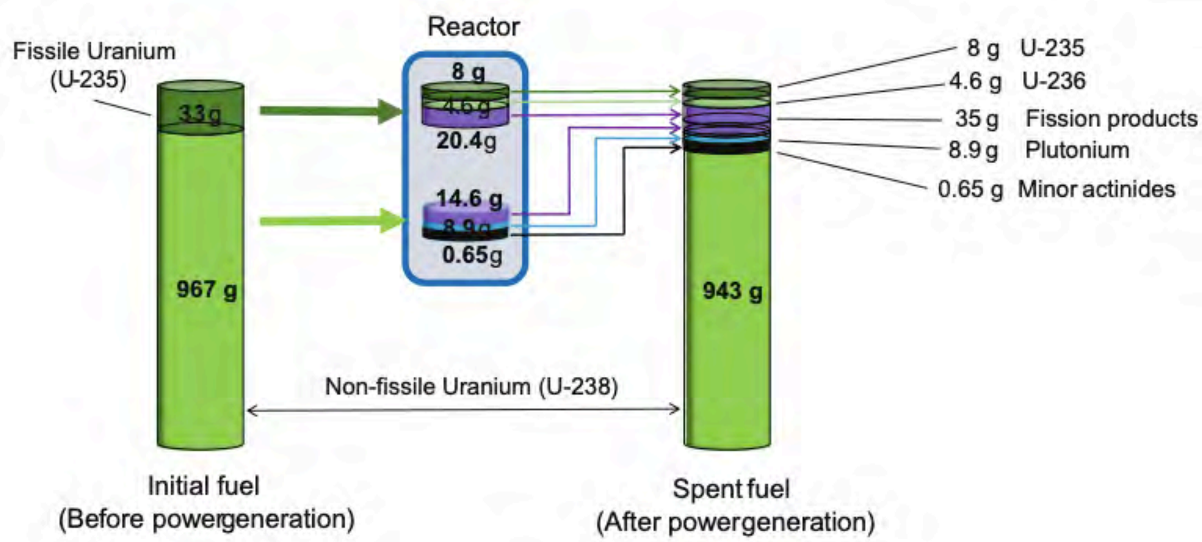


Figure 10 Fuel composition change for a conventional reactor, [2]

Reprocessing and closing the fuel cycle could reduce the amount of long-lived radioactive material severely and allow for reuse of a significant part of the fuel [8]. The other prominent option to reduce the amount of waste is the thorium cycle, which will be discussed in further detail in section 3.1.2. If none of these options are implemented the total spent fuel will simply equal the total fuel input of the reactor. A larger than necessary amount of spent nuclear fuel is considered unfavourable, indicating that for new concepts the following points (or a combination) are important: A high burnup is favourable, indicating better utilization of the fuel before it is depleted, a closed fuel cycle is favourable for a reduction of total waste products, finally a transition to a thorium-based fuel cycle has to be considered.

2.2 Public perception

Nuclear power has difficulties with its public perception, which is an important topic to address as the perception of the public influences the success and adoption of new technologies.

- Nuclear energy and nuclear weapons are associated by their history, with historical uses of nuclear reactors to provide material for nuclear weapons [10]. Although this would not be the purpose of marine reactors, it ties into the proliferation concern. Proliferation resistance is an important aspect of reactor design and ensuring that no material ends up in the wrong hands [33].

- Long lived waste is a concern when dealing with nuclear power, a recent survey[7] conducted in the United Kingdom determined this to be the main concern for the general public [37]. The spent nuclear fuel of currently used reactors has a part that remains significantly radioactive for a period up to thousands of years [10]. This long period causes the stewardship problem, where the fuel has to be stored and guarded. Some of the developments in the field of nuclear power specifically target this issue (notably: thorium fuelled reactors and “waste burner” molten salt reactors which will be discussed in detail in chapter 3).

- One of the publics other main concerns is safety and risk of accidents with nuclear power [37], despite nuclear energy having a remarkably good safety record. This good safety record is especially apparent when looking at the death rates for producing each Terawatt-hour of energy, which is lower by several magnitudes compared to other common methods of power generation such as coal, oil, or gas [38]. The prevention of both small- and large-scale accidents is seen throughout all aspects of nuclear engineering. Despite safety and regulations two large scale accidents have happened in the past: Chernobyl (1986), Ukraine and Fukushima Daiichi (2011), Japan. These two incidents are the only two incidents to receive the level 7 classification of the INES scale as shown in Figure 11. These accidents resulted in large scale evacuations and required significant clean-up efforts, despite the use of containment and mitigation measures radioactive material did enter the environment [2].

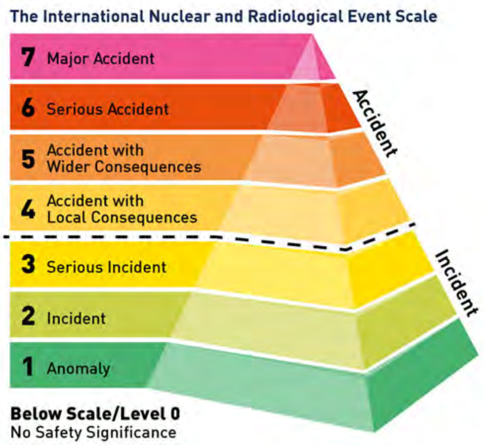


Figure 11 The international nuclear and radiological event scale [39]

This report will not go into great detail on the cause of these accidents, as they are covered extensively in other literature and news. Both events are however relevant to mention due to their influence on development, deployment, and perception of nuclear energy. For a concise description please refer to the publication: “Energy from Nuclear Fission” by De Sanctis, Monti & Ripani, in which both incidents are covered [2].

[7] Survey was focused on the land-based power generation application of nuclear power

- The application on board of ships is not often discussed, as in recent years there are very few commercial nuclear-powered ships in operation (referring back to Table 5). Although the later vessels (Mutsu & Sevmorput) suffered from negative public perception in their time, with Sevmorput being denied port entry and Mutsu's nuclear-powered operations cut short in part due to public/political concerns [27]. This is something that also for future applications is relevant to consider and address, with the study by Carlton, Smart & Jenkins mentioning it as difficult but not insurmountable problems [33].

2.3 Land based reactor licensing and safety regulations

The safety aspect of nuclear power is strictly governed by rules and regulation for safety reasons, a brief background is given.

2.3.1 Principle of defence-in-depth

Nuclear power facilities are subject to strict safety regulations and guidelines. These apply to both the design, construction, and operation of the reactor in all aspects.

One of the most important principles in reactor safety is the principle of defence-in-depth. This principle focusses on establishing a selection of hierarchical levels intended to act as "barriers' that mitigate abnormalities and incidents. The barriers range from level 1 to level 5, where each subsequent barrier is comes into play after the earlier has failed. The barriers are shown as the levels in Table 6. Defence-in-depth is intended as a measure that protects the workers, environment, and public at all times, even when levels fail the next level in the hierarchy remains a barrier [40].

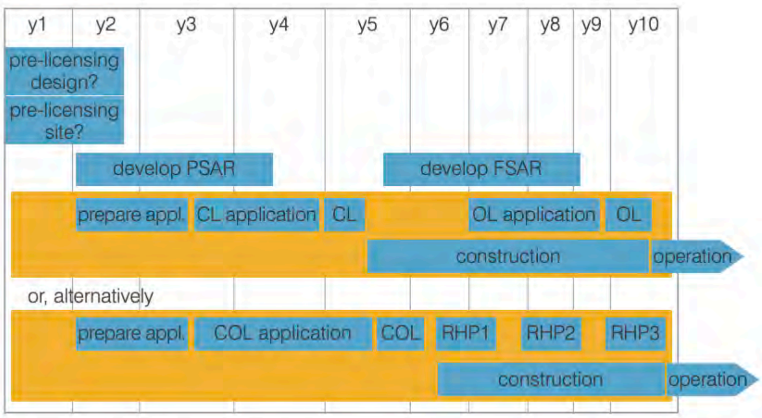
Level of defence-in-depth	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting of protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineering safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe events	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

Table 6 Levels of defence-in-depth, reproduced from [40]

The concept of defence-in-depth works in parallel with the concept of a design basis accident (DBA), where a DBA is a defined as a postulated accidental scenario that the nuclear facility must be designed and built to withstand exceeding authorized limits according to IAEA [41].

2.3.2 Licensing and regulations of (land-based) reactors and design safety measures

To ensure the safety of nuclear reactors the licensing process is quite extensive. The licensing process is fundamental to the design of the nuclear reactor, generally this process begins before the reactor has a defined site. This pre-licensing step is not required in all countries but is used to show the applicability of the reactor for its intended purpose. The projected site of the reactor, and the possible associated risks are also part of the licensing process for a plant and scrutinised before permission is given to build the reactor. This permission is then given in the form of the construction licence (CL) as shown in the timeline of Figure 12. Afterwards the operations and fuel handling of the reactor are equally subject to licensing stages, these are operator focused. If these are passed satisfactory the operating licence (OL) is awarded. Together these assessments cover a wide range of possible incidents and mitigation measures, but also design requirements and general provisions to ensure safe exploitation of the reactor. These licenses are given out by the local authority responsible for nuclear power, for instance in the USA, the Nuclear Regulatory Commission (NRC) and the ANVS (Autoriteit Nucleaire Veiligheid en Stralingsbescherming) in the Netherlands. Because of the involvement of local authority, the application processes can vary country-to-country. This development is a difficult track, as it is costly as well as time consuming. For large scale reactors this has already proven difficult, especially with the amount of different national and international regulatory bodies active in the field of nuclear power. Efforts to enact a global standard are underway which is proposed as something that that is also very relevant for smaller and novel reactor designs, this is an active project of the world nuclear associations CORDEL (Cooperation in Reactor Design Evaluation and Licensing) working group [42]. The entire process can be seen visualized in the timeline of Figure 12, where also the option of the combined operating and construction license is shown. From this timeline it can be seen that the current licencing of a reactor is time consuming, and in general should be considered as something that takes up to a decade [43].



CL: construction licence
OL: operating licence
COL: combined construction and operating licence
RHP: regulatory hold point (consent, permit, ITAAC....)
PSAR: preliminary safety analysis report
FSAR: final safety analysis report

Figure 12 Timeline of major licensing steps for nuclear power plants [43]

It should be noted that these regulations are heavily focussed on land-based applications, with a fixed site. In the case of ships the location is not fixed, however these are also subject to having an operating license. In case of NS Savannah, this was given out by the NRC as the vessel was both operated by a US based company and built in the US. This initial operating license for the Savannah was given out for a period of three years [30]. The operating license for the Otto Hahn was given out for a period of six years [44].

2.4 Regulations for nuclear power in marine applications

Regulation is already a dominant factor in the licensing and construction of a nuclear power plant on shore as mentioned in the previous section. Ship design is also covered extensively in regulation, giving a complete overview of all applicable regulations is beyond the scope of this study. However, if a marine propulsion system with a nuclear reactor is proposed this would mean that it is also subject to follow the general rules and regulations of the industry.

Even though nuclear propulsion was not adopted on a large scale there is still specific regulation covering it. This "Code of safety for nuclear merchant ships" set out by the International Maritime organization (IMO) in 1981 is currently the only specific document concerning technical regulations on the use of nuclear power for the propulsion of merchant ships. The code was formed in conjunction with the IAEA, as a part of the convention on the Safety Of Life At Sea (SOLAS) [45]. The code is restricted to the PWR reactor, as this is and was also then the most common type of reactor for naval and marine purposes. The document is comprehensive, although outdated due to all developments that have taken place over the last 40 years. The regulation [45] addresses the following topics:

- General purpose of the regulation and the code for ships falling under the code and introduction of the principle of defence in depth.
- Design criteria (reactor focused), with specific requirements on the installation and its safety.
- Design criteria (ship focused), with specific requirements for the vessel due to the type of installation and associated hazards.
- Nuclear Steam Supply System (NSSS) specific requirements and design criteria.
- Criteria for the main and auxiliary machinery required, including emergency propulsion arrangements
- Radiation safety and waste management
- The operation and documentation of the vessel
- Surveys of the vessel and installation.

As this report focuses mostly on a new generation of nuclear reactors the applicability is limited when the reactor is not of the PWR type, and the regulations are generally quite dated.

Besides this specific regulation, nuclear power is also mentioned in other legislation documents:

The United Nations Convention on the Law Of the Sea (UNCLOS) [46] specifically mentions nuclear powered ships multiple times. The rights of nuclear ships are identical to conventional vessels regarding their travel on the high-seas, the economic zone, and the territorial seas of countries. A requirement is that the vessel is compliant with all other regulations and follows the guidelines and codes applicable for the ship type. The only restriction that can be imposed is in the territorial seas of a country, the country can for the benefit of safety prescribe the vessel to follow certain sea-lanes such as channels.

Countries do however maintain control over entrance to their ports, and this was something that nuclear ships had issues with in the past. Governments of countries that were visited were hesitant with allowing nuclear powered ships into their countries [47]. This is something that in part could be attributed to the vessels of 50-60 years ago being the first of a kind, but is a consideration for the future nonetheless. This consideration can also be seen in the selection of conceptual studies [36], [35] into nuclear power for the marine application (as mentioned in section 2.1.4), which specifically show vessels very suitable for liner services which reduces this issue. Additional requirements are something that is commonly seen in the requirements of countries for visiting navies[8] with nuclear vessels. While some countries do not approve at all, others have specific rules and regulations to follow for the visiting vessel such as in Australia: documenting of radiation and observing protocols [48].

The final consideration should be given to the INF code, which is the international code for the safe carriage of packaged plutonium and high-level radioactive wastes. Although the reactor and its fuel do not directly fall under this code, this code can be applicable in the case of vessels that transport their own or the fuel waste of other vessels as their cargo [49]. As well as showing the possible road to new regulations as this code is a collaboration between the IMO and the IAEA, similar to the earlier mentioned "Code of safety for nuclear merchant ships".

In the study by Hirdaris et al. [34] it is noted that the regulatory framework around nuclear power for marine applications requires work, and that this is one of the main obstacles for the next generation of nuclear marine power. This is confirmed in the study by Schøyen and Steger-Jensen [31] where suitable regulations is mentioned as one of the requirements for nuclear propulsion to be possible. This has additional relevance because also new technology such as the SMR is still in a "grey" area regarding regulations, with regulations and recommendations being developed and adapted in an ongoing process as also mentioned in a publication by the IAEA [50]. Both the studies by Carlton and Hirdaris et al. are of note here, as both had authors involved with a classification society. The classification societies are important to the subject as they provide the link between legislation and operation.

Due to the nature of research and developments in the field of nuclear power and the lack of current regulations a shift from rule-based to risk-based design seems logical. Risk-based design has been increasing in ship design as technological developments developed faster than regulations. Nuclear engineering is also an industry where risk-based design is applied as this is also the field where it originated [51].

2.5 Chapter conclusion

Nuclear power in its current state has seen widescale application in commercial power and naval applications. The commercial marine application has lagged behind, with only a small amount of ships ever constructed. The commercial marine solution is the odd one out and falls between the two well developed domains of commercial power and the naval application as it cannot easily use their technology. The relatively stable power demand of countries is dissimilar to the varying loads of a ship, while the use of highly specialized military reactors with highly enriched fuel is not possible in commercial application for proliferation reasons. A limited amount of research is available on the topic, with most of the research only focussed on the by now older PWR reactor. Research shows that besides these concerns the rules and regulations concerning nuclear power are already difficult for land-based applications, with the marine application having outdated legislation with significant gaps in a fragmented international legislation environment. The interest from a classification society in research is however a positive note in this, as this indicates that there is at least interest. Finally nuclear power has two additional major issues: One of negative public perception, which is something that has to be addressed or at least considered when new applications are planned. As it has already been a problem for past applications. The second being the waste problem, which requires consideration, as this has long term consequences.

[8] Although the navy is not the same as a merchant/cargo vessel it is more logical that there are rules for naval vessels as these outnumber the nuclear merchant vessels greatly.

3 DEVELOPMENTS IN NUCLEAR ENERGY

This chapter will cover the developments in nuclear energy that are currently ongoing, focussing on three major developments: Generation IV reactors, thorium as fuel, and Small Modular Reactors (called SMR's), while setting initial boundaries for the applicability on board of ships and discussing the available concepts. This is done to answer the sub question: What are the developments in nuclear energy?

3.1 Developments in nuclear power

3.1.1 Generation IV reactors

Generation IV reactors, as mentioned in the previous chapter, are the proposed next generation of nuclear power plants. These plants focus on innovative designs that are different from the previous generations of reactors.

The generation IV reactors are defined by the Generation IV International Forum [23] as the following six types of reactors:

- Very high Temperature Reactor (VHTR)
- Sodium-cooled Fast Reactor (SFR)
- SuperCritical-Water-cooled-Reactor (SCWR)
- Gas-cooled Fast Reactor (GFR)
- Lead-cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)

The International Forum [23] also described these fundamental generation IV goals, irrespective of the type of reactor:

- Sustainability (Energy sustainability and long-term availability of nuclear fuel, minimize nuclear waste and reduce long term stewardship problem[9])
- Safety and reliability (Excel in safety and reliability, a very low likelihood and degree of reactor damage & eliminate the need for offsite emergency response)
- Economics (Life cycle cost advantage over other energy sources, have financial risk comparable to other energy projects)
- Proliferation resistance and physical protection (Be a very unattractive route for diversion or theft of weapon-usable materials, provide physical protection against acts of terrorism)

3.1.2 Thorium as fuel

Thorium as mentioned in section 1.2.2 is a fertile material, indicating that after neutron absorption and decay it can become a fissile material (in this case U233). Thorium is widely seen as an attractive solution and an alternative to the uranium that is currently in use. The main reasons that thorium is considered an attractive solution:

1. Thorium is abundant. There is more thorium on the world than there is uranium, and contrary to natural uranium, which must be enriched for use in most reactors, from thorium theoretically the full amount can be used. Due to its abundance, it could secure the fuel supply for the future.
2. Reduced long lived waste products: The thorium cycle relies on U233 as fissile material and Th232 as fertile material in the fuel which greatly reduces the waste products. The high-level

[9] The problem of having to take care of the fuel for many years after it has been used/depleted.

nuclear waste of a uranium-based reactor contains a large portion of plutonium, which is formed when the fertile U238 becomes plutonium. Plutonium is a large contribution to the long-lived radioactivity (thousands of years) of the spent fuel. In the thorium cycle the formation of Plutonium is significantly less likely, due to the reduced mass number (233 instead of 238), which requires an increased amount of neutron captures compared to U238 before plutonium is formed [10].

3. Reduced (total) waste generation. As theoretically the full amount of thorium can be converted to fissile uranium it is theoretically possible to use the full amount of fuel instead of only a small amount such as is seen in the uranium cycle (referring to Figure 13)

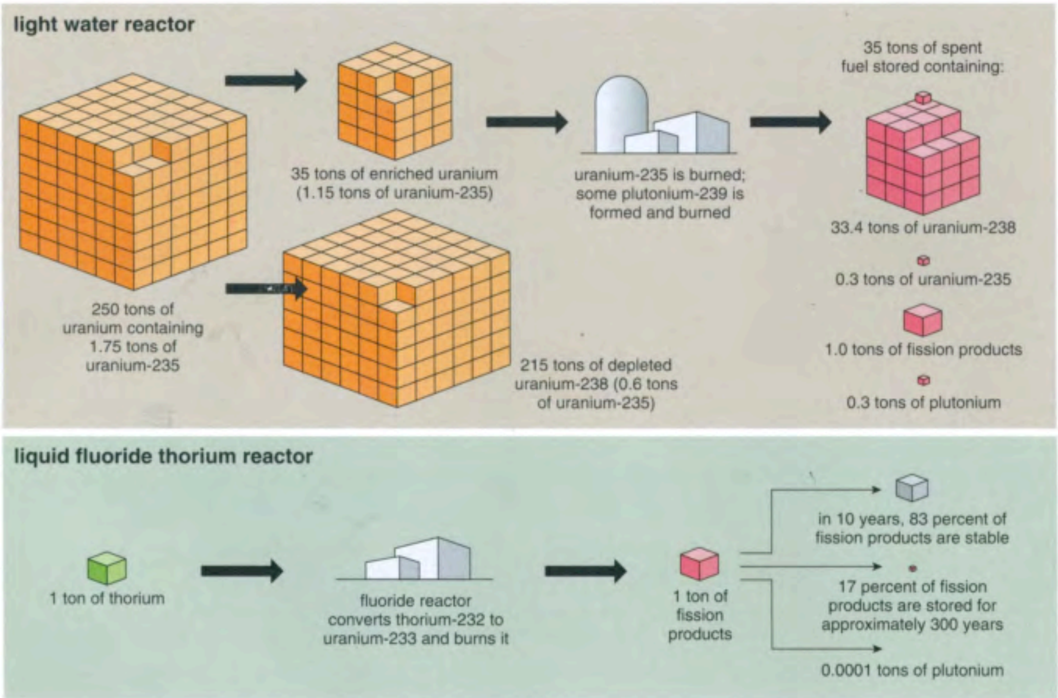


Figure 13 Difference between uranium-based fuel cycle and thorium-based fuel cycle [10]

4. Proliferation-resistance: The handling of U233 as fissile material from the thorium cycle is in general difficult due to the partial formation of U232. U232 has a relatively short half-life, and its decay products are strong gamma emitters, making the fuel hard to process but also giving it intrinsic proliferation resistance as it is dangerous for personnel as well as for electronics [10].

One of the downsides however is that thorium is fertile and contains no fissile material. The issue with this is that the reaction would not start, meaning that a purely thorium filled reactor could not go critical on its own. The overall solution to this problem is to “start” the reactor with a so-called driver fissile material such as U235 or Pu239. The ideal solution to this problem is to start the reactor on U233, taken from another thorium-based reactor as the driver fuel. This solution would completely eliminate the need for uranium (as Pu239 is not naturally occurring). Currently this is not feasible as there is no infrastructure yet to produce and transport U233 [52].

Thorium based nuclear power has been in development for many decades, although it lost the race for the primary nuclear fuel in the early 1950’s, due to it being less suitable for the development of nuclear weapons [10]. However, in recent years China has been making significant progress with the use of thorium [53].

3.1.3 Small modular reactors

Small modular reactors are defined as reactors of up to 300 MWe with a focus on modularization and assembly line construction/prefabrication; this gives the benefits of economy of scale production, reducing capital cost and construction time. The goal of this scale increase is to reach the Nth-Of-A-Kind (NOAK) type of serial production, as opposed to the more common First-Of-A-Kind (FOAK) production seen currently [54]. There is significant interest in the SMR as it could both make nuclear reactors more economically attractive and allow for applications that were before not possible for nuclear power [55].

This technology is mostly focused on the domestic energy grid, although some developments are also focused on process heat applications that can be used for industry, domestic heating, and others, which can be seen in Figure 14. A few of the concepts currently in development are marine based in their fundamental design, while most remain general purpose or land based [55].

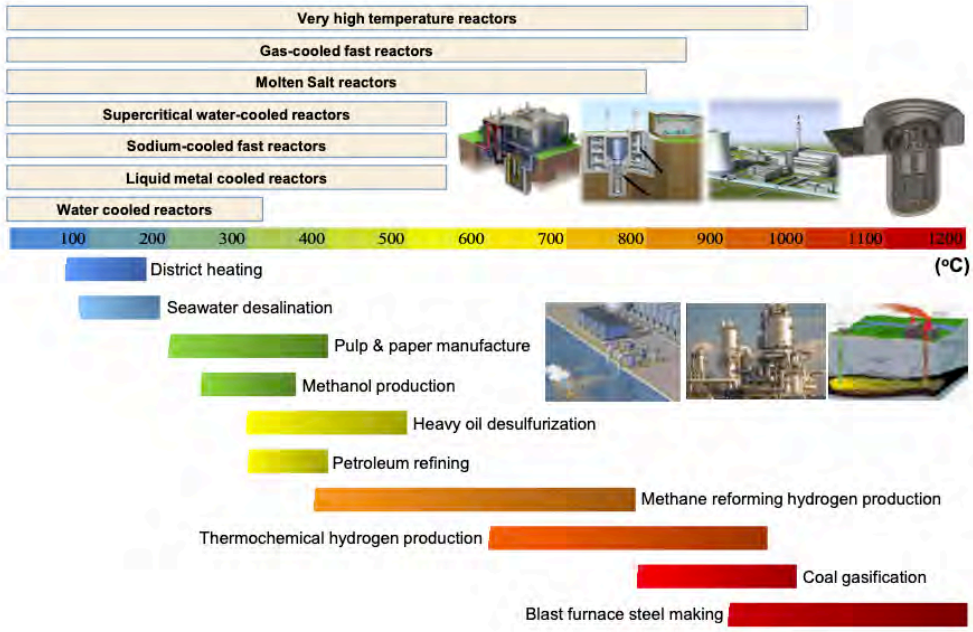


Figure 14 Process temperatures for non-electrical applications [55]

The current developments in SMR's generally coincide with the generation IV concepts and the overall focus on reliability and safety, although some older GEN II & III concepts are also being designed and produced to fit within the SMR definition.

The current studies on the economics of the mentioned new generation reactors show estimated cost reductions. A study by the Energy Options Network estimates the average construction cost per kW at 3782$, which would be a decrease of 44% from the current capital cost of a nuclear power plant [56]. Other sources stay closer to the current price of nuclear power such as the US Energy Information Administration, which projects a $/kW increase of 2.5% for SMR's over the current power plant capital cost [57].

The International Atomic Energy Agency maintains a database that tracks developments of advanced reactors including small modular reactors in a variety of different design and production phases, currently there are over seventy reactors in development [58]. A recurring publication lists these developments for the small modular reactors by category, with the most recent being from 2020 [55].

The mentioned publication on SMR's lists the reactors divided in five categories [55]:

- Water cooled small modular reactors[10]
- High temperature gas-cooled small modular reactors
- Fast neutron spectrum small modular reactors (liquid metal, sodium & gas-cooled)
- Molten salt small modular reactors
- Micro-sized small modular reactors (typically up to 10Mwe)[11]

The fuel that is used by these reactors varies, but the thorium cycle is proposed for a selection of these concepts and will be addressed in detail where applicable. A more visual representation of the reactors covered, and their category and relation is shown in Figure 15.

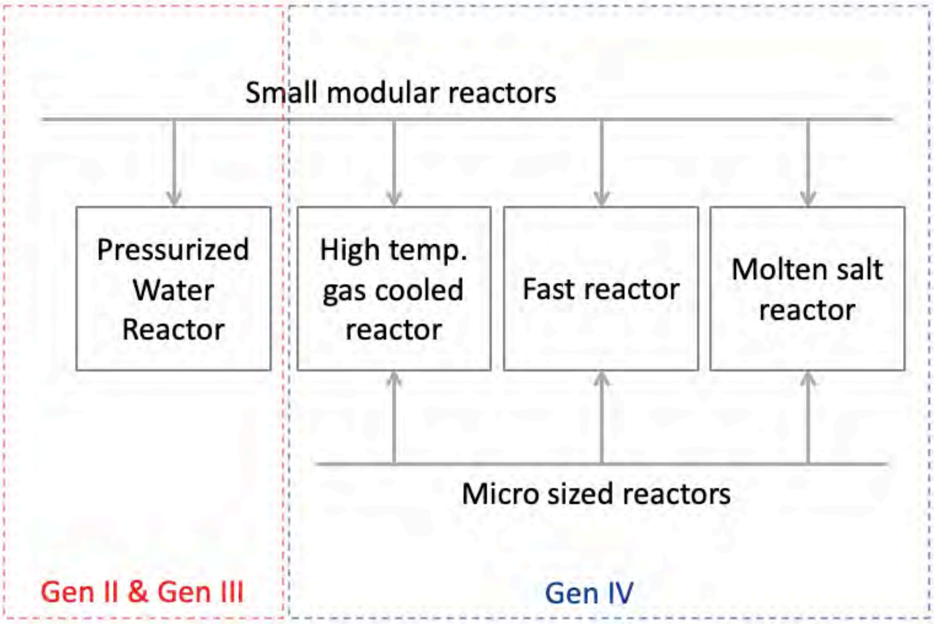


Figure 15 Overview of reactor concept and relation to small modular reactors, based on reactor types discussed in [55]

3.2 Initial filtering

As the application of this report is focussed on the marine propulsion and power generation plant some initial restrictions are placed on the reactor technology. Most prominently a power restriction, as the largest cargo vessels currently in operation have an installed power of approximately 80MW (brake power) for the propulsion. Additional power demand of vessels varies, as this depends on the application and is comprised by balance of plant, but also hotel load and cargo requirements. Additional power demand can be roughly estimated in the range of 10% to 25% of the installed power for the propulsion. This puts an upper bound of total required power at approximately 100 MW. As reactors are not specified by brake power but by their thermal power some initial estimate has to be made for conversion efficiency. This estimate is held at the for current reactors applicable 33% [2], indicating that for 100MW of delivered power reactors up to a thermal power of 300MWth are a

[10] An umbrella term under which the PWR resides, the PWR is considered here despite not being generation IV. It is both commonly used as well as having historic marine and naval applications, with significant development into the SMR versions of the PWR.

[11] Due to their design similarities here considered under their parent category of reactor types, as also shown in Figure 15. It should be noted that this is a simplification.

consideration.

This practically limits the application to the smaller of the SMR concepts for the marine propulsion and power generation system and excludes the Boiling Water Reactor (BWR) and Super-Critical Water Reactor (SCWR) from consideration, as these do not fit the requirements. Another consideration is that reactors should be capable of power generation, as some concepts are intended to be used purely as domestic/city heating [55] and therefore not suitable for a marine propulsion and power generation layout.

3.3 Criteria

The reactor types in development and under consideration are each distinctly different from each other. To highlight their differences in a structured way each will be discussed on the same topics. The topics addressed for each of the reactor types are a combination of development information and distinctions between reactors [55], as well as earlier (in section 2.1) established considerations that were discussed for a marine application. A short pros and cons list is included at the end for each reactor type, used to review the reactors relevance for the marine application. The complete list that will be addressed is shown in Table 7,

Development history	Brief history of concept and defining features				
Basic principles	Operating principle, details, and considerations	Neutron spectrum	Moderator (if applicable)	Breeding/ converter reactor	Coolant used
Fuel	Fuel type and composition	Fuel cycle (open/closed)	Fuel burnup	Waste production	
Power generation	Thermal power outputs in development	Output temperature range	Transient behaviour	Deadtime/ susceptibility to poisoning	
Safety	Passive safety	Active safety	Additional requirements/ considerations	Proliferation resistance	
Sizing	Size	Weight			
Technology readiness level [59]	Estimated TRL level				
Marine application	Pros & cons				

Table 7 Reactor criteria

3.4 Pressurized water reactors (PWR)

3.4.1 Introduction and history

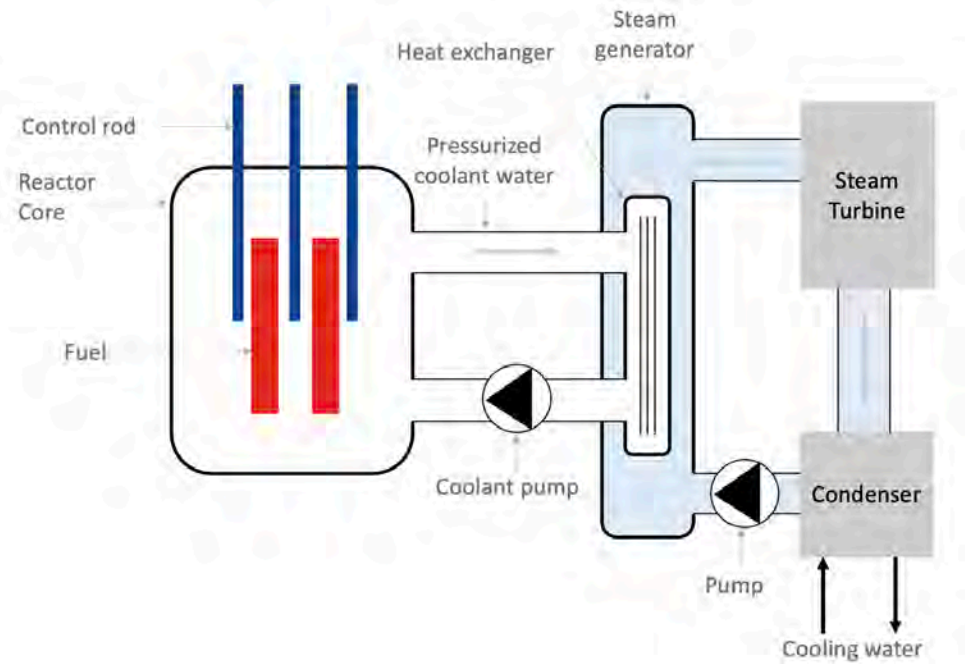


Figure 16 Pressurized water reactor, diagram based on information from [4]

The pressurized water reactor is currently the most used design in nuclear reactors. The reactor is a Gen II concept, which is used both in power generation, naval and commercial shipping applications. The PWR's heritage is rooted in the naval and maritime world, as it was the first reactor employed on a submarine (the USS Nautilus) in the 1950's [10]. The step to SMR's is a development of the already proven concept, specifically due to the historical developments in smaller and compact reactors for use in submarines.

3.4.2 Basic principles

The PWR is a water-cooled converter reactor with solid fuel that operates in the thermal neutron spectrum. Water acts both as the moderator and the coolant, with reactivity control commonly handled using control rods. During fission the pressurized coolant water (up to 15 MPa) of the PWR is heated, due to the water being pressurized it does not boil or form steam. The coolant transfers heat in a heat exchanger/steam generator to form steam in a secondary loop, this steam is used for power generation [4].

3.4.3 Fuel

The general fuel used is enriched uranium, with possibilities for other fuels. The pellet shaped fuel is placed inside fuel rods which are subsequently mounted in replaceable fuel assemblies [24]. The PWR generally operates on the open fuel cycle, with a fuel cycle length dependent on the reactor and the enrichment: the lower range being 1.5 to 2 years which is commonly seen in land-based reactors and the upper range being 7 years, which is seen in the marine SMR concepts [55]. Refuelling the reactor requires downtime, as the reactor can only be refuelled when stopped. The fuel cycle can be closed by reprocessing, this is a choice that has to be made from an economical and waste production perspective [8]. Burnup depends on the reactor type but is in general comparable to large scale reactors, which according to a publication by Lamarsh & Baratta is up to 45 GWd/tHM [4]. A report on the developments of small modular reactors by the IAEA confirms burnup in the same range, with some exceptions having lower burnup [55]. Waste production depends on both the height of the burnup and if the fuel is reprocessed or the ordinary Once-through cycle is used. Without implementation of these developments the amount of waste will be comparable (per power generated) to what is seen in current power generation reactors.

3.4.4 Power generation
Designs for the reactor vary from less than 10 MWe to 300 MWe [55]. The PWR reactors are constrained due to their coolant to lower temperatures than newer reactor designs. This means that the temperature output remains lower than 330 degrees Celsius, due to the properties of pressurized water. Reactivity response is expected to be limited, similar to the larger reactors currently in use: between 1 and 5% rate of change per minute. Transient behaviour varies between concepts, but generally operation is possible between 50 to 100% for extended time [17]. The PWR is susceptible to neutron poisoning, as described earlier in section 2.1.3. The build-up of fission products is an important consideration for the vessel, as it can limit low load operations severely. The solution of using highly enriched fuels as employed in the naval reactors is as mentioned earlier not possible in commercial reactors due to proliferation risk [60].

3.4.5 Safety
The reactors have a negative overall temperature coefficient of reactivity, combined with proven technology for the mitigation of design base accidents (DBA’s) and unacceptable conditions. Due to the high-pressure coolant the reactor must be housed in a containment structure built for the eventuality of a pressure vessel failure. Reactors do not have a built-in intrinsic/passive system for heat removal this capability is added separately [24], [61]. Proliferation resistance of the PWR is comparable to current day (power generation) reactors and will be lower than that of newer generation reactors.

3.4.6 Sizing and weight
The PWR can be small, dependent on the type of fuel and the degree of its enrichment, with higher fuel enrichment resulting in a smaller reactor [24]. SMR concepts in development are generally housed in a cylindrical reactor pressure vessel between 2 and 8 meters in diameter and between 4.8 and 17.7 meters high. Weights vary greatly in concepts between low (32 tons) and high (340 tons) [55]. This is without shielding.

3.4.7 Technology readiness level
The PWR reactor has been deployed successfully for more than half a century in naval as well as commercial power applications. Recently a PWR was commissioned and started operating in the SMR format on the Russian floating power station “Akademik Lomonosov” [55]. This technology (in SMR form) is currently in approximate TRL stage 8-9 (between complete & qualified and full competitive manufacturing [59]) with the first commercial units in use. Deployment in full scale “N’th of a kind” (NOAK) production as mentioned in section 3.1.3 for SMR’s is however not yet realized.

3.4.8 Pros and cons for the marine application

Pros	Cons
• High development TRL	• Lacks intrinsic/passive safety measures
• Maritime experience with reactor type	• Low burnup
	• Susceptible to reactor poisoning

3.5 High temperature gas-cooled reactors (HTGR) & very high temperature gas-cooled reactors (VHTR)

3.5.1 Introduction and history

The high temperature gas-cooled reactor (HTGR) and the very high temperature gas-cooled reactor (VHTR) are gas-cooled reactors, designed to operate with a high outlet temperature. The VHTR is one of the main options in the generation IV nuclear power strategy, proposed by the generation IV international forum. The VHTR is a development continuation of the HTGR, as they share the same concept with as difference the increase in operating temperature [23]. The reactor type has been in ongoing development for over 50 years, with a selection of prototype and test reactors built of varying designs and sizes in the past decades [62].

3.5.2 Basic principles

The gas-cooled reactors are moderated reactors (thermal neutron spectrum), the gas coolant of choice is helium for its favourable properties: staying in phase and being inert and neutron-transparent, although supercritical CO_2 is a possibility as well. These types of reactors are considered as an interesting generation IV option due to the high output temperature that can be provided, making it suitable for a variety of applications beyond electrical power generation. Development and prototype reactors are of the converter type [62].

3.5.3 Fuel

Two distinctly different fuel concepts exist for this reactor: The pebble bed and prismatic fuel elements. In a pebble bed reactor the fuel is in the form of spheres. These spheres have a uranium centre and are coated in carbon and ceramics (see Figure 17). The spheres are generally quite small (a few centimetres in diameter), and thus most reactors use a large amount of them (for instance 27000 in the 10 MWth HTR-10 reactor [62]). The benefit of using a pebble bed is that the pebbles can be moved in and out of the reactor with relative ease, allowing for what is called “online refuelling” where the reactor can be refuelled during operation without stopping. The most common fuel used in pebbles is low enriched uranium [55], although the addition of fertile materials such as thorium is possible and has also been proven in prototype reactors [62]. A downside of the pebbles is inherent to their spherical geometry, as the position and packing fraction of the pebbles influences reactivity in the reactor. Normally this is not an issue and is designed for however this can be of influence when the reactor is moved in an event such as an earthquake[12] which is covered in literature [63].

The prismatic fuel blocks are graphite blocks with dedicated channels in which fuel pins/compacts are placed (see Figure 17). These prismatic blocks are then stacked vertically in the core, this can be seen in Figure 17. Online refuelling is not an option with this concept and most developments show fuel cycles in the range of 1.5 to 2 years before refuelling [55].

[12] Although a ship is unlikely to experience an earthquake it does experience movement and acceleration over the lifetime. The earthquake is covered in literature as it is an unwanted (land-based) movement of the reactor.

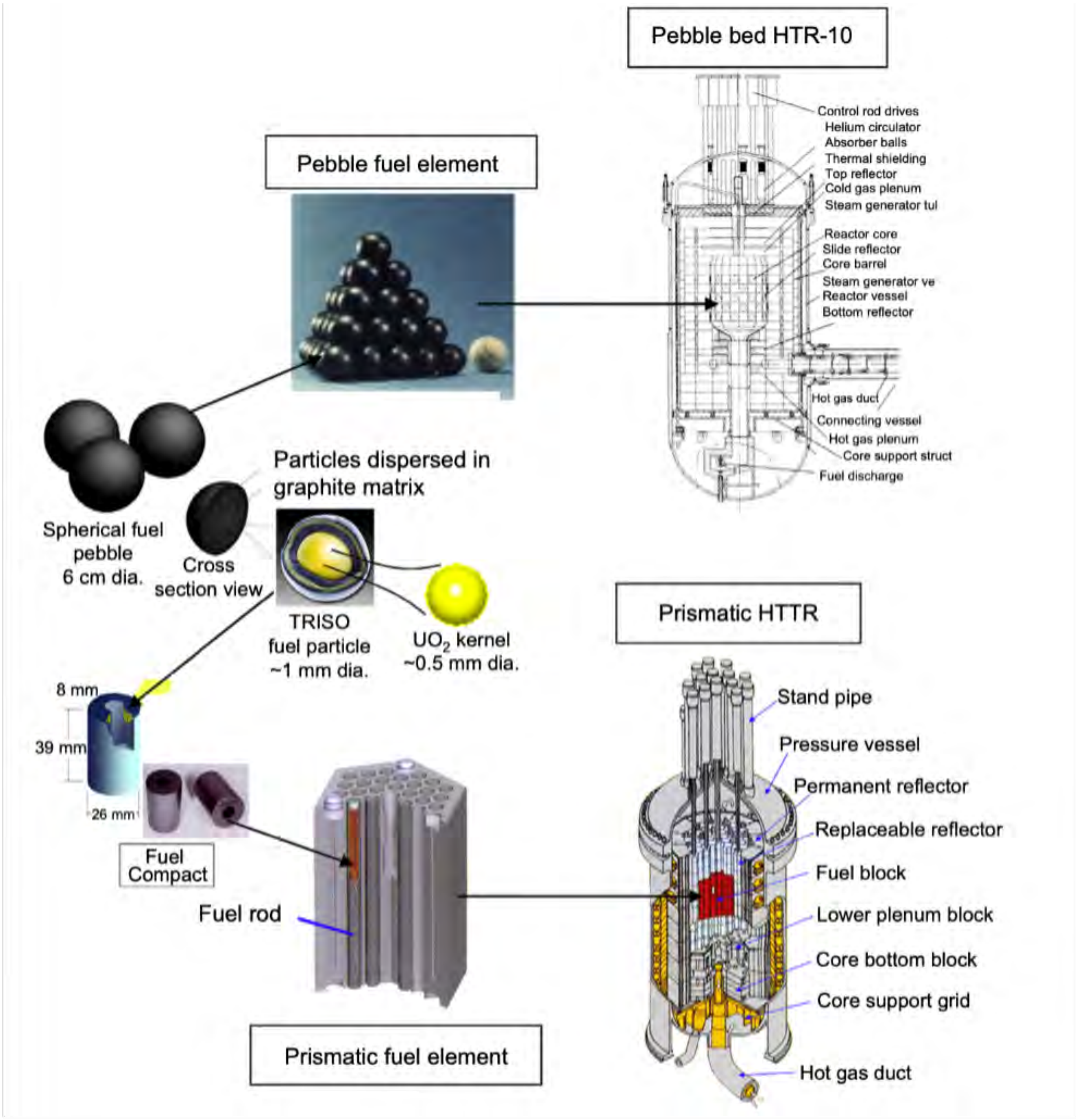


Figure 17 Pebble and prismatic fuel elements [62]

Multiple fuel cycles are possible but in general the fuel cycle is open, with a high burnup target, indicating that during the time in the reactor a significant portion of the available fissile and fertile material is used. Current reactors have high demonstrated burnup, going up to 90 GWd/tHM [62]. Higher burnup targets are being developed in the range of 150-200 GWd/tHM, although this can theoretically be increased even further [23]. One of the downsides of the pebbles is the reprocessing, which is considered difficult but under active development as mentioned in multiple studies [62], [64]. These reactors will (compared to the PWR) have a reduced amount of waste due to their increased burnup, further increasing this burnup is better. Reprocessing of the fuel, which as mentioned earlier is still in development, is important to reduce the waste production per power produced even further.

3.5.4 Power generation

Test reactors of the concept have been employed successfully over the last 50 years. The range of thermal power has been from low (10 MWth) up to quite high (882 MWth) [62]. Current SMR developments are within this range (10 MWth - 625 MWth) [55]. Output temperatures are high, the VHTR's are designed to operate at temperatures of over 950 degrees Celsius, although the more conservative 750 degrees Celsius associated with HTGR's is more commonly seen, especially in reactor developments of smaller size. The higher temperature allows for increased cycle-efficiency when used for power generation [65]. The reactor type is suitable for load following operations similar to other reactors, however as the fuel is enclosed the build-up of xenon from fission products occurs and should be considered [66]. The poisoning condition limits the operating power range of the reactor, reducing its possibilities to operate long term on low load. Recalling Figure 14 shows that high output temperature allows the reactor to operate as more than an electrical power reactor alone, showing that it is well suited for applications such as hydrogen production. The reactor concept is attractive in situations where it can operate in cogeneration with a hydrogen generation plant. This is shown in a study [67] where the two plants (electricity plant and hydrogen plant) work in conjunction on the same VHTR heat output. In this concept the electric power grid load is a percentage of the baseload thermal energy. The percentage is changed based on the load, if the electrical load increases more power is diverted to the electrical power and less to the hydrogen generation.

3.5.5 Safety

The HTGR has inherent safety due to its negative temperature coefficient combined with its large core with low power density, which gives the capability of passive cooling/heat rejection [62]. In a report by the Gen-IV forum it is mentioned that the robustness of the fuel pebbles also contributes to the safety of reactors that employ these [23]. Besides the passive safety systems, the reactors are also fitted with active safety and control measures. This is seen in both the pebble bed and the prismatic core, with both types using control rods for shutdown and reactivity control measures [62]. An interesting note on the topic of proliferation resistance is that due the high burnup the fuel leaves reduced long-lived waste, which combined with their difficult reprocessing and general generation IV development goals increases the proliferation resistance.

3.5.6 Sizing and weight

The HTGR's are in general quite large, due to their low power density and significant use of graphite [62]. The significant use of graphite in these types of reactors also contributes to the waste production, as nuclear graphite cannot be recycled at this moment and has to be stored [68]. Designed SMR concepts are generally cylindrical shaped, with diameters ranging from 2.5 to 6 meters and heights of 7.5 to 16.5 meters. Stated weight is in the region of 75 to 275 tons [55]. Besides the mentioned larger reactor, a containment structure suitable for reactors using a pressurized coolant is required as well as the shielding structure.

3.5.7 Technology readiness level

The HTGR and VHTR follow a similar development schedule as they are only different in their output temperature and not their fundamental principle. The HTGR is far in its development, the VHTR temperature goals are still in progress following the roadmap set by the Generation IV International forum that can be seen in Figure 18 [23]. In this roadmap/diagram three colours indicating different development states are used:

- Viability: indicating that basic concepts, technologies, and processes are tested under relevant conditions.
- Performance phase: indicating that processes, phenomena, and materials are tested and verified under prototype conditions.

- Demonstration phase: licensing and construction of first reactor and operation for extended period. [23]

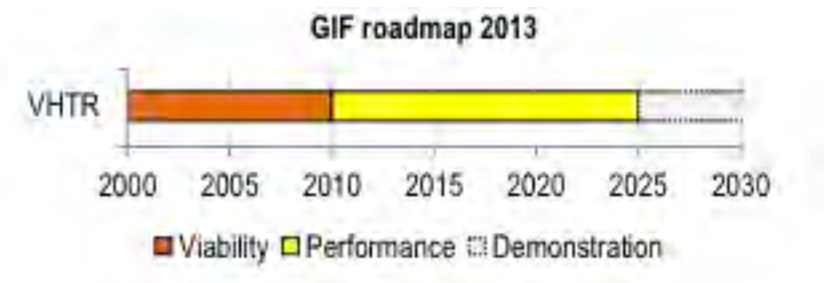


Figure 18 Roadmap on the deployment of the VHTR [23]

The HTGR and VHTR both are in active development: The HTGR with the mentioned selection of test reactors, indicating a TRL level of approximately 7-8 (demonstrated in operational environment, to complete & qualified [59]). The VHTR development is still further underway, following the diagram (see Figure 18) of the generation IV international forum at approximately TRL 6-7 (demonstrated in relevant environment to tested in relevant environment [59]). The lower TRL of the VHTR can be attributed to the material challenges that follow from the higher output temperature [23] and it being a progression of the HTGR that is also still actively developed.

3.5.8 Pros and cons for the marine application

Pros	Cons
• Passive safety • Increased proliferation resistance • High burnup achievable, reduced waste per power produced • Significant development experience (high TRL) • High temperatures allow for higher conversion efficiency • Can be refueled online (pebble bed) • Possibilities of using a part thorium as fuel	• Susceptible to movement (pebble bed) • Susceptible to reactor poisoning • Larger size • Graphite of reactor ends lifetime as waste

3.6 Fast reactors (GFR, LFR, SFR)

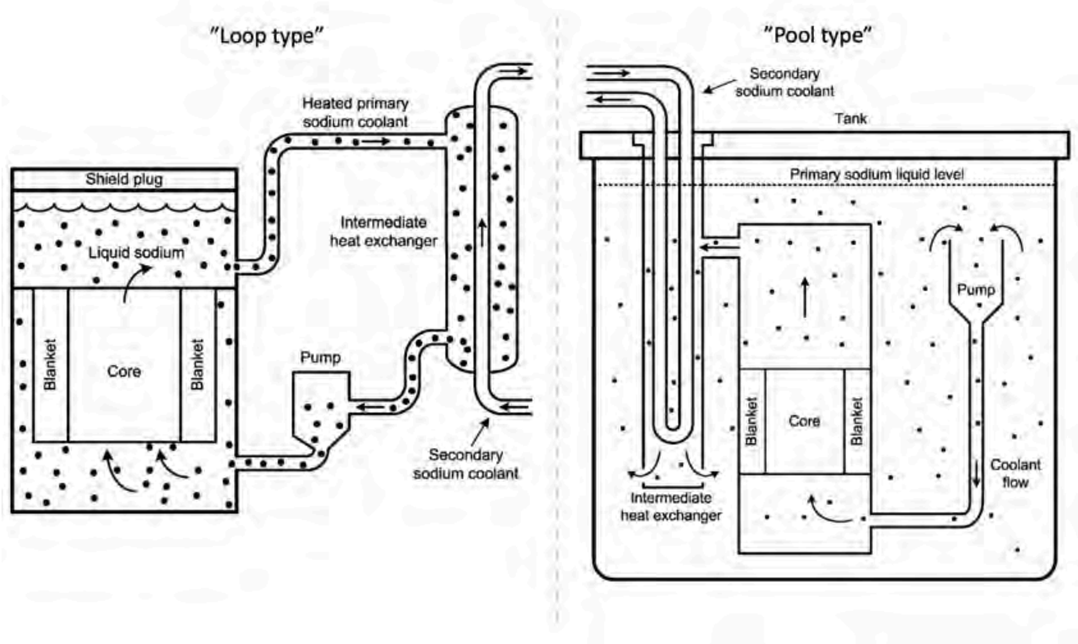


Figure 19 Fast reactors, pool and loop type [69]

3.6.1 Introduction and history

Fast reactors have been in development for almost as long as nuclear power reactors are in use. The generation IV types that are in development can be identified by their coolant medium as either gas-cooled (GFR), liquid metal-cooled (LFR), or sodium cooled (SFR). The operating principle for all is however the same. Historically the liquid metal-cooled reactor was employed on the Soviet "Alfa" class submarines, using lead-bismuth as coolant [24]. The defining feature of these reactors is the fast neutron spectrum, offering good utilization of fertile material which makes the reactors a very favourable choice for breeding [70]. An interesting note is that one of the liquid metal cooled SMR concepts specifically targets the commercial shipping application [55].

3.6.2 Basic principles

The fast reactors operate in the fast neutron spectrum. Depending on the coolant type there are some differences, important distinctions are the operating pressures and reactor form ("pool" or "loop" as seen in Figure 19). The main distinction between pool and loop is the position of the primary heat exchanger, in the pool design the heat exchanger is in the reactor pressure vessel and surrounded by the coolant. In the loop design it is outside of the pressure vessel.

- The gas type reactors are loop designs and operate at higher pressures due to their coolant, which is either helium or supercritical CO_2 [13].
- The Liquid metal reactors operate at ambient or close to ambient pressures and can be either in the pool design or loop design, coolant is either lead or a lead-based alloy such as lead-bismuth [13].
- The liquid sodium reactor is similar to the liquid metal-based reactor as it operates in near ambient pressures. The concept can be in both pool and loop design. The coolant used is liquid sodium [13].

These reactor concepts lend themselves to being breeder reactors, although converter is also possible.

3.6.3 Fuel
Fuel is enclosed in fuel rods/assemblies inside the reactor. The fuels proposed for the concept reactors is generally LEU up to 20% enrichment. The higher level of enrichment is a common solution for fast reactors, as due to the different neutron spectrum they require an increase of critical mass/fissile material [13]. Additional fertile material for breeding can be either uranium or thorium. Fuel cycle is generally open, although closed is possible with external reprocessing. Fuel cycle duration is between a few years for some concepts up to single fuelling for the entire reactor lifetime for other concepts [55]. In a report by the IAEA burnups of over 130 GWd/tHM have been confirmed, and theoretical gains are being made to further increase the burnup [71]. These higher burnups are favourable for the reduction of high-level waste per power produced. With the closed fuel cycle and breeding being able to reduce the amount of waste produced even further.

3.6.4 Power generation
Output power of fast reactors is being developed in ranges from below 10 MWth to 100's of MWth. Output temperatures are varying, depending on concept and coolant. The liquid metal cooled reactors are generally in the below 600 degrees Celsius range, while the gas-coolant based concepts display higher possible temperatures up to 850 degrees Celsius [55]. Sodium reactors operate in a similar temperature range to the liquid metal concepts, at around 500-550 degrees Celsius [23]. Reactors have negative temperature coefficients, following their design and the principles of generation IV safety. As the fast reactors employ the use of cladded fuel, there is still the build-up of fission products and their negative reactivity effect. However due to the use of higher enriched fuel the negative reactivity problem is reduced. This is confirmed in the publication by Sackett, where it is even mentioned as a "non-issue" [72], which would theoretically allow for a large operating power range. Load change is expected to be the same as current reactors (due to the use of cladded fuel), something that is also assumed in a study looking at system load response in fast reactors [73].

3.6.5 Safety
The fast reactors can be inherently safe, for the lead and sodium-based types this is due to their high thermal mass and passive cooling [74], [75]. The gas-cooled fast reactor can be passively cooled at lower power density/smaller sizes. At larger sizes these reactors require external (non-passive) cooling or lower power density construction [76]. The type of coolant for the reactor has implications for the safety of the reactor:

- Gas cooled reactors operate at high pressures, indicating the possibility for a high-pressure leak and associated required mitigating measures [77].
- Liquid metal cooled reactor are often proposed, the main safety related issue occurs if lead-bismuth is used. Neutron capture of bismuth forms the highly toxic element polonium when used as reactor coolant. This has to be considered [74].
- Liquid sodium as coolant has two safety considerations, the first being that liquid sodium can catch fire/combust during a leak scenario. The second is that liquid sodium reacts with water (which can occur in leakages of heat exchangers or other scenarios) and forms hydrogen (which is combustible). These are safety risks associated with sodium [75].

Fitting with the generation IV goals the fast reactors are also being developed to offer increased proliferation resistance [23].

3.6.6 Sizing and weight
Sizing can be very compact depending on size and reactor layout, the pool type is by definition bigger than the loop type of reactor. The weight of the reactors depends on the type of coolant, as well as on

the required critical mass. The size and weight of the reactor also depends on the enrichment of the fuel, as higher enrichment would reduce the required critical mass. As fast reactors operate in the fast spectrum there is no moderator that contributes to the weight. Power density of the concepts varies, due to the differences between coolant and layout. A downside is the sizing of the reactor if it is intended for breeding. This problem, where breakeven breeding was not possible/difficult at smaller scale, was already observed in an initial GFR concept by the generation IV international forum [23]. SMR sizes in development are cylindrical shaped with diameters of between 2 and 7.6 meters, and heights of 3.5 to 24 meters. Weights associated with these sizes are not stated often, the few stated values are between 200 and 280 tons [55].

3.6.7 Technology readiness level

The SFR, LFR and GFR are all ongoing developments. Following the timeline by the generation IV international forum (see Figure 20) would indicate TRL readiness levels for the SFR and LFR of 6-7 (demonstrated in relevant environment to prototype demonstration [59]), although this appears slightly enthusiastic considering the timeline for each of the SMR scale concepts in the publication by the IAEA [55]. The GFR is in TRL stage 4-5 (lab validated to validated in relevant environment [59]), fitting with the assessment of the Generation IV International Forum.

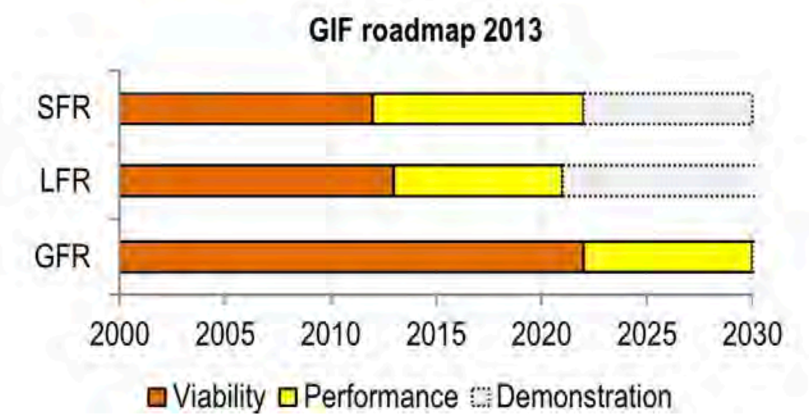


Figure 20 Roadmap on the deployment of the LFR and GFR [23]

3.6.8 Pros and cons for the marine application

Pros	Cons
• Passive safety (large scale GFR to be addressed) • Increased proliferation resistance • High burnup achievable, reduced waste per power produced • Not susceptible to reactor poisoning • High temperatures allowing for higher efficiencies • Very suitable for breeding • Possibilities of using thorium (partly)	• Lower TRL • Problems associated with coolant (safety and toxicity hazards) • Breeding at SMR scale identified as potential problem • Increased fissile load

3.7 Molten salt reactors (MSR)

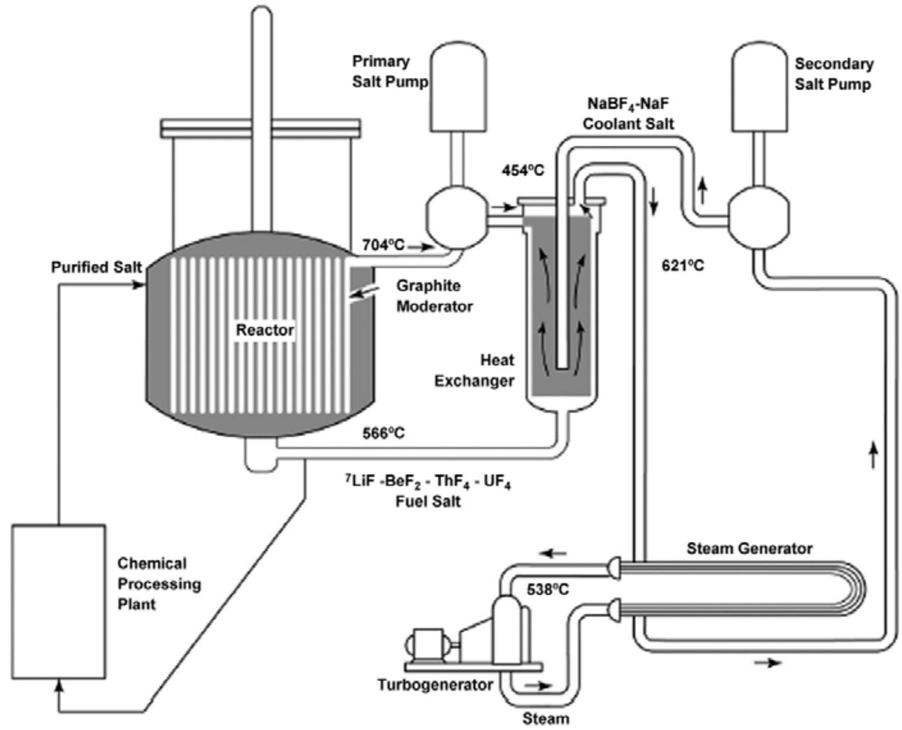


Figure 21 Schematic overview of a thermal molten salt reactor [5]

3.7.1 Introduction and history

The molten salt reactors distinguish themselves from the other reactors in that the fuel is not cladded/encapsulated but mixed in and freely moving with the coolant salts. The concept of the molten salt reactor dates back to the 1950's in the United States, where the first concept was as a small reactor designed for military aircraft use. Although a test reactor was built and successfully made critical, the concept never took off due to advances in other technology. The potential of the project however was realized, and the Oak Ridge National Laboratory (ORNL) followed with a test reactor concept that was both larger and designed to be capable of breeding thorium [5]. This molten salt reactor experiment (MSRE) was the second molten salt test reactor, with a power of 8 MWth [5]. Following the successful experiment, a new reactor was proposed as a continuation, a 1000 MWe denatured molten salt reactor, this was however never built [78]. Due to the construction of these test reactors the technological basis has already been proven. At time of writing[13] a new test reactor has been built in China: a molten salt test reactor capable of operating on the thorium cycle [53]. Interesting to note is also that in recent years there is commercial interest in the development and employment of a MSR for marine [79] and barge-based power plant [80] applications.

3.7.2 Basic principles

There are multiple different molten salt reactors currently in development, with a division between reactors in the fast and the thermal neutron spectrum [81]. Moderation (applicable to the thermal reactors) is done with either graphite or heavy water [55]. The coolant in the molten salt is in general a fluoride-based salt mixture with the fuel. This means that both the coolant and the fuel move through the core and the heat exchanger and can be removed/manipulated without stopping the reactor [55].

[13] December 2021

3.7.3 Fuel

The fuel used in the molten salt reactor can be either uranium, or a combination of other fuel types. The reactor is of particular interest because it can serve as a thorium breeder reactor, with a fissile fuel to start the reaction [81]. This fissile starting fuel can be uranium, but also plutonium is proposed as a way of removing it as possible nuclear weapon material [68]. The molten salt reactor can run a closed fuel cycle with a dedicated onsite reprocessing facility, where part of the fuel is diverged for processing. Reprocessing increases the efficiency of the fuel usage greatly compared to an open fuel cycle [5]. A different selection of concepts is built on the idea of a single fuelling, where the reactor operates on the same fuel load over a long cycle (30 years). This was proposed in a study as alternative cycle for the denatured molten salt reactor [78]. The proposed reactor concepts and designs have planned burnup targets that are significantly higher than those of current reactors, ranging in the 100's of GWd/tHM, up to as high as 900+ GWd/tHM [55]. This increase in burnup can be attributed to the reactor not having cladding/fuel rods as in conventional reactors the integrity of the fuel rods cladding is one of the limiting factors for the burnup [2], although it remains a theoretical increase for now. The produced amount of waste from the reactor will benefit greatly (waste reduction) from the increased burnups, closing the fuel cycle and reprocessing the fuel can improve this further. The biggest improvement can be made when considering the earlier mentioned thorium cycle (as seen in the earlier Figure 13).

An interesting side-track is in the development of molten salt reactors as a waste burner concept. A waste burner reactor uses spent nuclear fuel as its primary (fissile) fuel source combined with a fertile material such as thorium. This combination allows the reactor to start a breeding reaction and "burn" the spent nuclear fuel far beyond the capabilities of reactors in use today [5], [68]. Burning of old nuclear fuel can be seen as both favourable from an energy generation perspective, and from non-proliferation and waste reduction perspectives.

3.7.4 Power generation

The molten salt reactors currently being developed vary in sizes from 50 MWth up to 100's of MWth. The molten salt reactors operate at relatively high temperature outputs in the range of 600-700 degrees Celsius [55]. The use of high temperatures is attractive for electrical conversion efficiency as well as for the options of cogeneration, recalling Figure 14 where the temperatures of different processes are shown. The salt remains at near ambient pressures which is favourable as this reduces the requirements for high pressure on the pressure vessel [82].

Theoretical transient behaviour of molten salt reactors is good due to the strong negative feedback coefficient inherent to the use of fuel salt. This was determined in a study on the simulations of the response to transient loading for the fuel salt [83]. The benefit of this is that the reactor can automatically load follow when there is more demand, as an increase of electrical demand would result in a decrease of salt temperature, which in turn would stabilize due to an increase of reactivity and a following increase of temperature which would restore the equilibrium, this is shown in Figure 22.

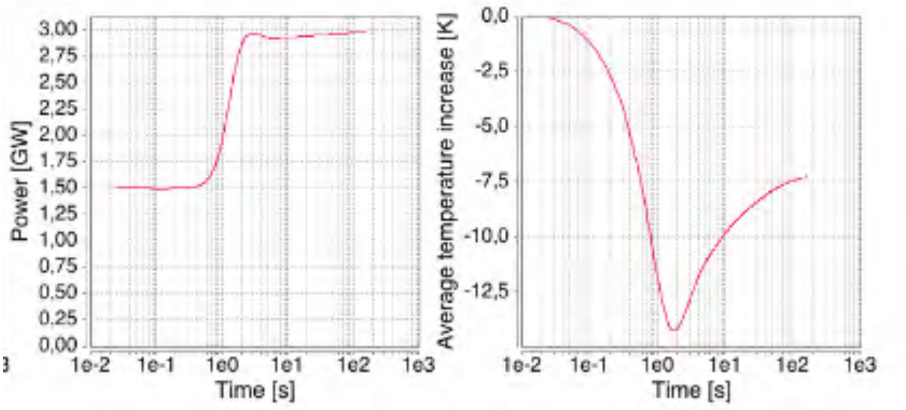


Figure 22 Load following of (Fast) Molten Salt Reactor [83]

It should be noted that these calculations focus on the theoretical response of the fuel salt, and not the other aspects of the nuclear power plant. Research has been done on components of nuclear plants[14] under load-following conditions, showing that the response is not only governed by the fuel. Due to the loading of the nuclear plant other components can cause a maximum number of cycles to be set [19]. A plant design with extreme load-following capabilities thus does not only require a capable reactor but also a capable complete plant. This is also shown in the earlier mentioned study, as later the more conservative 5%/min is used instead of the more extreme load-following capabilities indicated earlier [83].

A specific benefit of the molten salt reactor is that, as the fuel is not being contained in fuel pins/rods/pebbles, the build-up of fission products and associated neutron poisoning can be mitigated. This can be done by an off-gas installation by actively bubbling these gasses out with helium, where the helium “carries” out the fission products [84]. Another option is nozzle spraying, that does not rely on the use of helium, but serves the same purpose of removing fission products [68]. Successfully removing fission products means that the reactor is not susceptible to the problems associated with reactor poisoning, such as the stalling and deadtime that can occur due to Xe and Sm build-up in fuel rods. A reactor insusceptible to poisoning has a theoretical far greater operating power range.

Besides these benefits the use of salt is however also one of the downsides of the molten salt reactor, as the high temperature salt is a material-technical challenge due to corrosion. The corrosion issue is also identified by the generation IV nuclear forum as one of the points on the roadmap to the successful deployment of the molten salt reactor [23]. The other associated downside is that because the salt moves out of the core a higher amount of fissile material is required to fill the loop [83].

3.7.5 Safety

Molten salt reactor concepts have a built-in passive safety system due to the salt being used as the coolant and fuel, and the strong negative temperature coefficient, indicating that upon temperature increase the reactivity drops strongly. This prevents problems with stability, and, as mentioned earlier, makes the reactor follow load. Besides this in some reactors a passive “freeze” plug is employed. The freeze plug is a salt plug, that is kept cooled and solid, and in case of a problem melts due to the increased temperature of the fuel salt. The melting of the freeze plug then allows the molten salt mixture to flow into a passively cooled tank, where it can no longer undergo fission and slowly cools

[14] Not specific to MSR’s but covering the general components of a nuclear power plant and the balance of plant.

and solidifies [5]. Other reactor concepts employ passive cooling (oil filled channels) for removing decay heat from the reactor [68]. Active cooling can be done in a variety of ways and can be combined with the passive safety systems of the reactor.

The use of the salt mixture also comes with a safety downside, as the fuel and coolant salt leaves the reactor and passes the heat exchanger all these components become irradiated. This increases the maintenance difficulty and would require shielding for additional components in addition to the shielding of the core.

Proliferation resistance of the molten salt reactor ties into the height of the burnup (higher burnup = less residual usable material), with the proliferation resistance increasing further if the thorium cycle is used as this has significant non-proliferation benefits as described in section 3.1.2. This is accompanied by the general goal of increasing overall proliferation resistance of generation IV designs [23].

3.7.6 Sizing and weight

Molten salt reactors vary in size due to their different neutron spectrum, use of breeding cycles and duration of the fuel cycle. These all have strong influence on the eventual size of the reactor and associated plant. A few concepts are in development in the range of 2.4 to 3.5 meters diameter and 9 to 12 meters in length. No weights are stated for the concepts [55]. A conservative estimate would be to estimate weight similar to the other reactors.

3.7.7 Technology readiness level

The MSR's developments are in TRL level 4 (validated in lab [59]) when considering the timeline by the generation IV international forum (see Figure 23). At the present time developments have picked up speed, with the earlier mentioned small scale test reactor in China. These current developments together with the experience gathered at the ORNL (with the MSRE) indicate that a TRL level of between 4-6 (validated in lab to technology demonstrated in relevant environment [59]) appears to be more fitting in the current situation, especially for the thermal MSR.

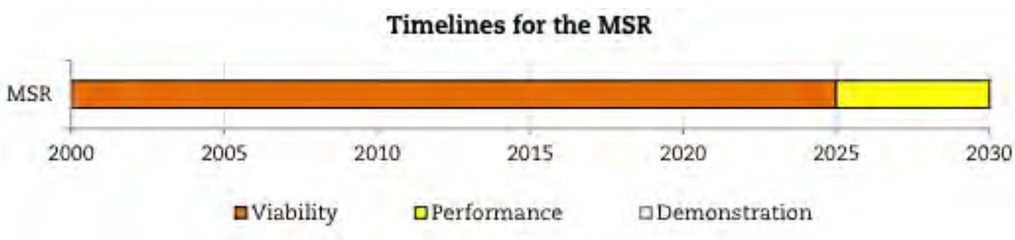


Figure 23 Timeline molten salt reactor [23]

3.7.8 Pros and cons for the marine application

Pros	Cons
• Passive safety • Proliferation resistance • High and possible very high burnups achievable • Flexible in fuel cycle (online refueling, long fuel cycles) • High temperatures indicating higher possible efficiencies • Not susceptible to reactor poisoning • Future capability to operate in thorium cycle (no/limited U235) • Theoretical possibility for strong load following	• Lower TRL • Material technical issues caused by salt • Irradiated salt leaving the core, requiring considerations with shielding and heat transfer

3.8 Overview of reactor technologies

A comparison of these reactor technologies can be seen in the summary of each reactor type that is provided in Table 8.

Reactor type	PWR	(V)HTR*, Pebble bed	(V)HTR*, Prismatic	SFR	LFR	GFR	MSR
Neutron spectrum	Thermal	Thermal	Thermal	Fast	Fast	Fast	Thermal/ fast
Fuel cycle	Open/ closed	Open	Open	Open/ closed	Open/ closed	Open/ closed	Open/ closed
Burnup (GWd/tHM)	45-75	90-200+	90-200+	130+	130+	130+	90+
Fuel type	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th
Uranium enrichment	LEU <5% HEU in special applications	LEU (3-20%)	LEU (3-20%)	LEU (5-20%)	LEU (5-20%)	LEU (5-20%)	LEU
Type	Converter	Converter	Converter	Converter/ Breeder†	Converter/ Breeder†	Converter/ Breeder†	Converter/ Breeder†
Thorium capable	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding/ continuous cycle
Refuelling	Offline	Online	Offline	Offline	Offline	Offline	Online/ offline
Refuelling cycle (low end)	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y	1.5 – 2 y
Refuelling cycle (high end)	7 – 8 y	Continuous	1.5 – 2 y	Lifetime (20+ y)	Lifetime (20+ y)	Lifetime (20+ y)	Lifetime / Continuous
Passive safety	-	+	+	+	+	O	+
Active safety	+	+	+	+	+	+	+
Baseload	+	+	+	+	+	+	+
Load following	-	O	O	O	O	O	+
Operating temperature	< 330 °C	< 700 °C (V)* 700-1000+	< 700 °C (V)* 700-1000+	500-550 °C	<600 °C	<850 °C	< 800 °C
TRL level [59]	8-9	7-8 (V)* 6-7	7-8 (V)* 6-7	6-7	6-7	4-5	4-6

*Table 8 Comparison of reactor technologies, summary of information from previous chapters. *Indicates specifics only associated with the "very" high temperature variety. † Indicates that breeding must be proven/demonstrated at the SMR scale.*

A figure showing which types and concepts are in each stage of development is shown in Figure 24, to give a better overview of what SMR types are currently in development and available.

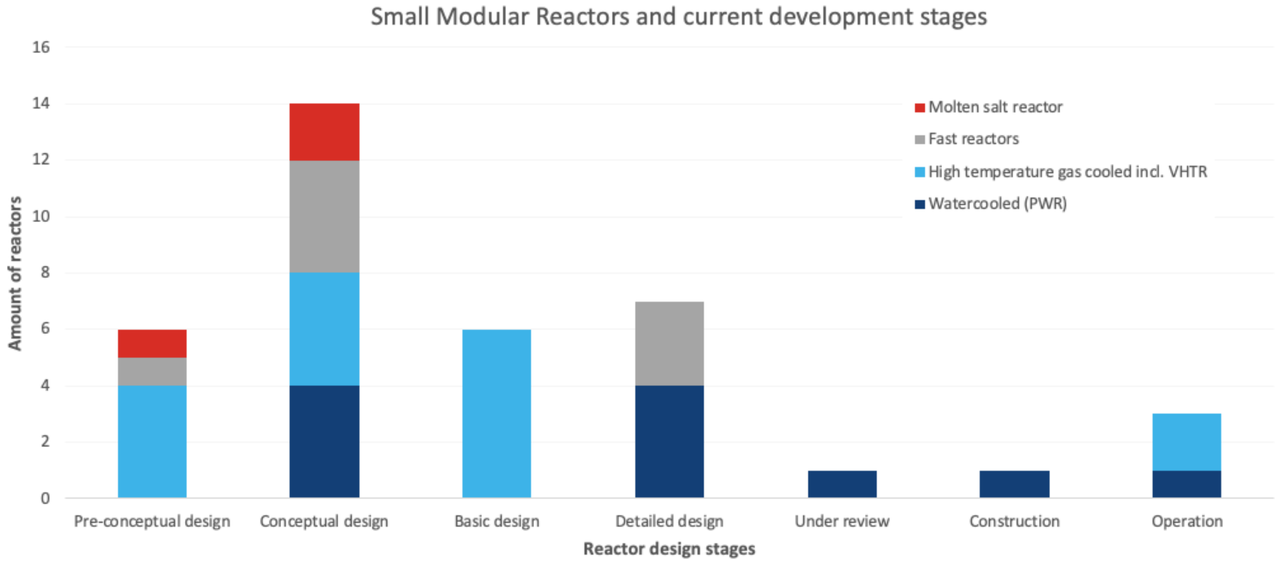


Figure 24 Development stages of small modular reactors, data from [55]

The division seen in Figure 24 is very similar to what is discussed previously for TRL levels, and the readiness of each type is reflected by the reactors in each stage of development.

Finally, each of the marine pros and cons as discussed can be compared, shown in Table 9.

Reactor type	PWR	(V)HTR	GFR, LFR, SFR	MSR
Pros	• High development TRL • Marine experience with reactor type	• Passive safety • Increased proliferation resistance • High burnup achievable, reduced waste per power produced • Significant development experience (high TRL) • High temperatures allow for higher conversion efficiency • Can be refuelled online (pebble bed) •Possibilities of using a part thorium as fuel	• Passive safety (large scale GFR to be addressed) • Increased proliferation resistance • High burnup achievable, reduced waste per power produced • Not susceptible to reactor poisoning • High temperatures allowing for higher efficiencies • Very suitable for breeding •Possibilities of using a part thorium as fuel	• Passive safety • Proliferation resistance • High and possible very high burnups achievable • Flexible in fuel cycle (online refuelling, long fuel cycles) • High temperatures indicating higher possible efficiencies • Not susceptible to reactor poisoning • Future capability to operate in thorium cycle (no/limited U235) • Theoretical possibility for strong load following
Cons	• Lacks intrinsic/passive safety measures • Low burnup • Susceptible to reactor poisoning	• Susceptible to movement (pebble bed) • Susceptible to reactor poisoning • Larger size • Graphite of reactor ends lifetime as waste	• Lower TRL • Problems associated with coolant (safety and toxicity hazards) • Breeding at SMR scale identified as potential problem • Increased fissile load	• Lower TRL • Technical issues caused by salt • Irradiated salt leaving the core, requiring considerations with shielding and heat transfer

Table 9 Pros and cons for each of the reactor types, specific to the marine application

3.9 Chapter conclusion

In conclusion it can be seen that quite a few reactor types are being developed actively, fitting in three major development themes: Generation IV reactors, thorium as fuel, and SMR's. Using the available information on development concepts and research, it is possible to establish the most interesting candidates for the marine application. This was done using the list of pros and cons as can be seen in Table 9.From this two reactor types are shown to be most promising: The (V)HTR and the MSR, both from the generation IV family with inherent passive safety, high burnups, high operating temperatures and capable of using thorium to some extent. The (V)HTR in its pebble or prismatic form has a higher TRL currently, indicating this as the near-term solution (with near term estimated at 10-20 years based on reactor developments). The properties of the molten salt reactor are however better with regards to its capabilities, especially on load following, although due to its TRL it is still further away indicating it is a long-term choice. From a perspective of fuel cycles both are interesting due to the possibility of continuous refuelling, although shorter fuel cycles with more "standard" reloading possibilities could also be suitable. The eventual transition to a full thorium-based[15] fuel cycle with the molten salt reactor makes this the attractive long-term choice (estimated at 20+ years).

The chosen reactor candidates surpass the PWR, despite its higher TRL, in passive safety features as well as output temperature and fuelling capabilities. Similarly the fast reactors are an interesting development, but a larger step due to their lower TRL, higher fissile load and difficulties associated with the coolants used. Compared to the MSR with a similarly low TRL these fast reactor types are less attractive as the long-term solution, especially considering that the MSR can also be a fast reactor.

It should be noted that again the developments are heavily land-based application focussed on their research and development, which is reflected most prominently in the load following capabilities of the reactors (<5%/min).

[15] "Full thorium based" as in replacing the earlier mentioned (section 3.1.2) "driver" fuel with U233 from other thorium reactors.

4 REVIEW OF MARINE PROPULSION SYSTEM REQUIREMENTS

This chapter covers the sub question: What are the defining conditions of a marine propulsion system? Detailing the basic layouts and their differences, as well as describing the criteria that define a marine propulsion system.

4.1 Definition of the marine propulsion system

The marine propulsion system including the power generation system comprises the entire selection of components required to both give a vessel the capability to move under its own power, as well as provide power for the operational tasks and accommodation. This power can originate from a variety of energy/fuel[16] sources, where the marine propulsion and power generation system is a method of converting and delivering this energy. Besides delivering power a percentage of the power is also consumed for the balance of plant (BOP), which refers to its own support systems necessary for the plant to deliver power. This overview is shown graphically in Figure 25.

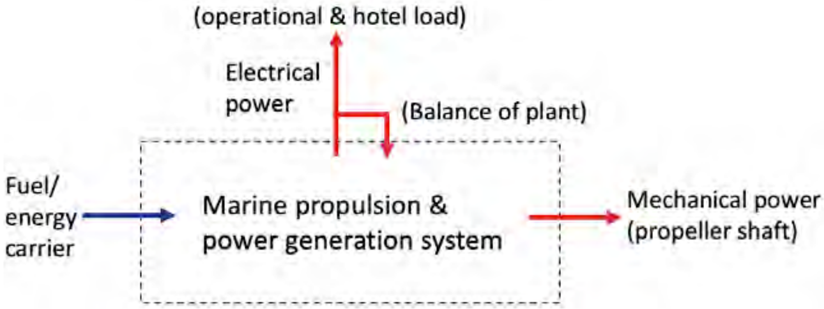


Figure 25 Basic schematic overview of the marine propulsion & power generation system

The marine propulsion and power generation system can vary strongly per type of vessel, especially if the auxiliary plant is considered as well in the broader context of marine engineering. This report is focused on the replacement of the fuel-based engine with a nuclear reactor-based option, replacing only the required systems of the fuel-based plant with the required systems for the nuclear reactor-based option. Therefore, systems that are not changed are not considered.

A variety of different layouts is possible, these can be divided into two main options for a marine propulsion and power generation system: Fuel-direct and fuel-electric, both shown in Figure 26.

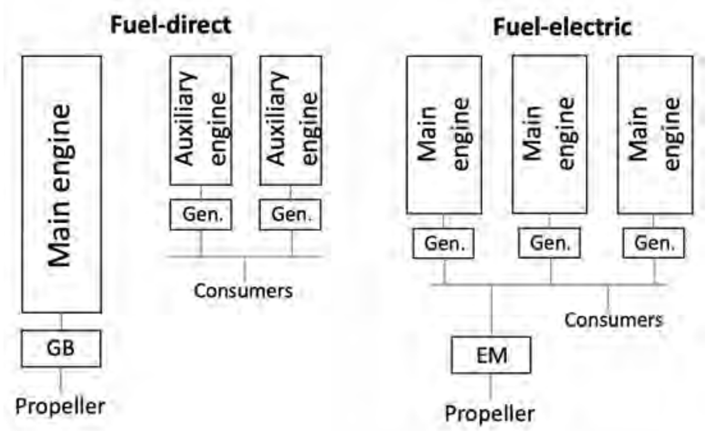


Figure 26 Fuel-direct and fuel-electric propulsion, (GB = Gearbox, Gen. = Generator, EM = Electromotor)

16 Fuel in marine context often means diesel, called fuel in this report to not exclude alternative fuels.

The first option, fuel-direct drive, is in the current situation comprised of a fuel-based engine or turbine (fuel or steam based) that directly drives the propeller shaft. This can be through a reduction gear or without, depending on the rotational speed of the engine/turbine.

Fuel-direct [85]	
Advantages	*Disadvantages*
• High efficiency in design conditions due to low conversion losses compared to other solutions • Generally, less costly than other options due to reduced amount of required systems	• Size and location constraints (as the engine has to be in line with the shaft) • Unfavourable fuel efficiency and characteristics when operating in off-design conditions • Requirement for power generation to be separate, either via generator sets or shaft generator (power take-off)

The second option is fuel-electric drive. In this situation the fuel-based engines or turbines provide power to the ships electrical grid via generators. This power is then converted back to mechanical rotation at an electromotor that drives the propeller shaft. This electromotor can be placed either inside the engine/machinery space, or in a podded propulsor/thruster.

Fuel-electric [85]	
Advantages	*Disadvantages*
• Flexible in arrangement (generators can be placed throughout the ship and are not required to be in-line with or near the propeller shaft) • Efficiency improvements in part load/off-design conditions due to load distribution over generators • Possible addition of battery systems for peak shaving/efficiency improvement	• Costly, due to increased installation requirements and additional electrical system • Lower efficiency due to conversion losses.

Although this option appears less ideal due to the conversion losses the flexibility increase is very valuable. The fuel-electric drive has many varieties in which different electricity carriers/producers are integrated in the ships net, allowing for more hybrid solutions [85].

4.2 Requirements of the marine propulsion and power generation system

The propulsion and power generation system requirements partly follow from the requirements from the vessel, regarding specifications such as vessel speed and required level of redundancy. Other criteria are independent of the application and include [86]:

- Efficiency
- Power density
- Load transients and system start-up
- Environmental impact
- Safety and reliability
- Economics

4.2.1 Efficiency

The highest possible efficiency should be the overall goal of each installation, although this is an interplay between the other factors such as safety and reliability (e.g., the addition of redundancy causing an efficiency penalty) and the economics of the installation and operation.

4.2.2 Power density

A system should have sufficient power density, indicating the amount of power it can produce per volume. This is especially important in mobile applications such as ships, as increased volume as well as weight negatively impact the cargo carrying capacity of a vessel. In a similar sense, if a system has insufficient power density it can hamper the endurance and autonomy of the vessel, which is dependent on the amount of energy that can be stored. Power density is a sense of compromise and not an individual metric, and this is connected to for instance efficiency but also economics.

4.2.3 Load transients and system start-up

Vessels are designed to operate at their design speed, which for conventional vessels close to the maximum power (with some margin for sea-state and adverse conditions considered [87]). Although this is not the only condition that a vessel is subject to: the marine propulsion and power generation plant has to be able to deal with a variety of situations, ranging from this “high load & full speed” scenario, to the “low load port stay” scenario. These situations can be quantified for a ship using a load profile, which is a log of either total power or propulsive power and electrical power separate. These logs give insight into both magnitude, deviation, and timescale of power demand.

In a paper on the application of hybrid propulsion systems the load profile of a group of post-Panamax ships is discussed. These Post-Panamax ships use a conventional diesel-direct drive for their propulsion, with their propulsive power being logged daily over long voyages. These operational profiles show that the propulsive demand for a conventional vessel can vary in the order of 10% loaded and 20% in ballast over the duration of the voyage [88]. Although this can vary on a vessel-by-vessel basis and on the location, it is shown that the baseload demand is not by definition purely stable over longer durations (day to day scale). Another paper focussed on the application of hybrid propulsion focussed specifically on the electrical auxiliary power of a RoPax ship. In this paper the timescale is smaller, resulting in more measurements per timeframe. Here it is established that, although the auxiliary power is relatively stable, it has distinct sharp peaks at specific times: when manoeuvring using thrusters. Thruster use on ships that run a fuel-direct setup with an auxiliary power plant means that power spikes of 50 to 100% of the auxiliary power capacity can occur [89]. On ships with larger baseload power draw, or diesel-electric based ships this effect would be slightly less extreme (as the percentage power of the thruster is distributed over a larger total electrical capacity). One exception being dynamic positioning ships, as these ships use thrusters to maintain accurate position over an extended time. The intermittent use of thrusters at varying power levels causes large fluctuations in the power requirements of the vessel, making this a challenging application for power generation. A study shows that these transients can be as large as multiple thrusters being used per minute at high power, with logged power spikes for a drilling rig as large as 30% of the total installed power in one minute [90].

Another consideration is the availability of the marine propulsion plant and power generation system, as it is unfavourable for operations if the power plant requires a significant period for start-up. A gradual but relatively fast start-up is preferred for this reason.

4.2.4 Environmental impact

Environmental impact is a hot topic, with many developments focussed on harmful emission reduction, although other forms of environmental impact also exist. Different metrics can be used, either tied to efficiency (such as CO_2 per kWh) or focussing on the large picture such as emissions per transport work (such as the Energy Efficiency Design Index, EEDI [91]). It follows that any new marine propulsion and power generation plant should meet the current requirements although preferably being significantly better. It should be considered that these regulations are heavily focussed on fossil fuels and down the pipe emissions, which makes solutions without these (such as nuclear power) both very favourable, but also the metric less valuable. A lifecycle assessment is better suited, especially in a comparison of different metrics (such as emissions and fuel waste).

4.2.5 Safety and reliability

Safety and reliability are vital to a marine propulsion and power generation system, both to ensure continuity of operations as well as ensuring that no harm is done to the crew, environment, ship, or cargo. Safety and reliability go hand in hand, systems should be as reliable as reasonably (and economically) possible and suitable for the application at sea. The marine environment has some specific differences to installations that are land based: There is movement in the form of acceleration and vibration that the installation is subject to. Additionally in case of both incidents as well as normal operations there is limited personnel available, as overall crew size influences the operational cost [92] they are for economic reasons not larger than necessary. The final consideration ties into this and is inherent to the nature of a ship: in case of an emergency this has to be addressed with the means on board, as it cannot be guaranteed that there is an immediate external emergency response.

4.2.6 Economics

Economics are often described in the form of capital expenditures (CAPEX) and operational expenditures (OPEX). The propulsion and power generation plant of a vessel is a large influence on the economics of the vessel. In current vessels the fuel costs are considerable and therefore a large contribution to the overall OPEX of the vessel [93]. For a marine propulsion and power generation system to be successful it should be economically viable/competitive in both CAPEX and OPEX. This ties into the other discussed factors, as without these it is difficult to achieve this viability.

4.3 Chapter conclusion

The marine propulsion and power generation plant imposes some non-trivial requirements on any power source/energy carrier that is used. The most difficult requirement being the varying loads, high efficiency requirements and maintaining suitable energy density. A suitable marine propulsion system has to satisfy the many criteria, as otherwise its implementation becomes difficult due to it not being economically, operationally, and environmentally feasible.

5 POWER CONVERSION AND BALANCE OF PLANT

This chapter covers the sub question: What energy conversion and balance of plant systems are suitable for a nuclear based marine propulsion system? This chapter will first look at the available options and then going into further detail on these.

5.1 Overview of systems

To operate a reactor as a power plant, a selection of other systems are required. These systems together form the balance of the plant and ensure that the heat generated by the reactor is converted to useful energy. An overview of power conversion methods and how these relate to marine propulsion is shown in Figure 27.

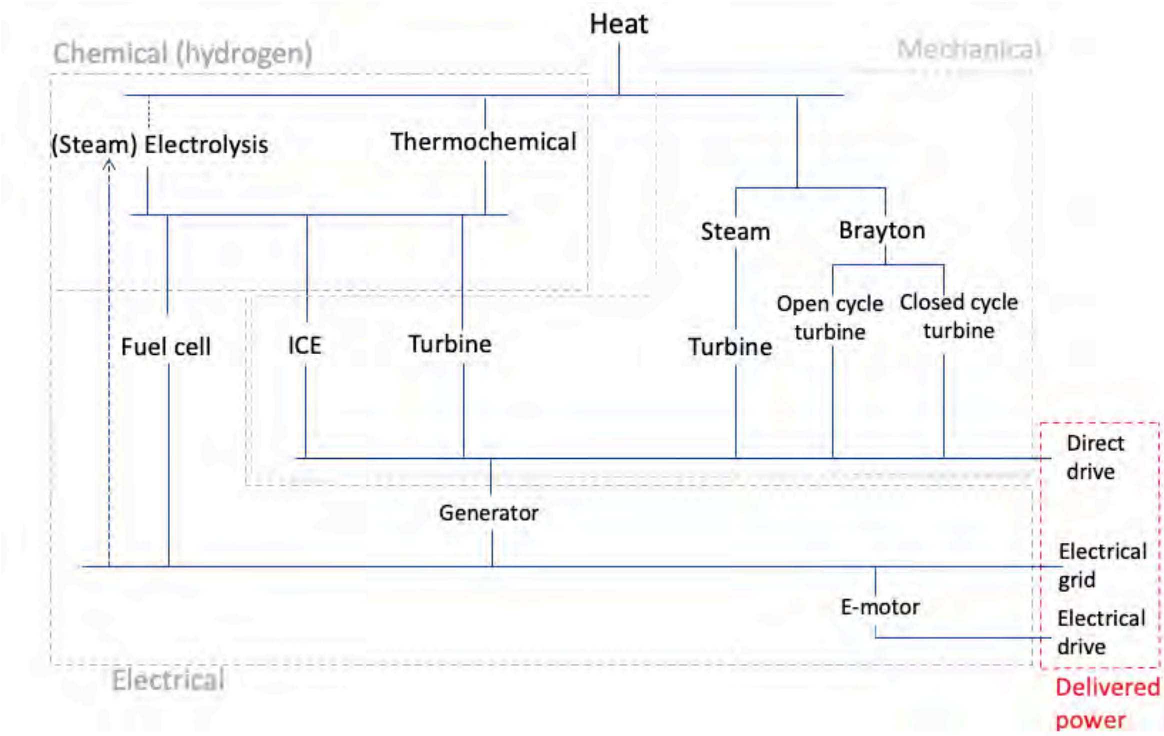


Figure 27 Overview of discussed energy conversion systems based on information from [94], [95], [96], [97] & [98]

5.2 Power conversion by steam turbine (Rankine cycle).

5.2.1 Rankine cycle background

The steam turbine is the most commonly applied power conversion method for power plants around the world [94]. The power generation station makes use of heat, either by burning fossil fuels or from fission, this heat is used to make steam using a steam generator[17]. The high temperature steam enters the steam turbine inlet, where through a series of stationary and rotating blades it converts (part of) its energy to mechanical rotation. To generate electricity this mechanical energy is converted to electrical energy by an attached generator. The steam exits the steam turbine and is condensed back to water in the condenser, before being pumped to the steam generator. This cycle is referred to as the Rankine cycle [99] and shown in Figure 28. This connected loop of steam generator, turbine & generator, condenser, and pump is referred to as the turbine island.

[17] In case of a fossil fuel fired plant called a boiler. Principle of steam generation remains the same.

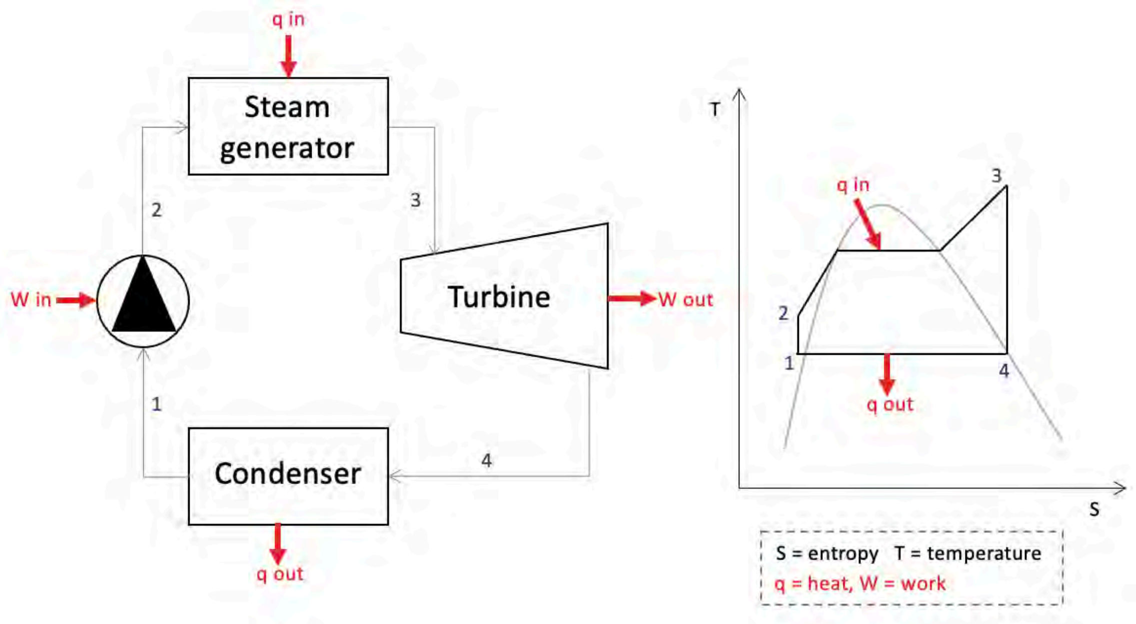


Figure 28 Rankine cycle overview, idealised cycle, based on [99]

The Rankine cycle can be employed at a variety of temperatures and with or without subsequent reheating. The steam used is superheated (indicating that there is no more water vapour in the steam) or supercritical (indicating that the steam is beyond the critical point and thus of even higher temperature and pressure than the superheated steam) [99]. See Figure 29 as clarification for the relation between the states of water and steam.

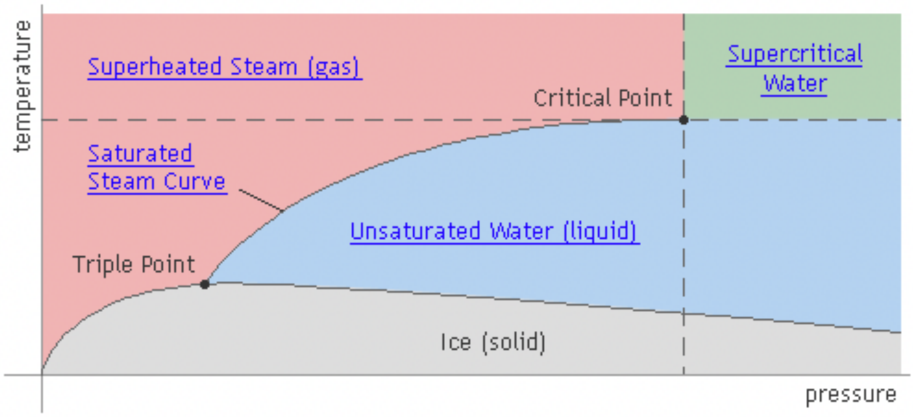


Figure 29 Relation pressure, temperature, and equilibrium phases for water/steam [100]

The inlet pressure of the steam has a large influence on the efficiency of power conversion, steam of higher pressure can ensure an increase in efficiency of a few percent. This higher steam pressure however also requires higher temperatures, as otherwise the steam would not be superheated steam anymore [99].

Current efficiency for nuclear power plants is in the range of 30-33% due to the relatively low temperatures associated with the LWR plants [2]. Coal burning plants have efficiencies in the range of 40% to 42% due to their higher boiler temperatures, which results in higher possible operating pressures and temperatures, increasing the efficiency [99]. These high efficiencies are not always possible using only a single stage/single heating pass. For this multiple stages and multiple reheating passes are used. Reheating means that after the first combination of heater and turbine another section with heater and turbine is added. This gives the benefit of higher efficiency, at the expense of system complexity and capital cost.

5.2.2 Steam turbines for marine propulsion

Historically steam turbines have been employed on ships as direct drive option, although at the present time largely phased out due to the diesel engine. Turbines operate at high rpm, suitable for a generator, but for a variety of reasons not suitable for the propeller of a ship. Reducing the revolution speed requires the use of a reduction gear, which comes associated with transmission losses. Besides the use of a reduction gear an additional downside is that ships with fixed-pitch propellers also require the shaft to be able to turn in the opposite direction, which requires a dedicated section of the turbine to be installed. This dedicated section for astern is detrimental to the overall efficiency of the steam turbine [95]. The historical application of nuclear power on commercial vessels also relied on the use of steam turbines, unfortunately no breakdown is shown for their exact installation size and only the power delivered to the shaft is given:

- Savannah, with 16.2 MW of total power delivered to shaft [29]
- Otto Hahn, with 7.3 MW of total power delivered to shaft [29]
- Mutsu, with 7.3 MW of total power delivered to shaft [29], [101]
- Sevmorput, with 29.8 MW of total power delivered to shaft [28]

Currently steam turbines can still be found on gas tankers [102] which burn their boil-off gas, and therefore have economic incentive to operate with a turbine plant. Steam turbines connected to generators have also seen application onboard of other ships, in the form of waste heat recovery systems. In this case the cycle does not make use a fired boiler but uses a heat exchanger/steam generator to extract heat from the exhaust gasses of an engine [103].

5.2.3 Load response and operational constraints

Steam turbines require some time to start up from cold, this is due to constraints of the materials associated with the operating temperature. In practice this results in steam turbines on ships requiring a gradual start-up and load build-up [95]. A study however shows that the start-up and ramping-up time of a powerplant can be reduced if measures are taken beforehand to reduce the temperature difference in the turbine [104]. A different study identified this so called “ramping rate” (the time required for a power increase) for steam-based powerplant turbines at 7%/min, with a minimum load of 30% of the total installed power [105]. A similar ramping rate of 3-6%/min is mentioned in a publication by Funahashi [106].

How a steam turbine responds to load is both temperature dependent and operating principle dependent, this can be either constant pressure, sliding pressure or a hybrid of the two. Constant pressure (of inlet steam) is used in baseload power plants, and this is very suitable for constant power applications. For load following and other behaviour sliding pressure is an attractive option, in this case the pressure is varied based on the load. In a study on steam turbines, it is mentioned that this only has some minor efficiency benefits but allows for more flexible load following behaviour and less material stress in the turbine [107].

Besides the response of the turbine other factors also influence the behaviour of a turbine plant. The constraints of temperature changes also apply on the steam generator and the condenser, where for both systems the temperatures influences the cycle efficiency and capabilities of the turbine. Lower temperatures for the steam generator, or higher coolant temperatures for the condenser can both affect the capability of the turbine to deliver full power and influence cycle efficiency.

The previous coincides with the behaviour in part load conditions. As in part load conditions turbine efficiency is reduced, this efficiency reduction is both discussed in literature for steam turbines (separate) and for fossil fuel power plants operating with a steam turbine. The efficiency decrease for part loads is mentioned as being approximately 2% (as seen in Figure 30) in the study by Karakurt and Günes [108], and approximately 4% for the more efficient steam turbine in the coal fired plant in the study by Roeder and Kather [109].

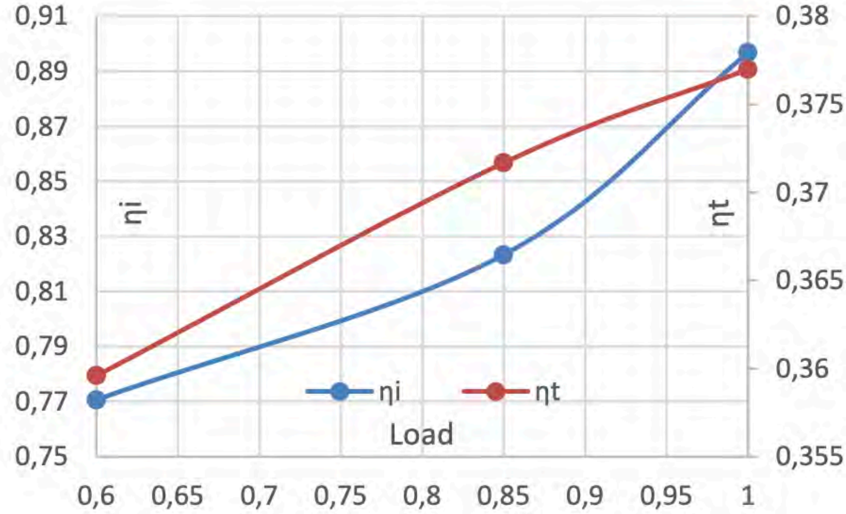


Figure 30 Thermal efficiency reduction for steam turbines on part load [108]

5.2.4 Weight and size of steam turbines and plant
Steam turbines can be estimated at weight and size respective to their power. A study on weight reduction of ships determined an equation that can be used to estimate the weight of a steam turbine plant based on the mass flow of steam [110]. Although due to the degree of experience in steam turbines the values of an equipment manufacturer can also be used for first estimates of weight and size.

5.2.5 Economics of steam turbines
Steam turbines are widely adopted, with moderate capital cost. According to the World Nuclear Association the entire steam turbine island can be estimated at 15% of the total capital cost of a (land based) nuclear power plant [111]. Steam turbines are known to have high reliability as well as long service intervals[18]. These service intervals can vary by manufacturer, but an indication is shown in Table 10, with a minor overhaul being an inspection and calibration indicated to last between 2-4 weeks. The major overhaul is similar to the minor overhaul but includes some additional disassembly tasks, it is indicated to last between 4-8 weeks. The 100000 hours major overhaul is special as at this time a performance assessment is done [112].

Equivalent operating hours	Years after commissioning	Type of overhaul
10000	Maximum of 4 years	Minor
25000	Maximum of 8 years	Minor
50000	Maximum of 15 years	Major
75000	Maximum of 20 years	Minor
100000	Maximum of 25 years	Major

Table 10 Typical multi-year steam turbine maintenance frequencies, reproduced from [112]

[18] Compared to marine diesel engines

5.3 Power conversion by Brayton cycle turbine

Another option for power conversion by turbine is the Brayton cycle. The Brayton cycle commonly applied in its open form (open Brayton cycle) in gas turbines where heat is added using combustion and expelled as exhaust gas, although this could also be done via a heat exchanger. In the nuclear power concepts, most studies focus on the closed cycle Brayton cycle, where the operating medium is cooled, compressed, and reheated instead of rejected as exhaust gas.

5.3.1 Background on the Brayton cycle

The closed Brayton cycle is in its most simple (ideal) form a cycle consisting of four stages. The medium used in the closed Brayton cycle can be varied, although the most prominent choices are either helium or supercritical CO_2 (sCO_2 for short). Both do not change phase during the cycle. The medium is compressed in the compressor as contrary to water the medium does not become steam with the associated expansion when heated. After the compressor the medium is heated in the heat exchanger, before expanding in the turbine. The expansion and subsequent temperature drop in the turbine results in mechanical power on the rotating shaft. Afterwards the medium travels through the heat exchanger where it is cooled before the cycle restarts. This can be seen in Figure 31.

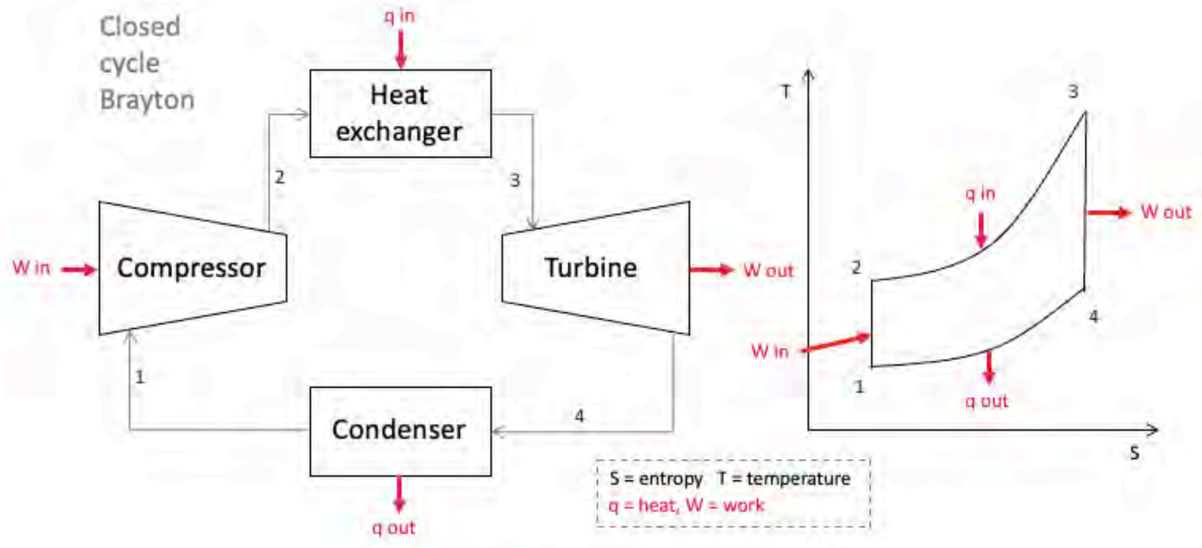


Figure 31 closed cycle Brayton, idealised cycle, based on [113] & [87]

The closed Brayton cycle can either be constructed with the turbines and compressor connected, or with separate shafts [114]. Separate shafts have been used in the open cycle gas turbines operating on combustion, for the benefit of not disturbing the compressor operation upon load change and allowing for a larger load envelope [87]. A split turbine design with a separate "load" turbine design after the compressor and attached turbine is an attractive option for non-constant speed applications for this reason [115]. A study concerning the sCO_2 turbine describes the application of the independent shaft layout, illustrating these benefits that come at the expense of minor added system complexity [116].

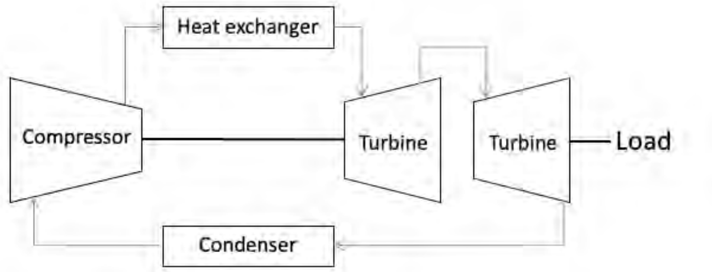


Figure 32 Closed cycle Brayton turbine, with separate load turbine, based on [115]

The Brayton cycle is especially interesting for applications that can provide relatively high output temperatures. In a study it is shown that the efficiency can exceed 45%, which is higher than Rankine/steam cycles currently in operation. The temperatures at which this is possible are 550 and 850 degrees Celsius for sCO_2 and He as coolant respectively. Associated pressures are 20 MPa and 8 MPa respectively for sCO_2 and He [114]. A study into the application for generation IV nuclear power plants already claim efficiencies over 50% for both He and sCO_2 at operating temperatures associated with MSR's and GFR's, with even higher efficiencies projected for the VHTR [113].

5.3.2 Application and development

Developments into the closed cycle Brayton turbine for power generation have been ongoing for an extended period. The idea has been receiving extra attention the past two to three decades due to the developments of the generation IV nuclear reactors and their increased output temperatures compared to older LWR designs [96]. Helium is considered as an option for plants that use it as coolant directly, because it is practically neutron transparent [117] (does not absorb neutrons/very limited) and has high specific heat capacity. Supercritical CO_2 is also a very suitable choice, exhibiting properties that are more favourable than helium (higher density and greater efficiency at lower temperatures) [113]. Both helium and sCO_2 have considerable downsides as well: Helium requiring higher temperatures as well as being more expensive than sCO_2, with sCO_2 being corrosive and less inert than helium [114]. An important additional consideration is the rpm (revolutions per minute) of the machinery, which exceeds the currently used gas turbine and steam turbines with rpm's as high as 75000 rpm reported in a study by the Sandia laboratory [118] and designs as reported in the study by Dostal as going up to 40000 rpm [114]. Both requiring attention regarding operational and construction constraints.

5.3.3 Load response and operational constraints

As closed cycle Brayton turbines are not in commercial power use yet the topic of load following is not covered in literature to a similar extent as with the Rankine cycle. Load-following and part load operation are addressed in a recent study on the load-following of (helium) Brayton turbines [117]. In this study control strategies are discussed, as well as modelled together with the transient response and efficiency. The efficiency reduction is shown in Figure 33.

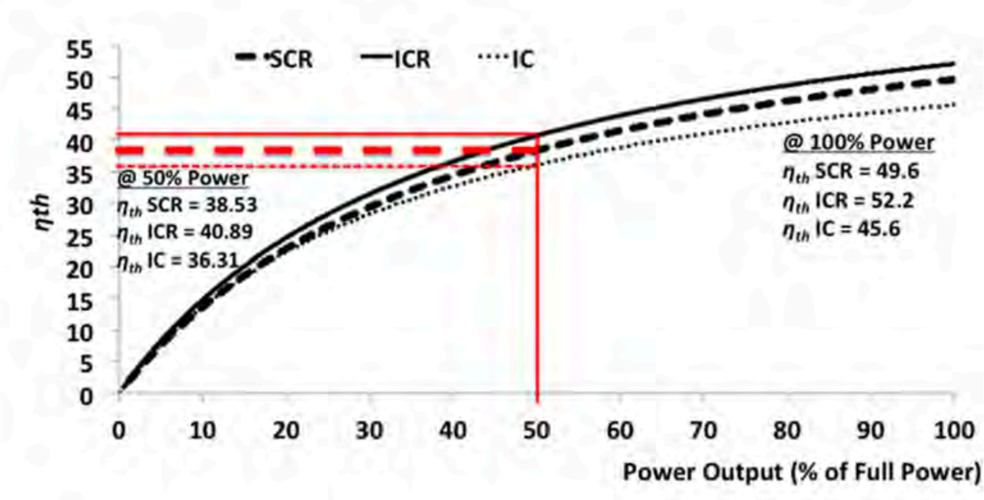


Figure 33 Power output and efficiency of helium Brayton turbines [117]

Response to load change is modelled, and according to the study remains in the range of 2.5% to 5% per minute depending on the exact variation of the cycle[19]. This however appears conservative in comparison to the capabilities of the conventional (combustion based) Brayton turbines, which can achieve significantly better load changes. An additional consideration should be the operating temperature of the turbine along with its very high rpm, which is considered a challenging environment for the materials [118].

5.3.4 Weight and size

The closed cycle Brayton turbine is significantly smaller than steam turbines of comparable power. In the study by Dostal a comparison is shown of steam, helium, and sCO_2, this is shown in Figure 34. It should be noted that the steam turbine is shown with its casing, while the others are shown without. The casing is however a negligible contribution to the overall length of the turbine and adds mostly to the bulk. For both the helium turbine and the sCO_2 turbine only the turbine side is shown, following the remark in the bottom of the image these lengths could be doubled as the compressor is of similar size [114].

[19] The study discusses different configurations in the Brayton cycle, with SCR (Simple Cycle Recuperated), ICR (Intercooled Cycle Recuperated) and IC (Intercooled cycle without recuperation).

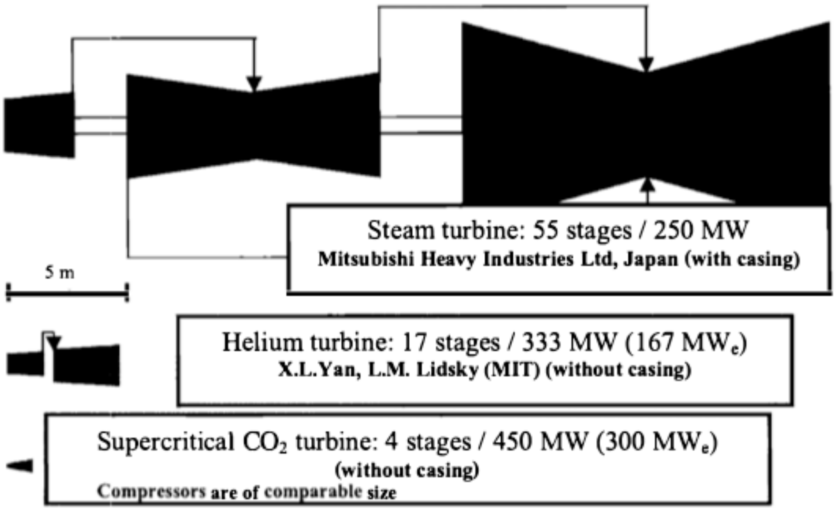


Figure 34 Turbine size comparison [114]

Besides a significant size reduction this subsequently also translates to a weight reduction, as well as a complexity reduction as is shown in Figure 34 where the Brayton turbines have a reduced number of stages.

5.3.5 Economics of Brayton Cycle turbines

The economics of Brayton cycle turbines are very favourable due to the high efficiency the turbines, improving the overall process efficiency. According to Dostal the capital cost of a sCO_2 Brayton cycle turbine island is 8% lower than that of a steam turbine island [114]. A decrease in capital cost is also mentioned in another research by the Sandia laboratory [118]. The reduction of 8% mentioned in the publication by Dostal is quite large and although a possibility in the future, for the first generation of commercial closed-cycle Brayton turbines appears unlikely. However even a price increase within reason can be justified when paired with a size reduction and higher efficiency.

5.3.6 Application of the open cycle Brayton turbine

The application of the open cycle Brayton turbine is also possible. The open cycle closely resembles the conventional gas turbine with the difference being the use a heat exchanger instead of combustion. This system is also referred to as an indirect combustion turbine [119], which allows for plants where the exhaust gas is not in direct contact with the turbine. The medium used in the open Brayton cycle is air, which allows the medium to be exhausted, and does not require the use of a condenser. This is shown in Figure 35.

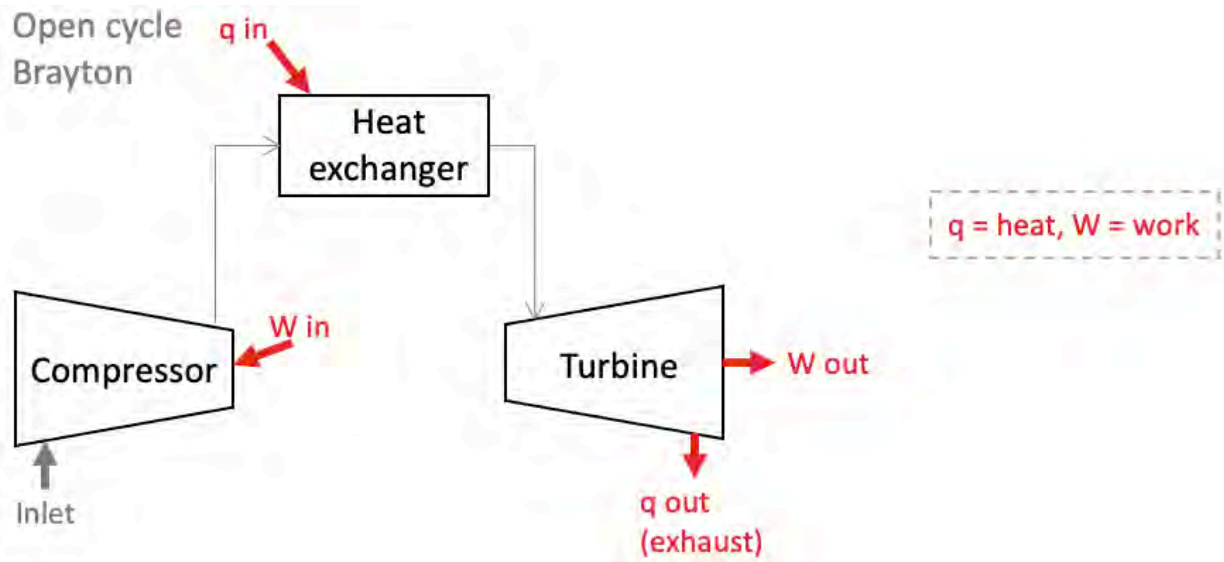


Figure 35 Open cycle Brayton, based on [87], T-S diagram not shown as this is similar to the closed cycle.

Although air is less favourable in properties, it is considerably easier to handle and does not suffer from the earlier mentioned problems as in the helium and sCO_2 based closed cycles. The application also lies much closer to the well-developed gas turbines, which is attractive from a development perspective. A publication shows that the open cycle can approach the efficiency of the closed cycle, when using multiple reheat passes and at higher temperature [97]. From this research it can be concluded that in general, the open cycle will be either more complex to implement or achieve lower efficiency at similar plant layout. The interest for this cycle in the field of nuclear power is in part because it requires less cooling water, as there is no condenser. The option remains attractive for locations where the cooling capacity is restricted, however this is not the case on board of ships. Ships have the added downside of their operating region being at sea, with air containing both moisture and traces of salt. This is unfavourable and therefore a consideration for turbines that are already in use on ships (gas turbines), resulting in installations in the inlet and outlet that decrease efficiency [87].

5.4 Power conversion using hydrogen

The energy transition has sparked significant interest in the generation of hydrogen, due to the high power and often significant process heat requirements nuclear power is very suitable option for hydrogen generation applications. The generation of hydrogen using nuclear power can be done either from thermal or from electrical processes. Different cycles are possible with a variety of different hydrogen sources as base. Water is considered here as the most logical option, options such as LNG, although technically possible [120], would make limited sense in the overall context of this project and are not considered because of this reason.

5.4.1 Thermochemical based hydrogen production

Hydrogen can be extracted from water using a variety of methods, when using thermal power this is done using a thermochemical process. These processes require the addition of significant amounts of heat during some/all steps in the respective process, as well as a constant feed of water (H_2O). The water is converted to hydrogen (H_2) and also the oxygen could be recovered (O_2). The chemicals used remain in the cyclic process. Multiple chemical combinations are proposed, one example is the sulphur-iodine (S-I) based plant, which is seen as a promising option. A schematic representation of the reaction is shown in Figure 36 [98].

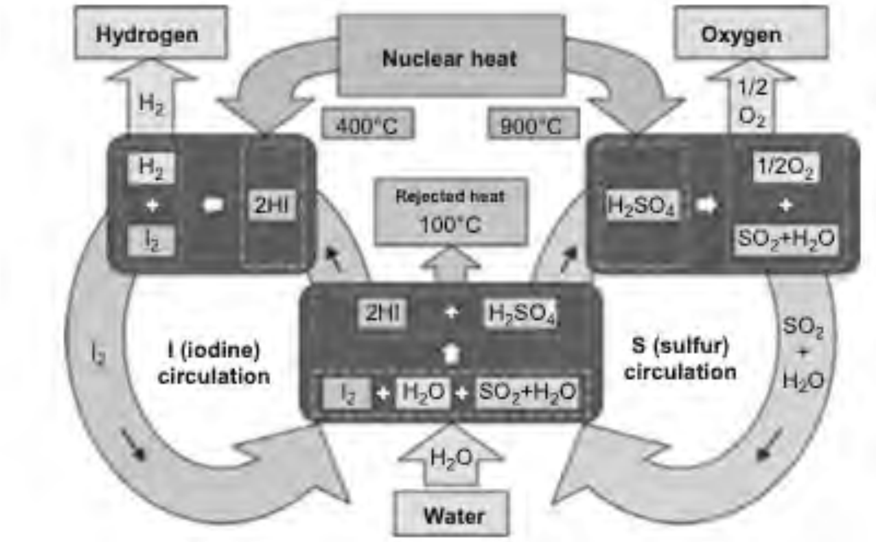


Figure 36 Schematic representation of the sulphur iodine cycle [98]

Besides sulphur-iodine there are also other options that rely on lower temperatures (S-I requires 850-900 ℃ [121]). Options like the copper-chlorine cycle requires the lower temperature of 500 ℃ [98]. According to the publication by Revankar [98] the cycle efficiencies for thermochemical hydrogen production are in the range of 35-45%.

The main downside to these plants is their complexity, using multiple mixing and reaction vessels for the chemical reaction and an additional selection of heat exchangers. Another consideration is that the plants must be used with another power source, as they both require the process heat as well as electricity (for pumps, control etc). Finally, these concepts rely on a significant distance between the hydrogen and nuclear plant (100+ meters), for safety and isolation reasons [98], which for obvious reasons will be more difficult to realize on board of a ship.

5.4.2 Electrical based hydrogen production

Electricity can also be used for the formation of hydrogen; this is done via electrolysis. The process of electrolysis consists of a cathode and an anode that are in contact with the medium (water), the addition of electric energy causes the water molecules to split into their constituents (hydrogen and oxygen) [121]. The basic representation is shown in Figure 37.

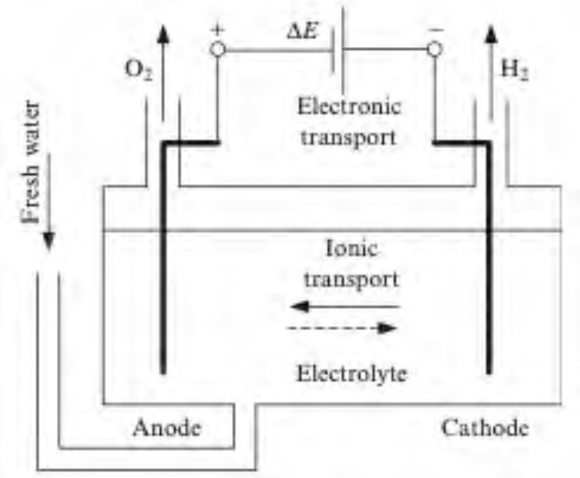


Figure 37 Electrolysis system basic representation [121]

The two common methods that are deployable at a commercial scale are the alkaline electrolyser and the Polymer Electrolyte membrane (PEM) electrolyser. Efficiency (based on hydrogen yield) of the alkaline electrolyser is 59-70%, for the PEM electrolyser 65-82% [122]. The downside to using electricity for hydrogen production is that the conversion losses from the nuclear power plant will be cumulative, as the thermal energy from fission first has to be converted to electricity before being used in the electrolysis process.

It should be noted that storing hydrogen at ambient pressures or temperatures is spatially unfavourable, compression or cooling are required to achieve acceptable energy density. Efficiency will decrease further if the compression/cooling for storage step is considered as well.

5.4.3 Hydrogen production from heat and electricity

Besides heat separate and electricity separate there is also a combined option: steam electrolysis. In steam electrolysis steam is fed into the electrolyser and split (using an amount of electrical power). Hydrogen and oxygen are separated and can be stored. This has efficiency benefits as the increased temperature reduces the amount of electrical power required [123]. According to the publication by Revankar [98] overall efficiency is in the range of 35-45 % for 800 degrees Celsius and can go towards 50% for 900 degrees Celsius.

5.4.4 Hydrogen to electrical/mechanical power

As hydrogen is of no direct use for the propulsion plant it has to be converted back to either mechanical or electrical power, hydrogen can be seen as an interesting intermediate step in the process. The main downside normally with hydrogen is its limited power density for long endurance on ships [86]. This space constraint would however be less of an issue if the hydrogen is produced and consumed on board. The downside is that the compression or cooling of hydrogen to store it requires power as well.

Hydrogen to energy conversion can be done in a variety of ways, including fuel cells, internal combustion engines (ICE) and turbines. The efficiencies of these conversions are shown for reference in Table 11.

System	Hydrogen to mechanical	Hydrogen to electrical
ICE (Otto cycle)	35-38%	34-37%
Turbine	58%	57%
Fuel cells	Not applicable	40-60%

Table 11 Efficiencies of hydrogen conversion, data for ICE: [124], data for Turbine: [125], Data for fuel cells: [126]
Conversion efficiency to electrical (by generator): 98%

What can be seen is that, although the individual efficiencies are quite good, the cumulative effect of the hydrogen production, storage and later conversion will diminish the efficiency significantly.

5.5 Heat exchangers

The heat exchanger is mentioned separately as it is such an integral part of the nuclear power system, as well as the marine propulsion plant. Its modelling is well understood, as well as its application proven. The main purpose is, as the name says, to transfer heat, in this case from one medium to the other. The heat exchanger is used in the steam/Rankine system both as steam generator and condenser. In the closed Brayton cycle for the transfer of heat in, as well as out by cooling via the condenser. Finally, the heat exchanger can also be used in the systems with intermediate coolant loops. The use of intermediate coolant loops can be done as a form of separation (separating the reactor coolant from the turbine medium), such as in the MSR with its irradiated fuel salts [127] or in the SFR with its reactive sodium [75]. Another reason to use an intermediate loop is in co-generation setups where the primary coolant is used for power generation and the heat exchanger is used to "branch" off part of the heat flow coming from the reactor without interfering with the volume and flow of the loop [67].

Common types of heat exchangers are the plate and tubular type, with the plate type being very suitable for lower pressure applications and the tubular "shell and tube" type being the choice for higher pressure applications [128]. Besides these common types also the printed circuit heat exchanger (PCHE) is proposed for nuclear power plants, this very compact block with etched channels is being proposed in a study specifically for the VHTR (and thus gas cooled reactors). In this study however also, the note is made that the tube heat exchanger has increased operational experience which still makes this concept attractive also for new applications [129].

A final consideration on why the heat exchanger is vital in the nuclear propulsion and power plant will be for heat rejection, as in case of an emergency or a severe power reduction the turbine(s) can be bypassed, and full capacity can be rejected directly to the condenser/heat exchanger to ensure the reactor remains within its safe operating temperature range [130].

5.6 Chapter conclusion

When considering the suitable power conversion and balance of plant systems, it can be concluded that hydrogen generation on board is not very suitable primarily from a spatial perspective but also from an efficiency and added complexity perspective. Although the application of hydrogen has merit, for a standard propulsive and power generation system the spatial constraints are challenging, combined with the significantly reduced efficiency and increased complexity making it less favourable than a significantly smaller and more efficient turbine. Both steam (Rankine) and Brayton turbines (closed and open) are a possibility for the application of nuclear power on board of ships. The steam option is considered as the "safe" option from the regard of its development. While the Brayton option despite being less technologically mature is considered as an interesting option as it is considerably smaller while also offering better efficiency. These technologies have had mostly land based research and application, with the only exception the steam turbine which has seen marine application and specific designs adaptation for marine use (astern sections).

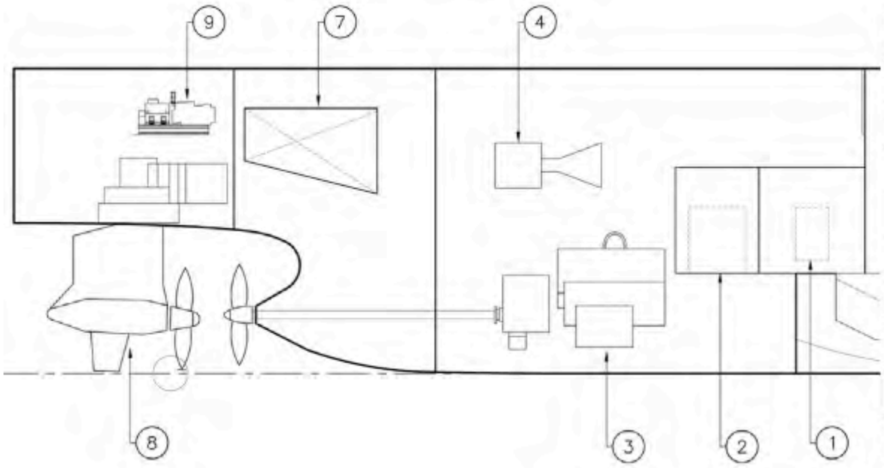
6 SPECIFIC CONSIDERATIONS FOR A NUCLEAR POWERED VESSEL

This chapter covers the sub question: what are the specific additional considerations for the application of the nuclear marine propulsion and power system? As nuclear marine propulsion both has been applied and researched in the past these issues and concerns are mentioned. First previous applicable concepts will be discussed, followed by technical issues and concerns that are specific design considerations for the marine application.

6.1 Nuclear powered concept vessels in other research

In section 2.1.4 some historical ships were discussed as well as more recent studies into conceptual nuclear powered ship designs. Now that the relevant aspects of nuclear power and its marine application are covered it is possible to consider these in greater detail.

The publication by Hirdaris et al. [34] ,which was mentioned earlier because of its relevance for the regulation, risk, and safety aspect in the development of marine nuclear power, considers a small modular reactor-based propulsion plant in a Suezmax tanker. In this paper a single manufacturers SMR type (from the now defunct gen4 energy) is considered. The type of reactor is a lead-cooled fast reactor with a multi-year fuel cycle, accompanied by steam generators and turbines. A downside of this study is the limit of only considering the reactor a single manufacturer, decreasing applicability to other concepts. The eventual application on the tanker appears functional, although suboptimal. The application of the reactor based marine propulsion system and its comparison to conventional is bulky, and the comparison is skewed by the employment of a contrarotating propeller and rotating thruster combination (placed for redundancy reasons) in the propulsion system. This choice alters the ship size (11% length increase) and weight, which again further decreases the applicability of a like-for-like comparison. Important to note is that this application focusses on the full power condition and offers no specific insights in load following and transient loading.



ITEM	DESCRIPTION
1	SMALL MODULAR RECTOR (ENCLOSED IN SHIELDED VAULT)
2	PB-BI TO STEAM HEAT EXCHANGERS
3	MARINE REDUCTION GEAR AND STEAM TURBINE
4	STEAM TURBO GENERATOR
5	EMERGENCY COOLING WATER
6	PUMP ROOM
7	RESERVE FUEL TANK
8	AZIPOD + CONTROL SYSTEMS
9	EMERGENCY HIGH SPEED GENSET

Figure 38 Cross section of SMR based Suezmax tanker machinery room [34]

When looking at still relatively recent marine reactor concepts, but preceding the definition of SMR's more research is available:

The publication by Jacobs [35], is a master thesis on the application of a (small) nuclear reactor for short sea shipping. This study was published in 2007, which shows as this is before generation IV and SMR's received the coverage in literature they have now. The paper discusses application on a short-sea container feeder vessel, which is a challenging application, as it concluded that the reactor conflicts significantly on the useful space of the ship. Although the viability of the concept is questionable for capital cost and size reasons this report details interesting considerations for both the CAPEX and OPEX of nuclear-powered ships as well as discussing infrastructure and requirements necessary around such a ship/fleet.

The final direct application paper with significant development is the study on the nuclear fast ship [36], which employs the largest power of all mentioned applications. The original "fast ship" is a container vessel concept of 1400 TEU capacity at a cruise speed of 37.5 knots. Which is then altered to become a nuclear concept (instead of gas turbines). This application was published in 2002, which can be seen from the application that by today's standards is an outlier with its low cargo capacity and high speed. This paper predates most of the SMR and generation IV developments, and due to its specific and very high-power application it is limited in broader applicability. It is however interesting in its detailed considerations of the capital cost of the application, which follows the recurring theme of nuclear power, significant in capital (CAPEX) and moderate in operational (OPEX).

The conference proceedings of Hill, Hodge & Gibbs [131] have to be mentioned, although focused on the naval application, it is relatively recent (2012) and considers the use of a thorium based molten salt reactor of reduced size in a naval surface ship. This publication is not as comprehensive as other literature and remains more of an initial concept/idea, it however shows that the idea of using what would now be considered an SMR and novel reactor technology does not have to be a strictly commercial marine or naval specific endeavour.

The research by Freire and de Andrade [132] focusses on a larger scale conceptual idea of nuclear power in a rapidly detachable modular section that can provide power to the ship, focusing on a PWR based designs. The rapidly detachable modular section is a novel concept, but the technical and especially safety related considerations of detaching and leaving the reactor are a considerable additional challenge. Both topics would require significantly more research than is done before an idea like this can be considered. The idea in this research of setting up separate companies/entities for the ship and the marine propulsion plant (which would then sell its power to the shipowner) are however interesting concepts, especially considering the high capital cost of nuclear power.

One additional topic that has been receiving significant interest recently, and therefore should be mentioned, is the application of nuclear power for green fuels and energy production in the marine environment. Although these concepts reside mostly on platforms [133], FPSO's [134], and barges [80] instead of ships. These concepts share a portion of their technology, legislation and application with the direct marine propulsion application and could be considered parallel tracks in development.

6.2 Nuclear marine implementation specific technical points

6.2.1 Shielding

Irrespective of which reactor concept is chosen, shielding will always be a requirement. The shielding enables the reactor to be operated without the risk of excessive radiation reaching locations and persons. In the case of the marine propulsion plant this means that the crew, passengers, ship, and cargo should be adequately shielded for sustained operations without immediate or latent negative effects. Shielding generally concerns only shielding for gamma rays and neutrons, as the alpha particles and beta rays both have very low penetration [4]. The penetration of different forms of radiation and their respective shielding is shown in Figure 39.

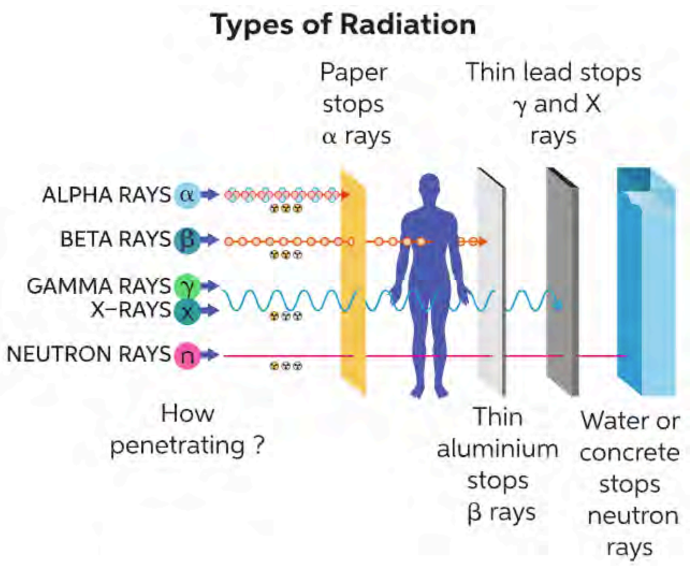


Figure 39 Penetrating power of radiation [135]

Shielding is calculated based on the source of the radiation and the allowable dose outside of the shield, which in practice is done using simulation. Applicable analytical methods are only usable as initial estimate for highly simplified reactors [4].

Common materials for shielding are concrete, water, lead, steel, and polyethylene. Historically these materials have also been applied on the earlier commercial nuclear ships such as the NS Savannah. The Savannah had a shield weighing 2053 tons (combination of concrete, lead, polyethylene, and steel) around the 74 MWth PWR [136]. A study on the NS Mutsu's shielding initial shielding calculations put the total shielding weight at 2260 tons [101]. A subsequent more recent journal article describes shielding that offers a weight reduction of 50% and volume by 70% compared to Mutsu for a reactor of greater power [137]. Combining this information with the previously known weight results in approximately 1130 tons for a PWR reactor of 100 MWth. This weight is similar to what is found in the study by Jacobs, wherein an initial simplified shielding assessment is done for a smaller high temperature gas-cooled reactor for shipboard application [35].

This shielding is structured completely around the reactor and encloses it from access, as can be seen in Figure 40.

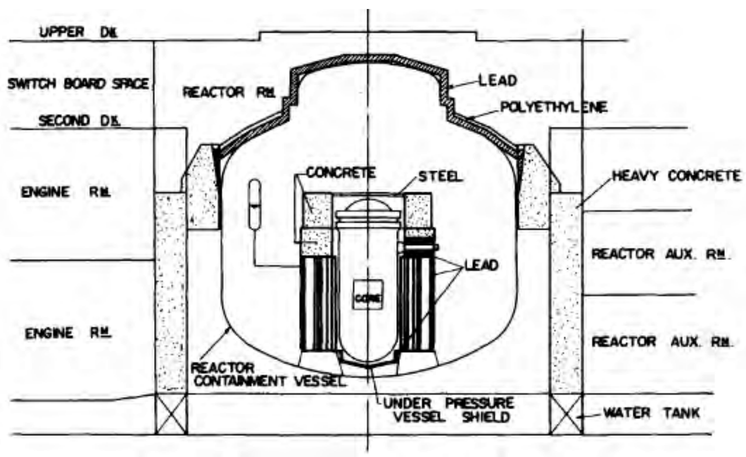


Figure 40 Reactor shielding of the concept Japanese ship [138], reactor compartment is approximately 15 metres in length

As the shielding encloses the reactor on all sides it is important to realize that the structure is quite large compared to the reactor itself and will comprise the bulk of the reactor plants size and weight. Openings in the shielding are possible as doors/plugs. These are required for any maintenance or entry into the reactor. These openings are however closed during normal operation.

Due to the almost probabilistic nature of reactor shielding it is difficult to make an exact estimate that would work for all reactor concepts discussed. Historic ship-based studies and applications give the best baseline for new applications, when the design of the ship and the reactor is more defined simulation must be used to confirm the assumptions.

6.2.2 Location

The conventional marine propulsion system as discussed earlier is in general placed close to the shaft and propeller. With the use of a fuel-electric propulsion system however the machinery space that houses the propulsion plant can be split. The nuclear marine propulsion system is constrained similarly to the fuel-electric system, as technically it could operate with only a power conversion step such as a turbine or electromotor at the shaft-line and the reactor on another location in the vessel. For practical reasons it however makes sense to put the reactor close to the propulsion plant, as this is both favourable from an energy conversion perspective (less losses over distance). As well as from the survivability and stability perspective. The survivability of the nuclear reactor in case of an accident is covered in studies on marine nuclear power as well as in the historical application. Historically the reactor was placed close to the accommodation in the centreline of the ship and as low as possible, his can also be seen as in for instance in the Savannah the reactor was also placed slightly in front of the accommodation based on collision data assessment [139]. Similarly for the Mutsu, although this ship was constructed with an accommodation at the forward the location remained similar close to the centre of the ship [27] (see Figure 41).

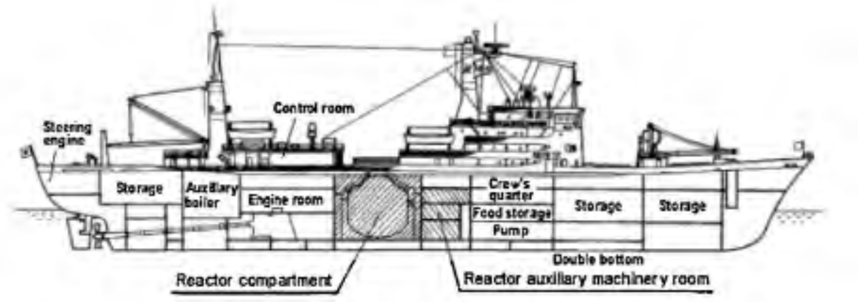


Figure 41 Nuclear powered ship Mutsu, reactor location. [27]

Placing the reactor close to the accommodation relatively centred in the ship is seen as the most suitable choice, in the study by Hirdaris et al. [34] The placement choice is confirmed by risk assessment as being not only the least likely for collision damage but also being acceptable with regards to influence from incidents from the cargo area (such as fires) and from a motions and vibrations standpoint. From a stability perspective this placement is logical as the reactor and its associated shielding are of a significant weight. From these application it can also be seen that the reactor should be placed in such a way that the top end is accessible for maintenance/refuelling.

6.2.3 Survivability

As mentioned earlier in section 2.3.1, the safe operation of the nuclear reactor is a key factor in its design. The concern for the release of radioactive material into the environment has only been increased after the Fukushima Daiichi accident, where radioactive material entered the environment and specifically the sea [2]. These concerns should be mitigated by adequate measures on the technical as well as operational side of the vessel, with these measures extending beyond accident conditions and including conditions where ill intent is in play (such as terrorism).

Mitigating measures to ensure that no material is released into the environment were already seen in the IMO regulations mentioned in this chapter [45]. The application of a “safety enclosure” inside of the ship (in the form of another barrier), is seen as one of these measures. This solution was applied in the earlier nuclear-powered ships as well, as these all have their reactors compartmentalized in the ship structure [27]. The increase in compartmentalization also is a good option from the perspective of fire safety and collision damage resistance, which are mentioned in the same rules [45]. Further implementation of collision damage resistance, for example those applied in the Savannah in the form of so called “collision mats” remains possible [139]. The final consideration is the sinking of the vessel: the worst-case scenario where the ship and reactor are lost. Again, the rules mention two valid points: Safety should be guaranteed in the condition of flooding and partial flooding (to prevent the release of radioactive material even when submerged, sinking, or completely lost). In this worst-case scenario where the ship and reactor have been lost it should be possible to salvage the reactor to prevent the radioactive material from contaminating the sea. This requires at least a possibility of removing the entire reactor and its safety enclosure from the ship without contaminating the environment [45]. The topic of salvage is also covered in the report by Jacobs, where the most promising solution appears to be the compartmentalization of the reactor and ensuring it can be cut free without issues in case of a salvage operation [35].

Although the rules on this topic are outdated and formally not applicable if a reactor other than PWR is applied, they offer a valuable base for the topic of safety and environmental contamination protection for all reactors applied in the marine environment.

6.2.4 Additional reactor cooling (emergency cooling)

The heat generated by a nuclear reactor is constantly transferred to the coolant and used to generate power, the secondary purpose of coolant is to ensure that the reactor is not damaged by this same heat in accident and off-design conditions. To ensure that the reactor remains cooled sufficient redundancy is required in the cooling system. For a reactor to be an approved type these concerns have to be addressed, fitting with the concept of defence in depth as mentioned in section 2.3.1. Depending on the reactor concept this is addressed either with external equipment such as an ECCS (Emergency Core Cooling System) for water cooled reactors [2], [61]. Or with passive designs such as a freeze plug for MSR’s or passive cooling for HTGR’s [5], [62]. When the reactor is placed in the marine engineering system this level of redundancy has to be maintained in the vessels entire arrangement, as a single point failure should not be able to cripple the entire cooling system. The concept by Hirdaris et al. [34] considers the use of additional coolant tanks as a precautionary measure for this reason.

6.2.5 Fuel handling and processing

Spent reactor fuel handling is not a trivial task, as the fuel is both radioactive as well as emitting a small percentage of its heat (decay heat). Besides these two concerns the fuel is also a proliferation risk, and thus requires adequate logistics for the storage and processing. Because of this the refuelling is something that has to be done in a controlled way. In land-based power plants this is done during downtime, with specialized equipment installed in the reactor building. This downtime is in the order of weeks, as mentioned earlier in chapter 2.1.1. The marine based reactor requires both equipment and time for this procedure as well (resulting in downtime of the vessel), although the equipment could be shore based as also mentioned in the study by Jacobs [35]. Similarly, equipment and supply lines have to be established for the introduction of fresh fuel into the reactor, following similar procedures. Reactors capable of online refuelling face the same issues, although these issues only happen when the new fuel and spent fuel is introduced to the installation (and not during the actual loading and unloading process, as this is then continuous). Some reactors are capable of on-site fuel reprocessing, this indicates that the reactor fuel can be directly processed without being shipped to a processing plant. Currently this concept is discussed for variations on the molten salt reactor, as the MSR is capable of diverting part of its coolant/fuel mixture for reprocessing as it is in a continuous loop [5]. In all cases this requires logistical support and adequate supply lines to be established for fuel related operations. These issues can be mitigated if a reactor is selected with a very long fuel cycle (beyond the lifecycle of the entire ship), or if the reactor refuelling is scheduled in predefined downtime of the vessel (drydocking periods) such as also identified as a possibility in the study by Carlton, Smart & Jenkins [33].

6.2.6 Vibration and movement (dampening)

A reactor that is integrated in the marine engineering system is subject to the vibrations and motions of the ship. These vibrations and motions are an important consideration for the design of the reactor and its viability to operate on board of the ship. The location on board of the ship is one of the variables that can be adjusted in this context, movement, acceleration, and vibration can change depending on the location of the ship. This was covered in the study by Hirdaris et al. [34] and was one of the earlier mentioned reasons to put the reactor near the accommodation and as low as possible in the vessel. If these vibrations and movements are considered significant it might be necessary to place vibration reduction measures, which would allow the reactor to operate under motions. The expected motion severity depends on the ship and its operations. Ship motions and vibrations are already part of the ship design process and covered by the classification societies, as they also influence the operations of conventional vessels [140], [141].

6.2.7 Noise caused by the reactor based marine propulsion and power generation plant

Underwater noise caused by ships has long been a concern for warships and has become more of a concern for commercial shipping as well, since it is detrimental for the sea fauna [142]. Nuclear reactors do not have fast moving parts compared to the commonly used combustion engines, with the most prominent movement being the coolant and the pumps required to deliver this coolant flow. While the nuclear reactor itself will have very little noise contribution (due to the reduced movement and vibration) it is integrated in the overall marine propulsion and power generation plant, where components such as: Turbines, generators, gearboxes, and the propeller do contribute to noise. With the propeller being the main contributor to underwater noise, while the machinery components such as the turbine, generator and gearboxes contributing to the internal ships noise and transmission through the structure of the ship [143]. This is especially important considering that open-cycle Brayton turbines operating on the combustion principle produce significant airborne noise [87], with the turbines proposed for the nuclear power plant being closely related in development.

From this it can be concluded that a nuclear reactor could theoretically be used for the beneficial reduction of noise. However, the other machinery and balance of plant have to be considered as well, which would require more detailed research into both underwater, internal noise, and relevant sound spectra. Currently there is no applicable research available for noise production by nuclear power for marine applications, with only the naval submarine application being close by association and even this having sparse available information [144].

6.2.8 Emergency propulsive measures

As the implementation of nuclear technology will be a departure of the conventional it is likely that some form of redundancy and emergency measures are required. This was already seen in the IMO rules on the PWR where it is stated that a system with unproven reliability onboard should be supplemented with a backup system [45]. Even if these rules are not applicable on the selected reactor this is not an unlikely/unreasonable request from an administration. Besides this it is also fitting with the entire concept of defence in depth (as discussed in section 2.3.1) to ensure sufficient redundancy in accident and off-design conditions. A scram of the reactor should not cripple the ship in its operation, and a way of maintaining manoeuvrability is seen as a logical implementation. A backup propulsion system was already seen in Savannah in the form of an electromotor coupled to the shaft that could be driven by a diesel generator [139]. In the more recent concepts, such as the one discussed in the report by Hirdaris et al. [34] a similar but more elaborate implementation is seen with diesel generators as backup power, powering a rotating thruster.

6.3 Chapter conclusion

Specific additional considerations to the use of nuclear power for the commercial application have both been determined from what is known for historic vessels, as well as from more recent conceptual designs and general research. Overall experience in the commercial maritime field is limited, with most of the conceptual design done still considering the older (mostly PWR) reactor concepts. With only a few studies of relevance when considering new developments in the field of nuclear power, indicating room for significantly more research.

A few recurring themes are seen in the conceptual designs and previous research, with the most important being the consideration of shielding, the location of the reactor and the implementation of an emergency propulsion and emergency cooling system. Other considerations are less severe, such as the fuel handling that needs to be addressed, and the possible use of vibration dampening. The difference in noise of a nuclear reactor even being a positive attribute.

These topics are however all considered significant departures of the current conventional fossil-fuelled ships and require considerations in the ship design.

7 PERFORMANCE CHARACTERISTICS FOR THE REACTOR BASED MARINE PROPULSION AND POWER GENERATION SYSTEM

This chapter covers the sub question: what are the most significant performance parameters for marine nuclear propulsion and power generation system components? Subsequently going in detail on the selection of the components that comprise the complete nuclear based propulsion and power generation system. The performance characteristics are stated, before the individual components are discussed: The reactor (discussed earlier in chapter 3), the shielding (chapter 6), the heat exchangers (chapter 5), the turbines(chapter 5), the marine propulsion and power generation plant (chapter 4), and finally the additional systems required for the balance of plant (not discussed in earlier chapters).

7.1 Performance characteristics

In the previous chapters different properties of nuclear power and its components have been discussed, as well as properties that define conventional marine propulsion and power generation systems. For a successful implementation the recurring important component characteristics are defined:

- weight
- volume
- reliability
- efficiency
- load response and part load capabilities
- complexity
- safety
- waste production and emissions
- cost

Of these the first six are discussed on the component scale, with the safety, waste production and cost returning in greater detail in the next chapter when considering the overall implementation. These characteristics are discussed for each of the components when relevant, considering that each of these components has to be used together in a coherent marine propulsion and power generation system. The building blocks of the nuclear marine propulsion and power generation system are shown in Figure 42. Each item is named and will be discussed in greater detail in the following sections (according to the given section numbers).

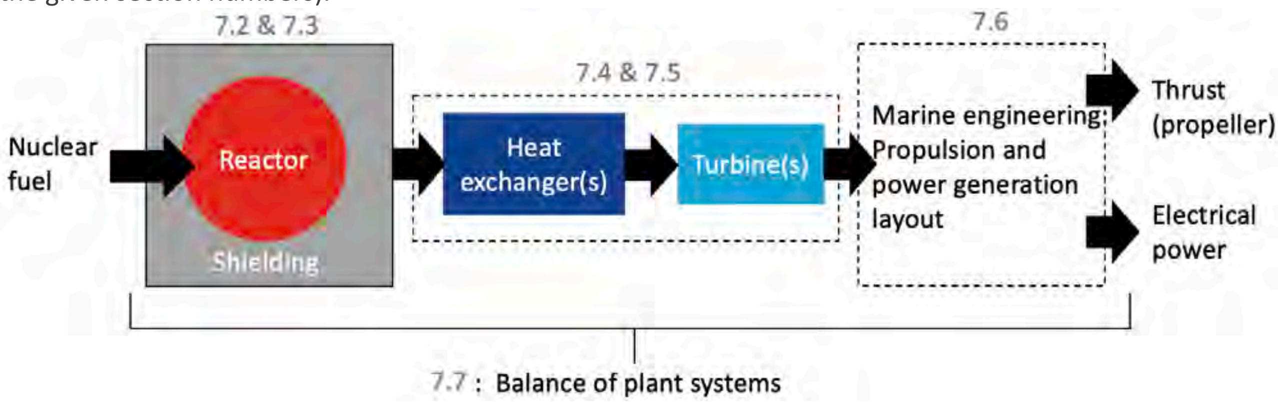


Figure 42 Components of the nuclear-powered marine propulsion and power generation system

A table is added to indicate which properties are considered relevant for which of the components, this is shown in Table 12.

Parameter/ component	Reactor	Shielding	Heat exchangers	Turbines	Layout	Balance of plant systems	
Weight	X	X	X	X			
Volume		X	X	X			
Reliability					X	X	
Efficiency	X		X	X	X	X	
Load response	X			X			
Complexity			X	X	X	X	
Safety	X						Further addressed in chapter 8
Waste & emissions	X						
Cost							

Table 12 Relevant characteristics per component

7.2 Reactor

The two reactor types that are evaluated are the (V)HTR and the MSR, as established in chapter 3. These two generation IV reactors were selected as the most promising options for marine application due to their high burnup (Indicating a high fuel efficiency) and their built-in safety measures and proliferation resistance (safety related). The (V)HTR is considered as the near-term (estimated 10-20 years) solution due to its higher TRL, while the MSR is the long-term (estimate 20+ years) solution that offers greater capabilities in terms of burnup and the possibility of operating on the thorium cycle (reducing waste longevity).

The reactor types are different in aspects such as temperature and coolant, which is important to consider for the implementation. Peak temperature output of both types is expected at 750 degrees Celsius, which could become higher for the VHTR but is kept as a singular value for the following analysis. The reactors are fundamentally different in their coolant and inlet temperatures despite being capable of delivering similar outlet temperatures. The (V)HTR has a significantly higher temperature difference of 500 degrees currently, while the MSR operates in a smaller temperature difference window of 100 degrees Celsius. This is reflected by the mass flows of coolant in the reactors and the properties of their respective primary coolant. These are shown in Table 13 for the helium of the (V)HTR as well as a fuel salt of the MSR. The coolant mass flow is shown per MW of thermal power and calculated based on the other values.

Coolant	Specific heat (kJ/kg*K)	Temperature difference reactor (degrees Celsius)	Coolant mass flow per MW thermal (kg/s)
Helium	5.19 [145]	500 [55]	0.43
Fuel salt (FlIBe*)	2.35 [146]	100 [55]	4.25

*Table 13 Coolant properties of the (V)HTR and MSR, * different fuel salt compositions are possible with FLiBe shown as indication*

The considered reactors as they are developed now are assumed to operate in their operating window of 50% to 100% rated power at constant temperature with variable coolant flow rate to regulate power. This method of operation is not unusual and seen in a variety of the SMR designs that are in development [55]. This method of operation also allows for all subsequent systems to operate on constant temperature and variable flow, which allows for scalable calculations. As mentioned earlier in section 3.7 this operating range could be theoretically improved in the future, especially for MSR's. For now, however, the 50% lower limit is kept as a conservative assumption with all developments towards greater operating ranges seen as favourable. Similarly, the discussed 5%/minute load change is considered as a reasonable estimate for the reactors currently in development, which is why it is used for in the ongoing assessment.

In chapter 3 it was determined that reactor weights can vary between the types and sizes of reactor, with weights as low 75 tons and as high as 300 tons for the chosen power output range. The estimate of 250 tons is used for further calculations for both types of reactors, as an estimate that is on the heavier side. The volume of the reactor is not discussed, this firstly depends strongly on the type and its manufacturer. Secondly the reactor will be fully enclosed in the shielding on all sides, indicating that its volume contribution is of no influence on the implementation.

7.3 Shielding

Shielding is not a trivial matter and the major contributor to the weight and volume of the total reactor based marine propulsion and power generation system. With historic applications quickly ranging in the 2000+ tons of shielding (see section 6.2.1).

Shielding is in all cases a reduction of the exposure for both the personnel as well as the equipment. These limits are shown in Table 14, for both the radiation worker and the "general public". This limit is shown for the full year, although it can be converted to an hour value if divided by the hours in a full year.

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

Table 14 Radiation exposure values [147]

Additional factors and assumptions can be added such as distance from the reactor in normal operation and the number of hours a person is actually on board as part of the full year. These are not considered in this initial assessment. For the initial assessment the general public value is considered, instead of the radiation worker as this would allow for a baseline that is also suitable for passengers and external personnel.

The amount of exposure is a combination of the four different types of radiation: alpha, beta, gamma, and neutron rays. In the earlier Figure 39 it was shown that alpha and beta radiation have very limited penetration, which is why shielding is generally only calculated for the gamma and neutron radiation [4]. The actual solution for a shield relies on quite complex simulations, however for ship design a size and weight estimate is valuable. For this estimate an analytical approach is considered: the analytical "removal-attenuation" calculation for neutrons is considered alongside the analytical simplified method to determine exposure to gamma rays based on the so called "point kernel method" and the halving distance of a shielding material. The analytical method considers a simplified reactor, operating on uranium as fuel. The different types of reactors and fuel compositions will have influence on the shielding although this is expected to be relatively minimal, as the materials and reactors have relatively limited differences.

7.3.1 Neutron shielding

Starting with the reactor thermal power and the recoverable energy of $3.2*10^{-11}$ per fission event of U235, the established power density of the reactor core (2.5 kW/litre from literature [148]), and the reactor power, a core volume is established. The model is simplified to resemble a spherical core, to allow for the analytical approach to be used. Based on the assumption of the spherical core and its volume it is possible to determine the radius *R* of the reactor. Following this it is possible to determine fission density, which is the amount of energy (thermal power) divided by the energy per fission event ($3.2*10^{11}$ as shown earlier) divided by the volume of the core.

For neutron shielding the amount of neutrons “leaking” out of the shield are of interest, as reducing this is the reason for shielding.

For the neutron shielding calculation macroscopic cross section of the materials used in the reactor and the desired shielding are determined from lookup tables (values shown in Table 15). The neutron shielding will be either water or concrete, as these materials have historically been used in both land based as well as marine applications. The uranium is mentioned as it is part of the core and contributes to the removal of neutrons.

Material	Macroscopic cross section (cm^{-1})
Water	0.103
Concrete	0.089
Uranium	0.174

Table 15 Macroscopic cross section of materials, [4]

Value α (which represents the total paths the neutrons can travel) is determined using the equation shown below, where f is the fraction of metal in the reactor core, which is estimated at 50%. R_w represents the other part of the reactor core, which for many older reactors was water (hence the subscript *w*) however in this case this is considered as air or empty[20]. R_m represents the metal in the reactor (which the metal being the fuel of the reactor, and parts of the fuel rods if these are used).

$$\alpha = (1 - \mathrm{f}) \sum R_w + f \sum R_m$$

The amount of neutrons leaking out of the core is defined as θ and determined using the equation below, with *A* being a lookup value of value 0.12 [4]. R_s is the removal cross section of the shield, which is the macroscopic cross section times the shield thickness (shield thickness *a*). S is the amount of neutrons per fission, which can be determined from the earlier fission density multiplied by the neutron yield for U235 (which is given as 2.42 [4]).

$$\theta = \frac{S\,A}{4\alpha}\left(\frac{R}{R+a}\right)^2 e^{-\sum R_s a}\left(1 - e^{-2\alpha \mathrm{R}}\right)$$

The result is in neutrons/cm^2-sec, although this can be converted from to dosage by a dose equivalent of 6.8 fast neutrons per mrem/hr [4] (1 mrem/hr = 0.01 mSv/hr). This is used to determine (using a programmed solution) how thick the shielding has to be to only deliver half the allowed radiation dose at the edge of the shield. The thickness of the shield (shield thickness *a*) is varied until this is achieved. This was done for both water and for concrete as shielding material separately. The reasoning behind the half dosage is that the other half is then reserved for the gamma rays, which are not sufficiently reduced in a shield that is designed for only neutron shielding.

7.3.2 Gamma ray shielding

The gamma ray shielding is an additional consideration on top of the already determined neutron attenuation shield. The gamma ray shielding is built-up from a lead outer layer around the neutron

[20] As neither helium nor fuel salts are provided in the lookup tables

attenuation shield of either water or concrete.

First the gamma ray build-up at the edge of the previously determined neutron attenuation shield is determined as either the water or the concrete offers some degree of gamma ray shielding. The amount of fissions is determined similarly to how this was done earlier for neutron attenuation (using the recoverable energy from a fission and the delivered thermal power of the reactor).

The gamma ray calculation is done for each of the "energy interval" groups that comprise the prompt gamma ray emissions. The groups and their values are shown in table Table 16.

Group number	Energy interval (MeV)	Prompt decay
1	0-1	5.2
2	1-3	1.8
3	3-5	0.22
4	5-7	0.025

Table 16 Energy interval groups and prompt decay, [4]

The number of gamma rays per second defined as *S* is determined by multiplication of the amount of fissions per second and the prompt decay for each group. This is then used in the equation as shown below:

$$\Phi_b = \frac{S}{4\pi R^2} B_p(\mu R) e^{-\mu R}$$

With μ being values in a lookup table for the attenuation coefficient, different for each material and each energy interval (the values used are added in Appendix B: Calculation shielding). *R* is the radius from the core as established earlier. B_p is a value for the buildup factor that is also from a lookup table, however this changes for each of the configurations which is why a Taylor expanded form is used, as discussed in the publication by Lamarsh and Baratta [4]. With the coefficients of this Taylor expansion form from a lookup table, this is necessary for a programmed solution to be possible. The Taylor expansion form for each of the energy intervals is added in Appendix B: Calculation shielding.

After determining the amount of gamma rays at the edge of the shield this can be converted to exposure again, this is done using the equation below.

$$\dot{X} = 0.0659\, I\, E\, (\mu_a/\rho)^{air}$$

With $(\mu_a/\rho)^{air}$ being the mass absorption coefficient for air, which is different for each of the groups (values used are added in Appendix B: Calculation shielding). *I* is the gamma ray intensity and *E* is the energy. The dosage is then calculated and evaluated for the total of the groups.

Lead shielding is added, with an average halving-distance of 1 cm [149] being used to reduce the amount of gamma rays until an acceptable radiation level. This is done using a programmed solution that gradually increases the amount of lead with each step until the acceptable level is reached. This "acceptable level" is when the level of exposure goes below the half the allowed dose. This way the total dose at the edge of the shield is below the acceptable level, when considering that both the neutrons and the gamma rays are shielded.

7.3.3 Combined shield

The total shielding size and weight is then determined, as the weight is simply the volume of the spheres inner shell (either water or concrete) and the outer (lead) shell, volume times respective density then gives the weight.

The analytical simplification is shown visualized in Figure 43.

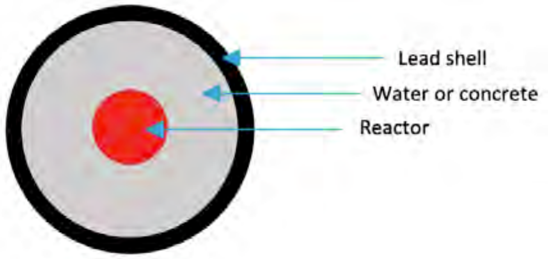


Figure 43 Visualization of reactor shield

The weight is plotted, together with the available information on previous marine reactors and significantly developed concepts. As these are only 6 datapoints, establishing a reliable curve fit from the historic data alone is not possible. The historic data is however used to check if the analytical estimate is sensible. the available data shows that the upper bound given by the concrete shield is more applicable for the shielding. With two outliers lying above it (Mutsu [101] and the application from the study by Hirdaris et al. [34], plotted for both a single as well as double reactor fitted as this has allowance in the shield). Both being on the bulky side for the application, with the novel PRX [137] design with integrated shielding below the lower estimate for water.

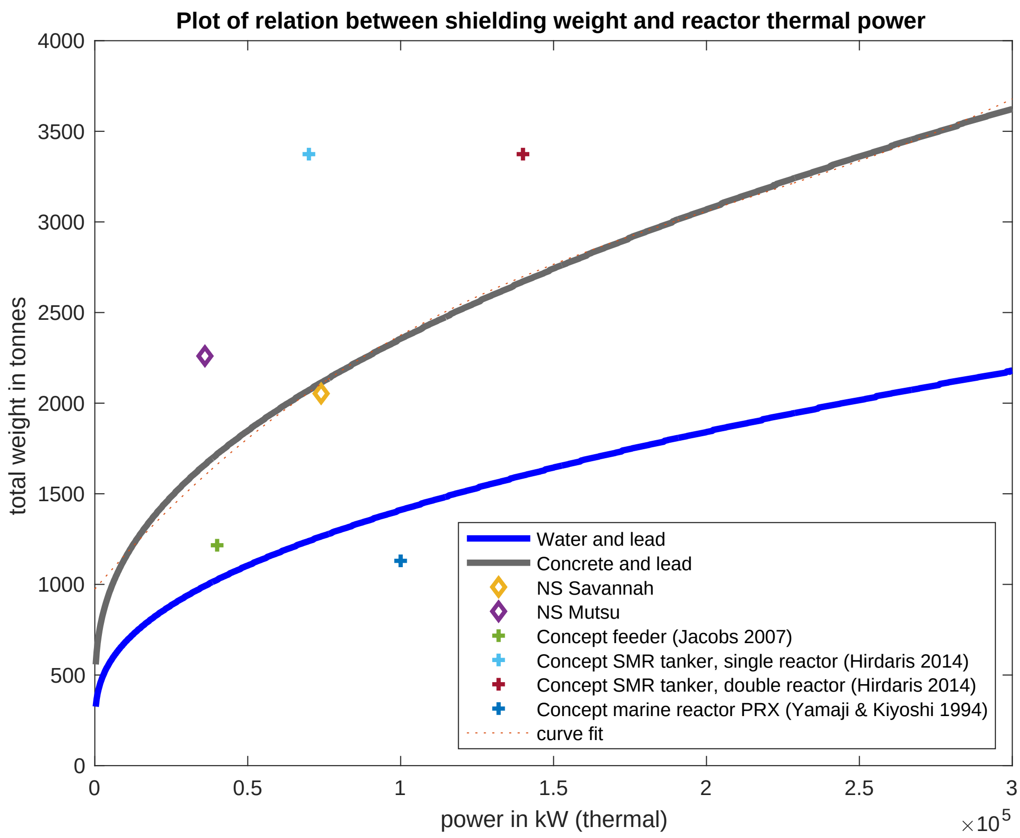


Figure 44 Plot of shielding weight, with shielding weights from available historic and conceptual vessels plotted, data from [136], [101], [35], [34] , [137]

A weight upper and lower bound is established to form an expected range for the shielding weight. The concrete bound is used as the centreline, with a 50% allowance both down and up. This estimate is shown in Figure 45. A curve fit is established for easier plotting and following calculations, information on this curve fit is included in Appendix C: Shield curve fit.

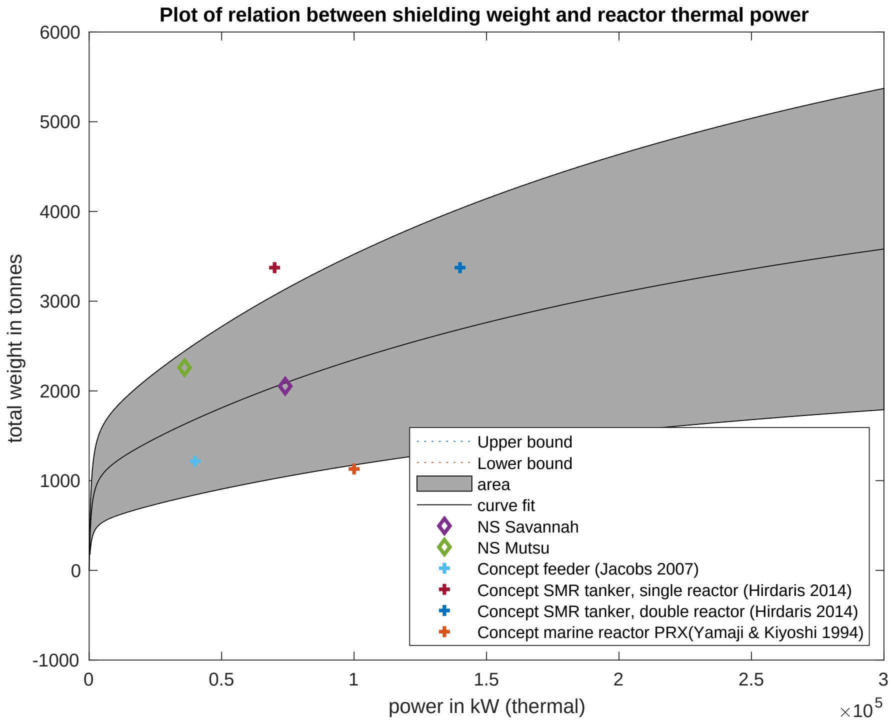


Figure 45 Plot of curve fit with 50% upper and lower bounds. Shown in relation to the shielding weights of the conceptual and historic vessels

The oversimplification of the spherical core reactor ignores the space around the core where the RPV is and some of the additional components that are within the shield of the reactor. For reference, see Figure 46 with the layout of the NS Savannah. There is however a significant volumetric margin (50% higher due to the estimated margin) which would allow for additional items in the shield and shape variations in the RPV.

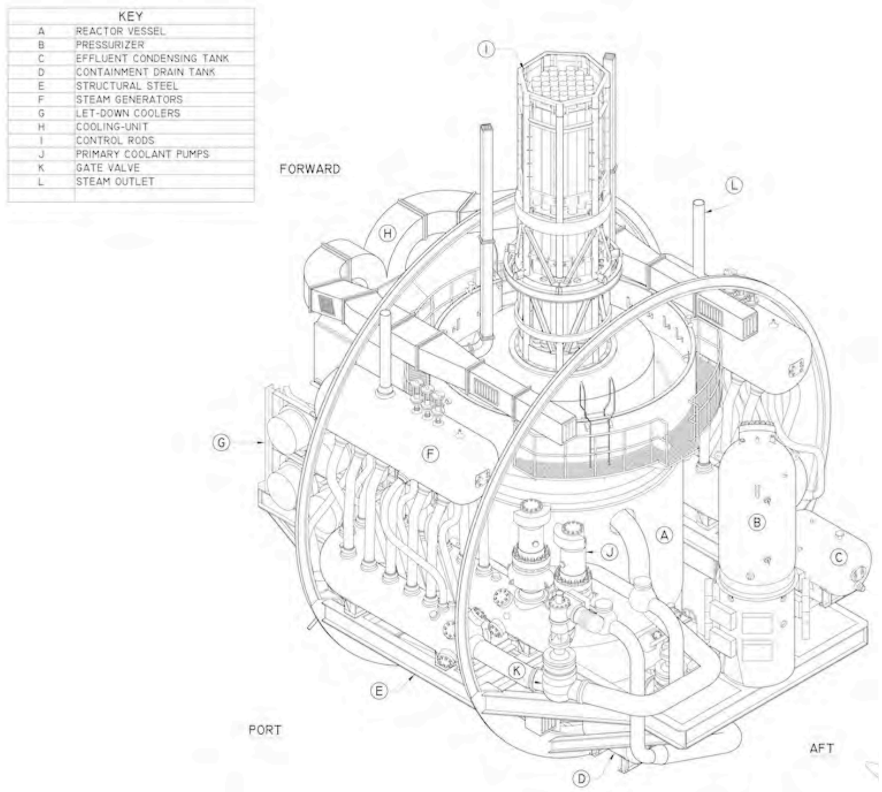


Figure 46 layout NS Savannah [150]

A similar implementation as shown in Figure 46 would seem logical for future applications as well. For a simplified arrangement the radius of the entire setup is determined and represented as a boxed layout, the radius is shown in Figure 47 and the graphical representation in Figure 48. Considering here the margin to be held for the other equipment within the shield, which was also considered earlier as the 50% upper bound. Due to the cubic nature of the box volume this results in a maximum radius increase of 14.5% (cube root of 50% increase) over the value shown in Figure 47, with this value used for the further implementation.

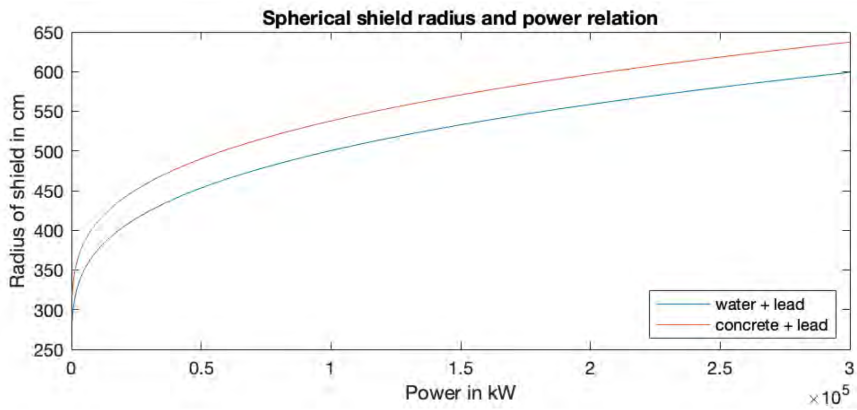


Figure 47 Radius of spherical shaped shield, shown for both water and concrete

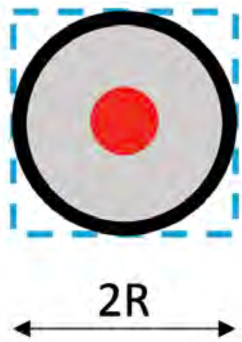


Figure 48 Shield in box shaped arrangement

7.4 Turbines

As mentioned in chapter 5 there are three “families” of turbines that can be considered for the power conversion: Rankine, closed cycle Brayton and open cycle Brayton. These three turbine types are discussed after each other, evaluating which option would be best suited for the application.

Considering the performance characteristics that are determined to be relevant: Weight, volume, efficiency, system complexity, and load response.

7.4.1 Rankine cycle (Steam)

The steam cycle is employed in a variety of different applications, but when implemented for the ships application there is a consideration in system complexity and installation efficiency. This immediately becomes important when considering the high temperatures that the proposed reactors can deliver. These higher temperatures are linked to the use of higher pressures, which is due to the nature of steam. The conventional steam turbine as used in the now common LWR reactor plants [2] are possible but not recommended due to their lower operating temperature and efficiency. When operating at these temperatures the plant must either employ superheating, or even reheating. This requires consideration as this is CAPEX, installation complexity, and installation size intensive [151].

To determine the efficiencies and sizes of the plant it is important to discuss the cycles and efficiencies. Cycles used in calculation are generally idealized, indicating that there are no losses. However, in the real situation losses will occur. These losses are indicated by the isentropic efficiency, which for the Rankine turbine is estimated at 85%, as an estimate that is also seen in literature [152]. Similarly, the limit of 12% maximum moisture content and the end of the turbine is used, this is a practical limit as water droplets can damage the turbine blades [153]. Maximum moisture content is also referred to as steam quality, where steam quality is the percentage of steam in the mix (88% steam quality = 12% moisture content). Each of the calculations is based on a thermodynamic assessment with the properties at each point such as temperature, entropy, enthalpy determined from the Pyromat water database [154]. Further explanation is added in Appendix D: Calculation Rankine (steam) turbine.

Cycle with superheat

Considering the cycle with superheat as shown in Figure 49, the peak temperatures of the reactor remain unattainable for a steam plant. Operating at 4 MPa and 480 degrees Celsius superheat temperature would give an efficiency (including losses) of 29% while maintaining steam quality of 88%. Each kg of steam/water in the system results in 1035kW of power delivered by the turbine (determined from the ideal value of enthalpy drop on the turbine).

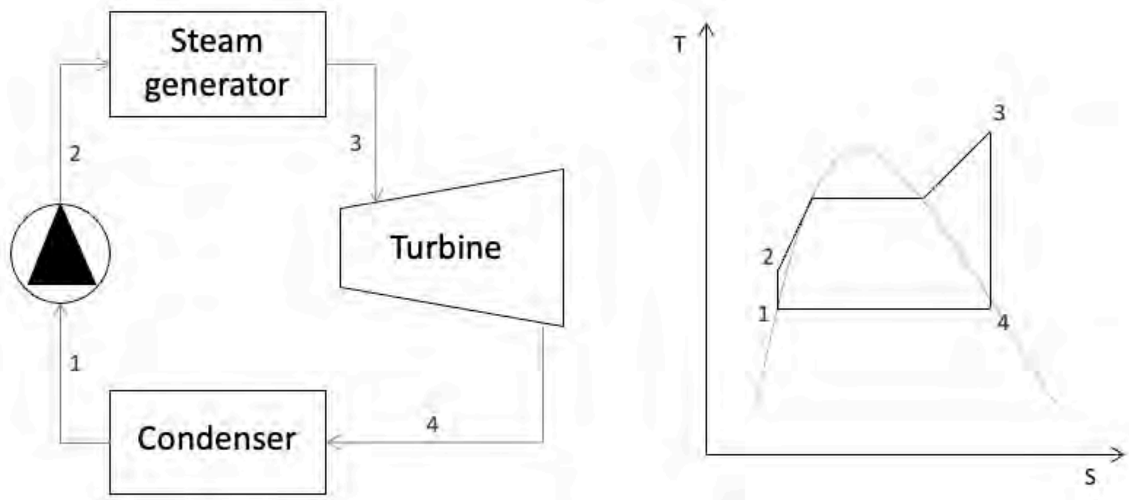


Figure 49 Rankine cycle with superheated steam, with ideal T-S diagram shown

Cycle with superheat and reheat

Considering the cycle with not only superheat but also reheat improves the efficiency further, theoretically this can be done multiple times although this requires serious consideration on the topic of capital cost and if the losses do not become too severe. Operating at 9.5 MPa and 525 Celsius, with the reheating occurring at the lower pressure of 4 MPa would give an efficiency of 38% while maintaining a steam quality of 90%. Each kg of steam/water in the system results in 1736kW of power delivered by the turbines (determined from the ideal value of enthalpy drop on the turbines).

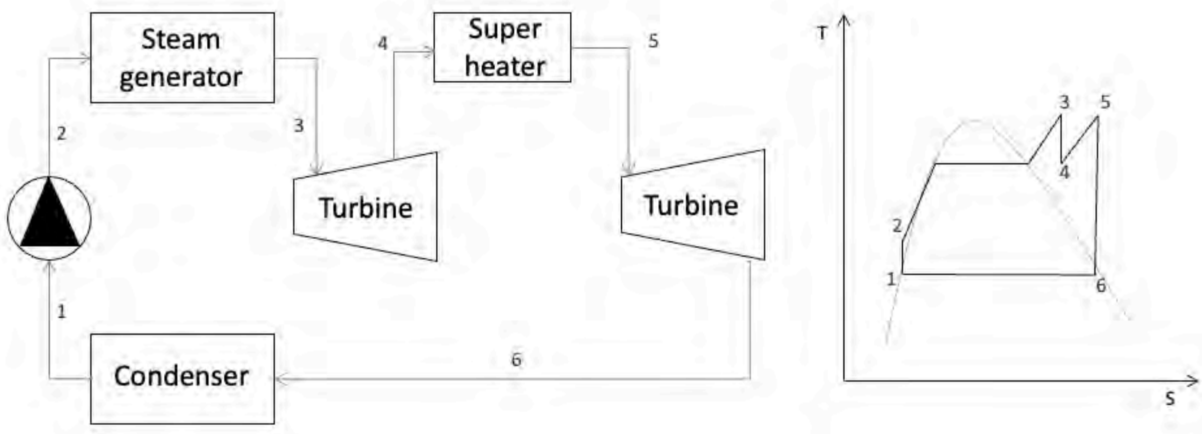


Figure 50 Rankine cycle with superheating, with ideal T-S diagram shown

Cycle with superheat and feedwater heating

Heating the feedwater can further improve cycle efficiency slightly by diverging a small amount of steam from the turbine for the heating of the feedwater. This is however a significant complexity increase, requiring 4-6 stages of heating (based on the plant size) [99].

Turbine size

The turbine size can be estimated based on manufacturer data [155], with a weight of 1.5 ton/MW and a volume of 3.5 m^3/MW. Ratio of dimensions can be approximated as 2:1:1 (length:width:height), making the turbine relatively compact. While the turbine is relatively compact, steam is associated with large other components. The steam generator and condenser are components of significant size which should be considered for the overall implementation. A more detailed assessment is added in Appendix E: Sizing Rankine cycle additional components, where it is noted that these components are significantly bigger than the turbine itself and bigger than the components of their Brayton counterparts.

Load response

The load response of the steam turbine was discussed earlier in section 5.2, where it was seen that this is limited between 3-7%/min change. This is relatively similar to what is expected/assumed from the reactor, however not sufficient for rapid load changes in all circumstances. Systems that bypass steam directly to the condenser are in use, with the use mostly for sudden heat rejection and start-up [156]. The use of systems like this can help broaden the operating range although it increases the complexity.

7.4.2 Closed cycle Brayton

The closed Brayton cycle is still in ongoing development, with the success of the application of the Brayton cycle highly dependent on the developments. Specifically concerning applicability, complexity, and efficiency. The Brayton cycle does not rely on a phase change in its medium, making it require the use of both a compressor and a turbine. The use of both a turbine and compressor makes it more sensitive to isentropic losses, as these are cumulative.

For closed cycle Brayton the two main options of media, He and sCO_2, are evaluated, this is done for a simple cycle application as well as an application with a recuperator (shown in Figure 51 & Figure 52 respectively). A recuperator is one of the least complex ways of increasing efficiency, as it is only a single heat exchanger that recovers otherwise wasted heat.

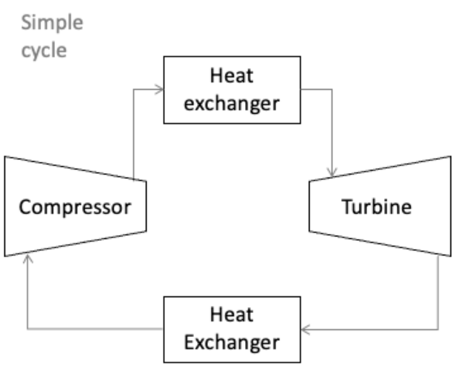


Figure 51 Closed simple cycle

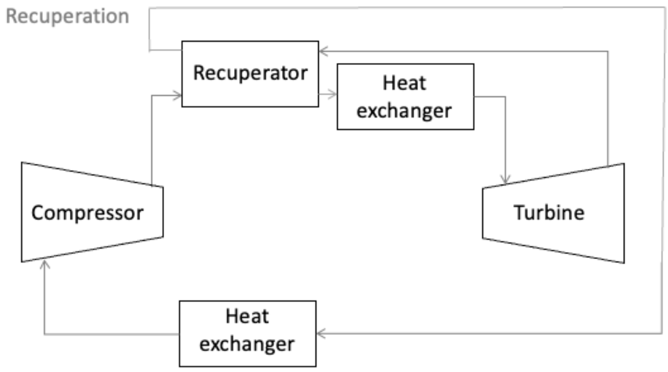


Figure 52 Closed cycle with recuperation, based on [97]

Efficiency

In the closed cycle the consideration has be made for temperature, peak temperature will be close to the reactor outlet temperature (with a small reduction due to the effectivity of the heat exchanger). The lowest temperature (outlet of the cooler/inlet of the compressor) depends on the capabilities of the heat exchanger used for cooling but also of the coolant. For sCO_2 this temperature is 31 degrees Celsius, as the lowest critical temperature [157]. For helium there is no such limitation. Both are however limited by the effectivity achievable by the cooler, as they are cooled by seawater. Seawater temperature can vary on different locations and in different seasons, it is best practice to at least consider a worst-case scenario. In heat exchangers effectivity is defined as a ratio of the actual temperature difference between the fluid and their maximum temperature difference. The temperature difference over counterflow cooler is shown in Figure 53, with the effectivity of a cooler defined as: $\varepsilon = \frac{\Delta T_{hot}}{\Delta T_{max}}$, where the hot liquid is the liquid to be cooled.

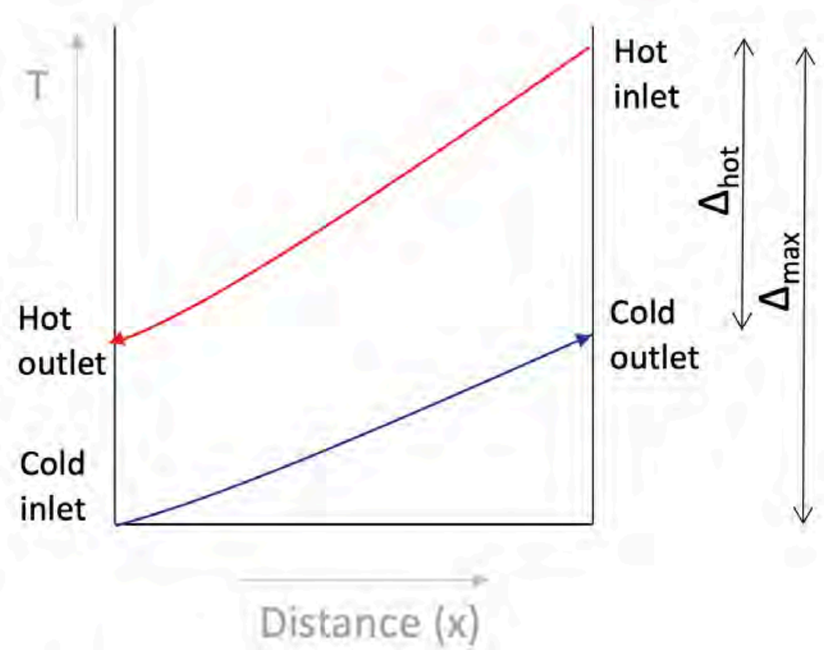


Figure 53 Counterflow heat exchanger, based on [128]

Assuming seawater temperatures above 0 °C up to a maximum of 32 °C (worst-case scenario [158]), together with a maximum outlet temperature of 50 °C for the seawater. The cooler efficiency is estimated at 95% effectivity, allowing for the outlet temperature to be determined (with the results shown in Table 17).

Seawater inlet (°C)	Seawater outlet (°C)	Cooler effectivity (%)	Cooler inlet (°C)	Cooler outlet (°C)	Possible operating media
0	50	95	284	14.2	He
10				23.7	He
20				33.2	He & sCO_2
30				42.7	He & sCO_2
32				44.6	He & sCO_2

Table 17 Closed Brayton cycle cooler, influence of seawater temperature

Besides the temperature of the coolant the other important factor is the isentropic losses. Isentropic losses are a significant penalty to the efficiency as is shown visually in Figure 54 & Figure 55. Efficiencies are estimated at 90% which is fitting with what is found in multiple studies as well (where efficiencies are either 89% or 90% [159] , [97], [160]).

The Brayton cycle efficiency is calculated (and plotted) based on the ideal cycle, both losses for the compressor and turbine can then be implemented in this calculation. The properties of both helium and CO_2 are taken from the Pyromat database in a programmed solution. The programmed solution is further explained in Appendix F: Calculation Brayton turbines.

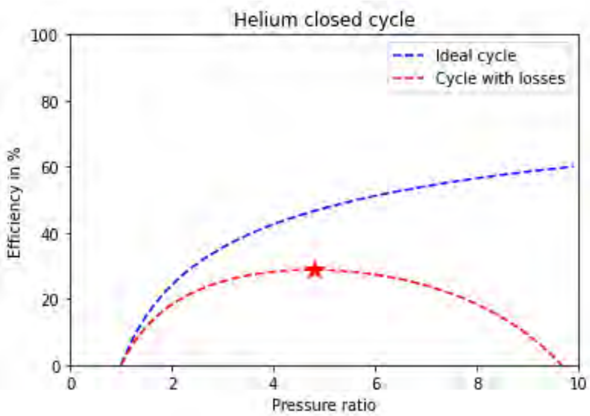


Figure 54 Helium closed cycle Brayton efficiencies

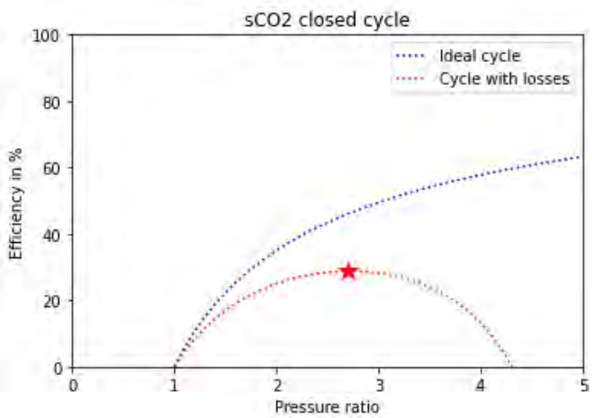


Figure 55 sCO2 closed cycle Brayton efficiencies

Efficiency for the turbines as shown in Figure 54 and Figure 55 is 29%, when the temperature of the cooler outlet is considered at 45 degrees Celsius. The earlier mentioned influence of warmer seawater temperature can be shown as an efficiency decrease, as is shown in Table 18.

Seawater inlet (°C)	0	10	20	30	32
Efficiency (%)	32%	31%	30%	29%	29%

Table 18 Efficiencies of closed cycle Brayton turbines at different seawater temperatures

These "simple cycle" turbines (Figure 51) can be supplemented with a variety of systems, most importantly the recuperator (Figure 52) that returns some of the lost heat before the main heat exchanger. Installing a recuperator (of estimated 80% effectiveness, as is available for open cycle turbines [161]) in these systems yields approximately 4-5 % thermal efficiency increase, which is substantial. This can be supplemented by an intercooler (layout shown in Figure 56) as well, but this would be a complexity jump, as this both requires an additional heat exchanger and a cooling system for a significantly smaller efficiency gain.

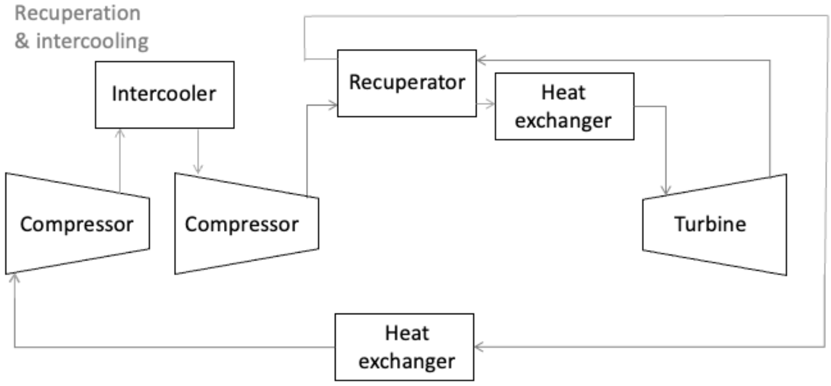


Figure 56 Closed cycle Brayton with intercooling and recuperation, based on [97]

Turbine size

As mentioned earlier the closed cycle Brayton turbines and compressors are significantly smaller than the steam turbine. This is mentioned in the publication by Dostal [114], there are however no commercially available units as of this moment, resulting in no values for the weight of the installation. Weight can be estimated to be rather limited, considering the significantly reduced size. The size can be estimated at 30% of the steam turbine. This estimate is based on the figure from the publication by the earlier mentioned Dostal. The volume would decrease to 0.1m3/MW, with the weight shrinking (proportionally scaled) to 0.05 ton/MW. Besides the turbine there would be the heat exchangers for heating and cooling. These heat exchangers however do not rely on a phase change (such as with steam) and are expected to be reasonably compact due to the favourable properties of the operating media.

Load response

For load response purposes the closed cycle Brayton turbine is limited by the capabilities of the heat exchanger. The overall load response will be limited similar to the reactor’s capabilities. Sudden heat rejection and load following capabilities can be supplemented using systems that are researched which alter the amount of media going through the turbine. These systems are proposed for enhanced load following capabilities but come at the price of increased system complexity, which is seen when considering the diagram as proposed for inventory control in a recent study [117]. In this system a part of the working media is diverted to a storage tank when the power is reduced, in case of a power increase the media is returned to the circuit.

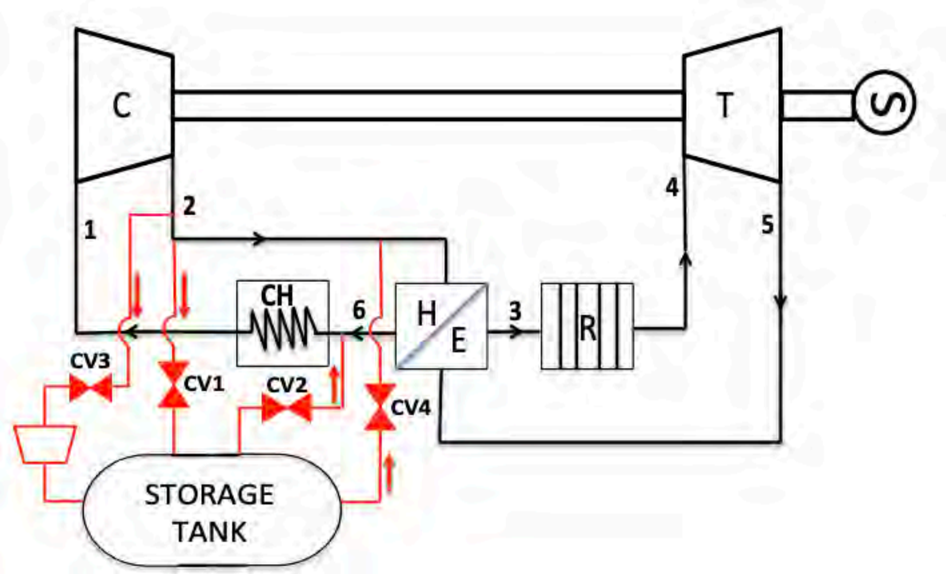


Figure 57 diagram for Pressure regulation for closed recuperated Brayton cycle, implementation for load response improvement [117]

Systems as proposed in Figure 57 are possible, but not commercially proven or available for marine application.

7.4.3 Open cycle Brayton

The open cycle Brayton turbine is in its development closer to the current marine gas turbine, operating with air as the medium. The main difference with the conventional marine gas turbine being the use of a heat exchanger to supply heat instead of using a combustion process. One of the benefits of open cycle is that it does not require a condenser or heat exchanger for cooling, as the used air is simply rejected. This however comes at the expensive of having inlet and outlet ducting that are associated with performance and pressure losses and a space requirement [87]. In Figure 58 & Figure 59 the simple cycle and the recuperated cycle are shown. In these images the similarities with the earlier closed Brayton cycle can be seen.

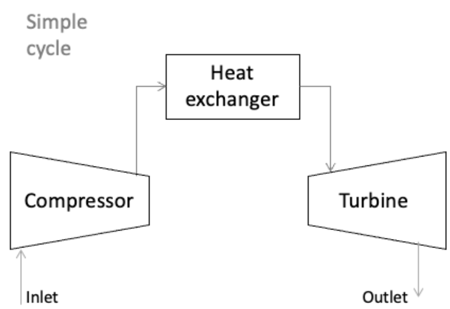


Figure 58 Open cycle Brayton, simple cycle

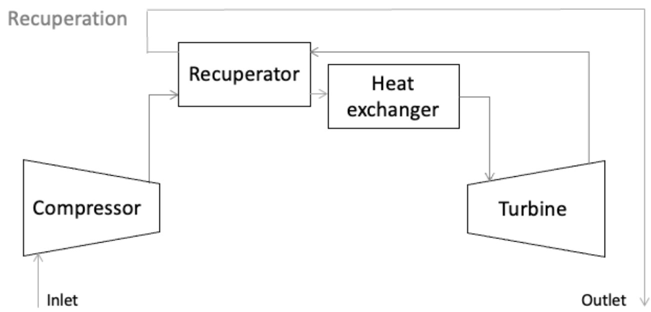


Figure 59 Open cycle Brayton, with recuperation

The high temperatures of a nuclear reactor can easily be handled by an open cycle Brayton turbine, compared to the current combustion variety which operates with higher peak temperatures [128]. Indicating that this application falls within the developed properties of the turbine. The downside of the lower temperature being that it reduces the efficiency of the turbine.

Efficiency

For the open cycle isentropic efficiency is estimated at 90%, which is identical to the estimate for the closed cycle as given earlier. This gives an overall peak efficiency of 28% (for the simple cycle) as can be seen in Figure 60, using a calculation similar to that of the closed cycle Brayton turbine, which was discussed in the previous section. The downside of the open-Brayton turbine (being its inlet and exhaust ducting and the associated losses of 2% and 1% respectively [87]) are already considered here, with these temperatures and considerations still making it a comparable choice compared to closed cycle Brayton. This is in part because it does not have a cooler, which makes it easier to achieve suitably low temperatures for the intake, and thus increase the temperature difference (favourable for efficiency).

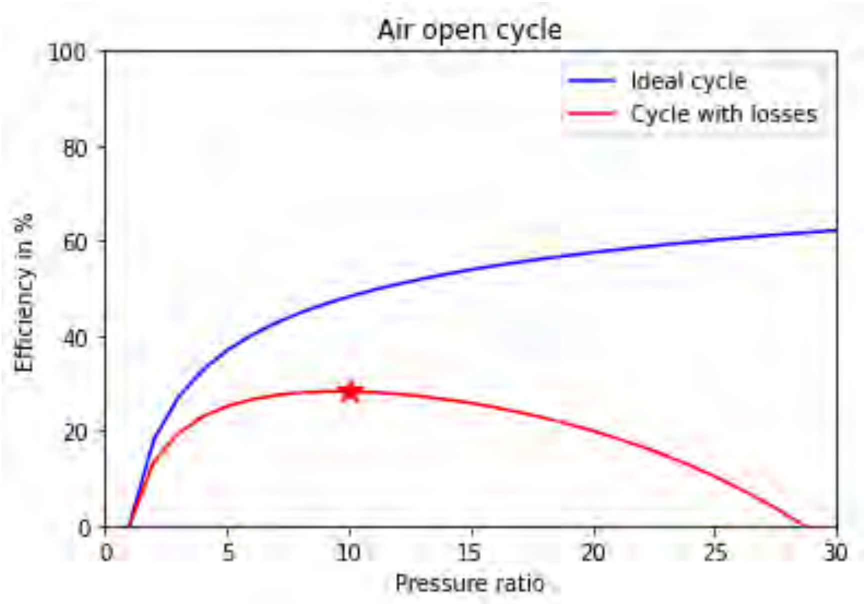


Figure 60 Air open cycle Brayton efficiencies

Again, many cycle variations exist, with the most important being the recuperator that allows some of the heat of the exhaust air to be recovered. A recuperator can for this setup increase the efficiency with 5 % making this quite a valuable addition without changing anything in the turbine layout. The layout with a recuperator is shown in Figure 59.

The use of an intercooler would require the compressor to be split into sections. Theoretically this can be an increase in efficiency when used together with a recuperator although this has to be considered from a CAPEX and OPEX perspective, this layout is shown in Figure 61.

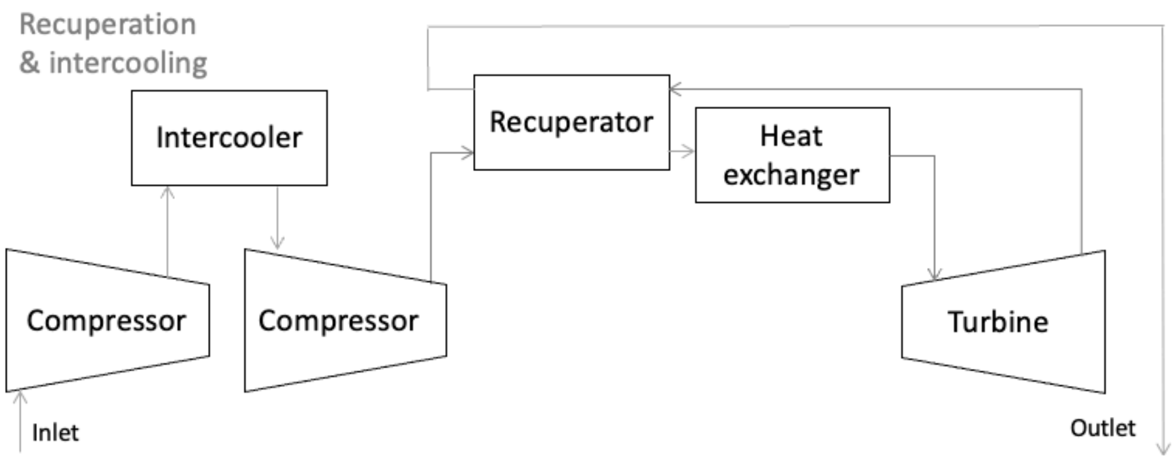


Figure 61 Intercooled and recuperated, open cycle Brayton

Finally, there is the option to split the turbine section, which splits the turbine in a part dedicated for compressor operation and a part that is used for the load. This a generally favourable and commonly applied option in combustion open Brayton turbines, as it ensures that compressor operation is not interrupted during load changes. This option was also shown earlier in section 5.3.

Ducting

As open cycle Brayton relies on inlet and exhaust ducting this has to be considered. Both because these require filters/water traps in the inlet as well as for their size and more importantly flow area. The Ducting size of these turbines increases quite rapidly with the required mass flow of inlet air. Basing this on commercially available marine gas turbines [162] allows for the following estimate: 0.063 m^2 intake cross section per kg/s of air mass flow. The exhaust can be slightly reduced in cross sectional flow area, although this difference is minimal. At these cross-sectional areas, the air speed remains below 20m/s or 72 km/h.

Turbine size

Open Brayton turbines are quite light and compact, when assuming that the open Brayton turbine will be similar to the aero-derived marine gas turbines currently available. These current turbines weigh in between 1-2 ton/MW produced, with a volume of 2-4 m^3/MW produced [87]. This then has to be supplemented by a heat exchanger, instead of the now used combustion section. This heat exchanger is sized separately in section 7.5. For general sizing of a turbine the ratio of dimensions can be considered as 2:1:1 (length:width:height). The heat exchanger that is required will be sized in detail in upcoming section 7.5, however the size is relatively compact (same order of magnitude as turbine).

Load response

For load response the open cycle Brayton turbine is again limited by the reactor and its heat exchanger. The aeroderivative open Brayton turbine can operate on far greater load responses when operating on the combustion process. A greater load response similar to this can be achieved when considering load rejection strategies.

Consider the earlier mentioned split turbine design, where the compressor has a dedicated turbine section to deliver the compressor work before being led through a mechanically separate power turbine. This layout allows for a simple yet very capable load following strategy, where excess power is diverged and dumped instead of directed to the power turbine. This way the constraint of the reactor load change speed is mitigated, as the reactor can be ramped up to slightly higher loads. The extra heat input can be vented of with only the required portion of the air (and thus power) being sent to the power turbine, the possible layout is shown in Figure 62. Rejecting excess flow in turbines is not something new, rejection of gasses is already done on (engine) turbochargers where the rejection is handled by opening a “waste gate” [163].

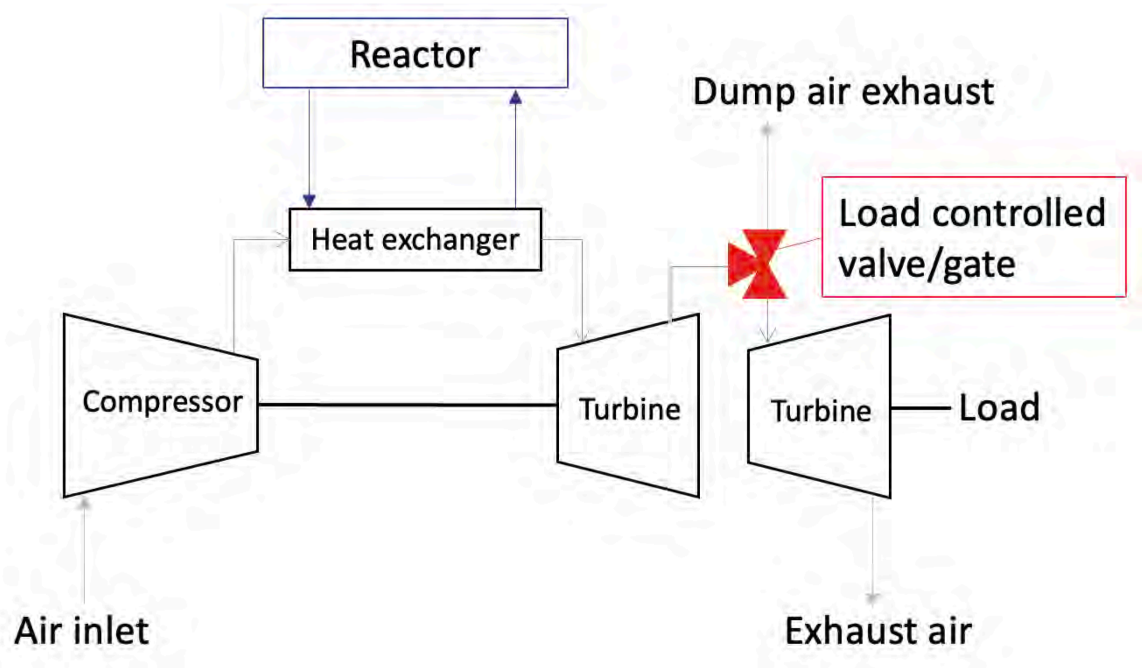


Figure 62 Dumping enabled load following turbine as concept for the marine application, compressor and turbine are connected by shaft. Power turbine is mechanically separate and only connected to load.

The layout can be simulated on the simple cycle Brayton turbine for a cycle with consideration for isentropic losses. The cycle is shown without recuperator, as this would require some reworking of the ducting. The use of 10% additional heat input is shown, although this could be changed dynamically, with the lower limit of the reactor output set at the assumed 50%. The first turbine operates in such a way that the compressors back work[21] is satisfied, while the power turbine is loaded depended on the vessels load demand, with any excess power being rejected as waste heat and not being sent through the turbine. The split turbine arrangement is a benefit here, as it enables the flow of air to be continuous and the compressor operations uninterrupted. In Figure 63 the turbine efficiency is shown, where an ideal turbine without constraints is shown as the baseline. The load following turbine is shown with a stable thermal power of 50% as assumed lower limit, this is done up to 50% power demand. In Figure 64 the 10% power increase and possible load following is shown, again also shown with unconstrained conversion efficiency.

[21] In turbines the back work is the amount of power the turbine needs to deliver to sustain compressor operation. Available shaft power beyond the back work can then be used as mechanical power.

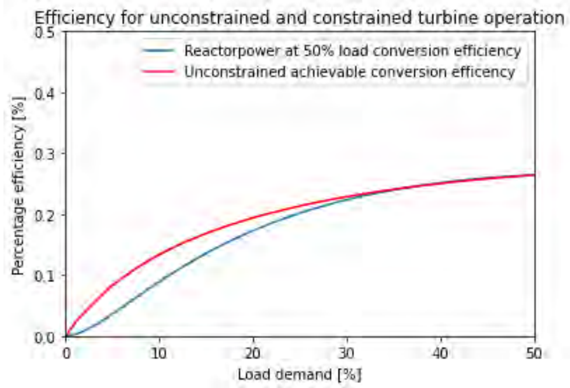


Figure 63 Turbine power conversion efficiency for loading below 50% (reactor power fixed at 50% thermal power)

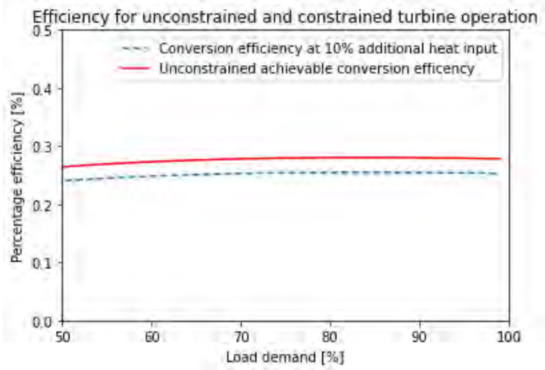


Figure 64 Turbine power conversion efficiency for loading above 50% (reactor power increased by 10% for load following)

The previous two figures are merged (with some smoothing to eliminate the sharp step at 50%) and shown in Figure 65, with a graphical representation shown in Figure 66.

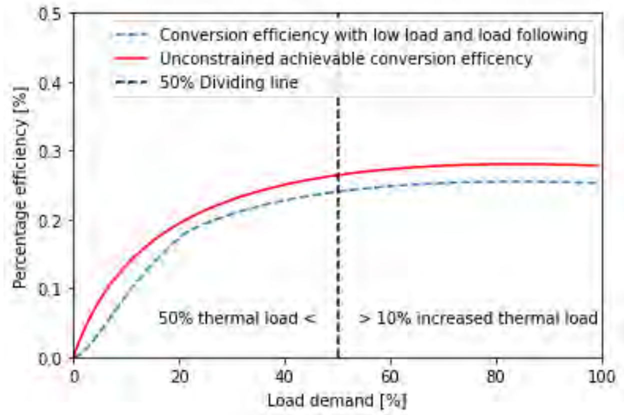


Figure 65 Efficiency of turbine in increased thermal load "Dumping enabled load following turbine" arrangement

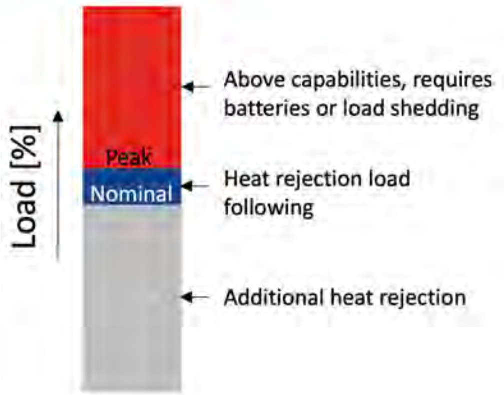


Figure 66 Load following capability and limitations when operating with dumping

The consideration that the power turbine does not operate on constant rpm (due to the varying mass flow when heat is rejected) can be mitigated by an inverter and rectifier and has been researched before (for combustion based open Brayton turbines) as something that does not have to impose a severe penalty and can even benefit system efficiency [164]. It should be considered that this is however an additional system with associated complexity and increased cost.

This idea of additional heat production and heat rejection for the benefit of load response is not exclusive to the open Brayton turbine, however it is the easiest implementation as it is open cycle and thus not require the re-use of the medium. This allows for a significantly simpler heat rejection system, and no additional coolers or cooling capacity.

7.4.4 Selection of turbine type

To summarize, the properties identified for each of the turbines are shown in Table 19.

Turbine/property	Rankine (steam)	Closed Brayton	Open Brayton
Efficiency	++	+	+
Volume (system)	-	+	0
Weight (system)	-	+	0
Complexity (system)	--	-	+
Load response	+	+	++

Table 19 Summary of turbine performance properties

Based on the information in Table 19, the most efficient turbine is the steam turbine. However, the Brayton turbines offer some distinctive advantages, the closed cycle is the smallest although the open Brayton turbine is also fairly compact. The open cycle turbine is significantly less complex and offers very capable load following performance when operated using heat rejection. Surpassing the capabilities of the (assumed in section 7.2) normal reactor operation, this and the relatively low system complexity when operating at reasonable efficiencies is why open Brayton is considered the most favourable turbine for the marine application.

7.5 Heat exchangers

7.5.1 Heat exchangers for open Brayton system

Heat exchangers are a vital component in the overall implementation of the reactor in the marine propulsion system. Due to the different temperatures and properties of the coolants it is important to consider the (V)HTR and MSR separate, which is why they are shown side by side. Again, the relevant characteristics of size, volume, complexity, and efficiency are discussed.

For the heat exchangers: the conventional shell and tube and related helical coil heat exchanger can be considered, alongside the modern PCHE. For visualization these are shown in Figure 67, Figure 68 & Figure 69.

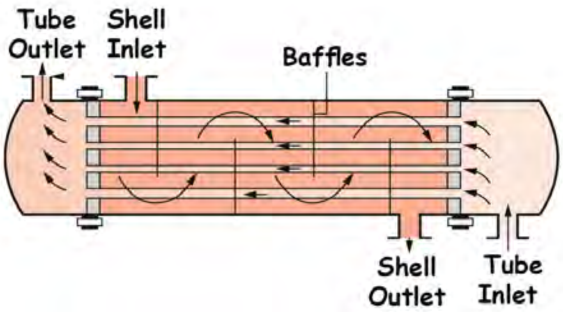


Figure 67 Shell and tube heat exchanger [165]

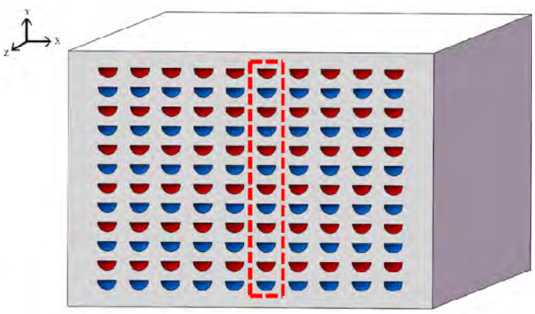


Figure 69 PCHE heat exchanger, red = hot channel, blue = cold channel [167]

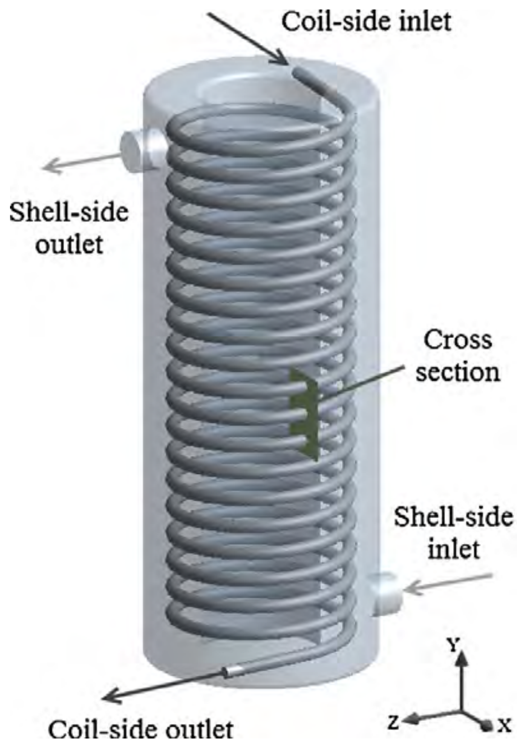


Figure 68 Helical coil heat exchanger [166]

With the information in Table 20 derived from the paper on heat exchangers for modern nuclear power plants by Oh, Kim and Patterson [168]

type/parameter	Shell and tube	Helical coil	PCHE Heat exchanger
Heat transfer coefficient ($W/m^2 *K$)	500	1000	2000
Surface density (m^2/m^3)	75	80	1100

Table 20 Heat exchanger types and properties, derived and rounded values from [168]

The shell and tube heat exchanger is the simplest of the considered heat exchangers, although also the most sizable. The helical coil heat exchanger is more favourable as it has a higher heat transfer coefficient [169], besides this it also has seen use in the nuclear power field specifically in helium-based systems [96]. The PCHE is a more modern development, and both has a high heat transfer coefficient as well as a very high surface density, both attractive properties from a size and weight perspective [168]. Concepts are already being developed intended for use with molten salt, although mostly for use in the renewable energy industry (non-radioactive salt, used with solar power) [170]. The PCHE is however still shown for reference, as a possible development.

This results in primary heat exchangers of different sizes for the different coolant types, as shown in Table 21. These are shown as m^3 of volume per MWth installed. The proposed intermediate coolant loop is used to segregate the main loop (in contact with radioactive material) from the secondary, this loop is helium filled as helium is relatively neutron transparent. Each of the heat exchangers is assumed at an effectivity value of 0.95. The direct heat exchanger is shown first, followed by the loop with intermediate heat exchanger.

		He cooled reactor			Salt cooled reactor		
	Heat exchanger/ media	Tubular (m^3)	Helical coil (m^3)	PCHE (m^3)	Tubular (m^3)	Helical coil (m^3)	PCHE (m^3)
Direct heat transfer	To air (direct)	0.68	0.32	0.011	Technically possible, but not selected due to possible irradiation of the air (contact with the radioactive salt)		
Paired loop with intermediate coolant (helium)	To He (Intermediate HEX)	1.29	0.60	0.022	0.33	0.16	0.0056
	To air (He to air)	1.48	0.69	0.025	0.26	0.12	0.0045

Table 21 Heat exchanger volume (m^3) per MWth of reactor power to be transferred, calculation in Appendix G: Calculation heat exchangers

A heat exchanger for decay cooling can be placed this cooler is intended for cooling the reactor when no power is generated. The main scenario in which this can occur is after a reactor stop, when the reactor has just stopped its decay heat has to be removed. Peak decay heat is up to 7% of the maximum thermal power [4]. The coolant used is seawater, which cannot be used with the PCHE due to fouling (PCHE's are only usable for clean fluids due to the small channels [171]), which is why it is not shown. This cooler is not a major contribution to the overall size, as shown in Table 22.

Condenser type/coolant	Tubular (m^3)	Helical coil (m^3)
Seawater (on He loop for MSR)	0.0033	0.0016
Seawater (on He loop for VHTR)	0.0044	0.0020

Table 22 Heat exchanger volume (m^3) of decay heat cooler, per MWth installed power, cooling 7%

7.5.2 Selection

If the possible layouts are considered their total heat exchanger sizes can be shown relative to each other, allowing for comparison. This is shown in Figure 70, with Table 23 used to indicate which components are fitted in which setup. The setups are shown with and without the intermediate heat exchanger when possible.

Setup number	1	2	3
Reactor coolant	He	He	Salt
Turbine type	Open Brayton	Open Brayton	Open Brayton
Intermediate heat exchanger	No	Yes	Yes
Turbine layout	simple	simple	simple

Table 23 Possible different reactors and heat exchanger setups

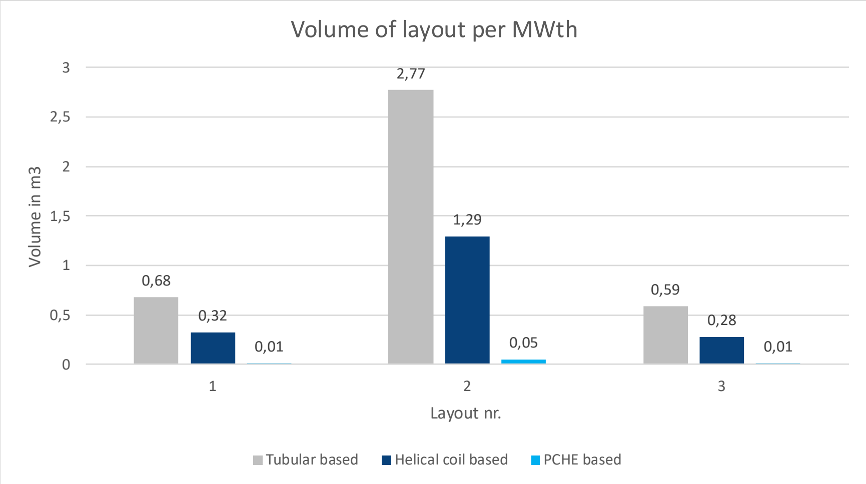


Figure 70 Volume of heat exchangers per layout, shown per MWth

From Figure 70 it can be seen that the differences between heat exchanger types is large. The PCHE is for this purpose very favourable, the helical coil is however also not unfavourable and more conventional and widely used.

Despite the volumetric downside selected layouts always operate on the segregated layout with the intermediate heat exchanger, for segregation and safety purposes.

Regarding the use of the helical coil or PCHE, both are suitable however the helical coil is more developed and proven, which is why is selected for the implementation.

7.6 Layout

For the layout of the reactor based marine propulsion and power generation plant the reliability, complexity and efficiency were described as the relevant characteristics in the earlier Table 12. First options for the layout will be established before one is selected for the implementation.

7.6.1 Layout options

Selecting the layout to be used for the reactor plant depends on multiple criteria as established earlier, relating directly to the three identified performance characteristics. These criteria are addressed in the following three points:

- Insusceptible to single point failure (indicating a high degree of reliability)
- Minimal/no more systems than necessary to achieve redundancy (complexity related)
- Acceptable from an efficiency standpoint

Using the points mentioned, it can be established that the vessel requires two propellers, or a form of alternative propulsion in case of a propeller, shaft, or gearbox failure. This requirement comes from historical applications (discussed in chapter 6), as it is very important for the application to remain operational even in a reactor stop scenario. This is to prevent any secondary danger, where the reactor could be subjected to danger following a loss of propulsion.

Similarly, the vessel should be fitted with either a double reactor, or a single reactor but with a secondary power source. Double reactors are a possibility, although not considered in detail in this report. A double reactor would be a significant hurdle for the design due to its weight, alongside a significant CAPEX increase as nearly all systems have to be doubled up. The secondary power source discussed in this report is based on conventional (fossil fuelled) engines.

Using these criteria and the previously established information only a few options remain. Where the emergency propulsion arrangements are shown as well because these influence the overall efficiency in some layouts even when inactive (gearbox with multiple inputs).

Possible vessel arrangements are shown, shown only for a single propeller layout side. Red bordered components are linked to the nuclear plant. The emergency arrangement shown in the dotted area is used when the reactor cannot provide power.

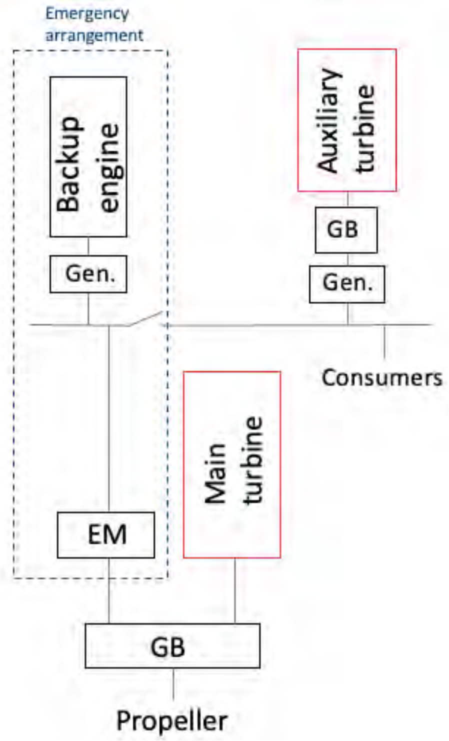


Figure 71 Layout: Turbine direct, emergency engine electric

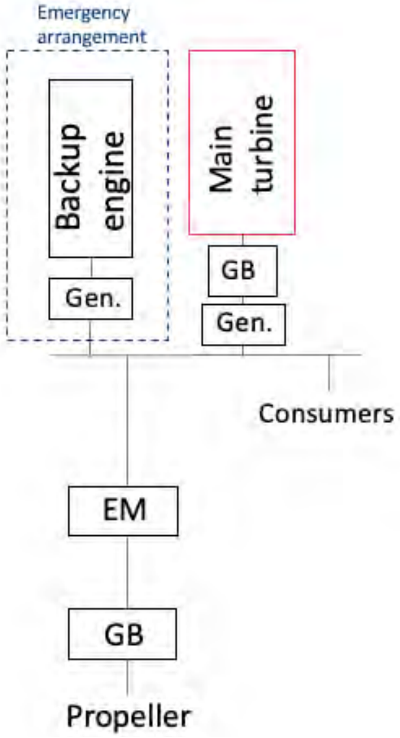


Figure 72 Layout: Turbine electric, emergency engine electric

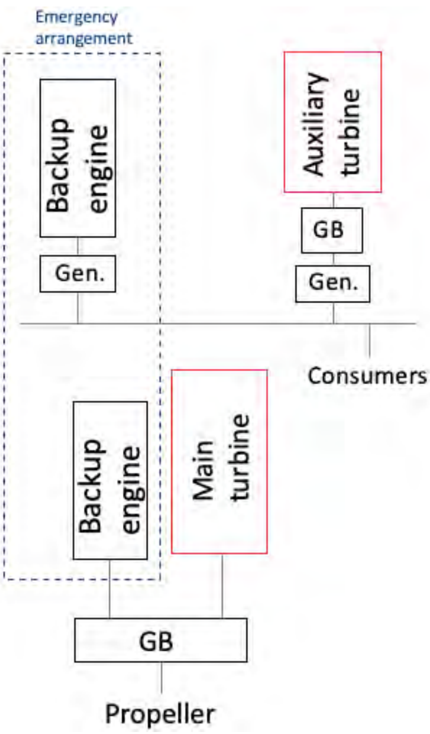


Figure 73 Layout: Turbine direct, emergency engine direct

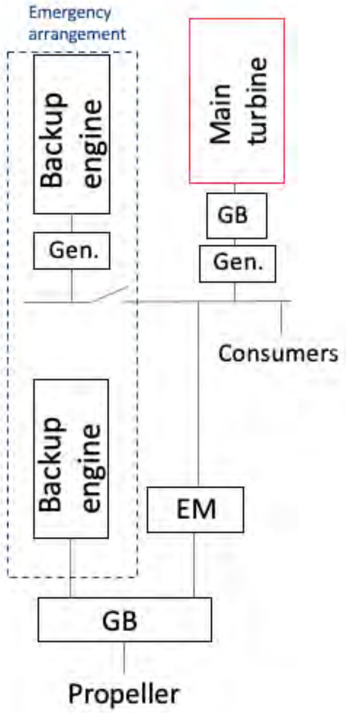


Figure 74 Layout: Turbine electric, emergency engine direct

Each of the proposed layouts can be evaluated for their efficiency from input shaft to output shaft, the "single point failure" criterion is satisfied for each when considering a double propeller setup. Notes are made for each of the layouts, specifically for relevance to efficiency, complexity, and load response.

Layout	Efficiency	Notes
Layout: Turbine direct, emergency engine electric (Figure 71)	95%	Efficient, can theoretically be supplemented by battery power although this increases gearbox complexity. Does rely on two turbines (of possible different size) for propulsion and power generation.
Layout: Turbine electric, emergency engine electric (Figure 72)	90%	Easiest to supplement power by battery system, least complex gearbox arrangement.
Layout: Turbine direct, emergency engine direct (Figure 73)	95%	Efficient, cannot be supplemented by batteries for propulsion. Does rely on two turbines (of possible different size) for propulsion and power.
Layout: Turbine electric, emergency engine direct (Figure 74)	89%	Power can be supplemented by batteries although this increases gearbox complexity, requires separate backup engines (propulsion and power generation).

Table 24 Layout efficiencies, based on efficiencies and components shown in Table 25 and Table 26

The efficiencies calculated for Table 24 are detailed in Table 25 and Table 26.

Item	Efficiency	Source
Gearbox (single)	0.99	[87]
Gearbox (multi)	0.96	[87]
Generator	0.97	[172]
Switchboard	0.99	[172]
E-motor	0.97	[172]
Shaft	0.99	[87]

Table 25 Static efficiency values of components

Component/ layout	Gearbox (multi)	Gearbox (single)	Generator	Switchboard	E-motor	Shaft
Turbine direct, Emergency E-motor	x					x
Fully electric		x	x	x	x	x
Turbine direct, Emergency engine direct	x				x	x
Electric, Emergency engine direct	x	x	x	x	x	x

Table 26 Components used in each drive trains efficiency calculation

7.6.2 Layout selection

To select the layout that is most suitable for the application, both efficiency and reliability has to be considered. Reliability in this case being mostly related to the overall system, instead of the individual component level. Indicating that the reliability is realized mostly by redundancy considerations in the system.

The layouts with the direct turbine have the highest efficiency in design condition, the downside is that the gearbox has to be able to accept two inputs simultaneous in case of an electromotor as supplemental power. The other option to run the backup engine in direct connection is possible, although this would negate the possibility of battery supplementation (for propulsion purposes). The fully electric layout is less optimal from an efficiency perspective, although not in an extreme sense. The setup uses the simplest gearbox arrangement, as well as being the easiest to supplement with battery power for load changes. A final benefit is the reduced amount of high-speed machinery, as all can be used to generate power for a single power grid. This layout is selected as the least complex in both operation and implementation for the overall system.

The all-electric layout is doubled up to form a double propeller layout, this is done to prevent any single point failure disabling the vessel and subjecting the vessel and the reactor to possible secondary danger. The layout selected is shown in Figure 75.

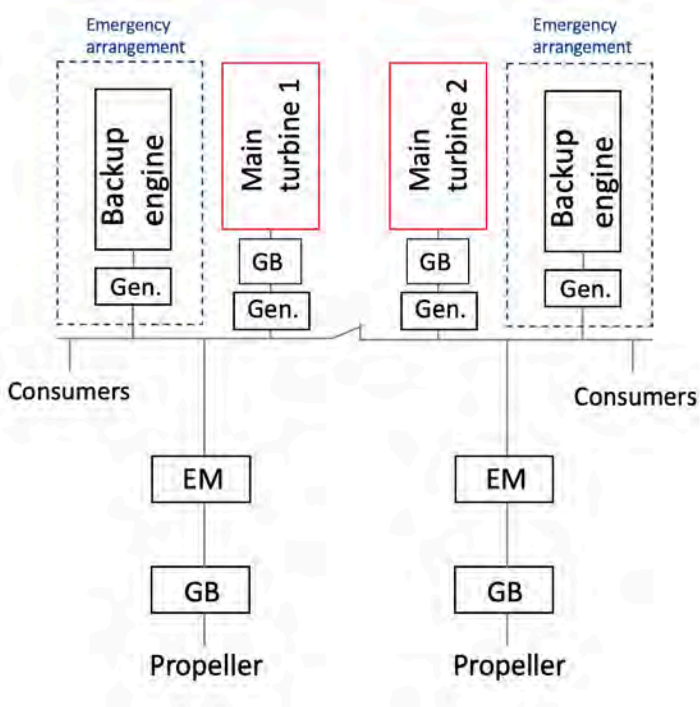


Figure 75 Double propeller layout, insusceptible to single point failure. Switchboards are connected by normally closed tie breaker that can be opened to separate the switchboards in case of failure.

7.7 Balance of plant

The balance of plant is the final selection of components required for the entire layout to be functional, this mainly consists of pumps and fans for both coolant circulation and cooling. Secondly the earlier mentioned batteries (mentioned in the previous section) are detailed here as well, as these are an additional component that can be added for the benefit of load response.

7.7.1 Pumps and fans

The selected nuclear power plant requires some additional balance of plant and systems that consume power for the benefit of power generation. These components are also shown parametric (shown per MW thermal produced), so that they can be used for each of the design sizes. Required mass flow is determined by dividing the thermal power by the specific heat and temperature difference. The required pressure head is estimated at 30 meters for each of the pumps. For each of the systems the pumps considered are of the centrifugal type, with pumping efficiencies of 75%. This is also the case for molten salt, as molten salt can be pumped with specific versions of these pumps, this also sees commercial application in the renewable energy sector (molten salt used in solar power plants) [173].

Redundancy is again a consideration, the amount of pumps chosen, as well as capacity division reflects this. For the final application it might be necessary to further split the pumps into a selection of smaller pumps to allow for more conventional pump sizes in the larger plant layouts. For their overall power rating however, this is of negligible influence.

Pumping power is calculated using the following two equations [128]:

$$P_{fluid} = \frac{\dot{m}_{pump} \cdot (\rho g z^{++})}{\rho}$$

$$P_m = \frac{P_{fluid}}{\eta_{pump}}$$

Where z^{++} is the pressure head, and P_m the mechanical pumping power. This information is shown in Table 27 & Table 28, where this information is shown for the possible pumps to be fitted.

Purpose	Amount of pumps	Amount active in normal operation	Operating media	Pressure head (m)	Temperature difference (°C)	Mass flow total (kg/s)	Pump power total (kW)
Main coolant pump salt*	3	2	Molten salt	30	100	4.3	1.67
Seawater pump decay cooler	2	0	Seawater		40	0.70	0.27
Freshwater circulation pumps gearboxes	2	1	Freshwater		50	0.016	0.01
Freshwater circulation pumps electromotors	2	1	Freshwater		50	0.049	0.02
Seawater pump, general	3	2	Seawater		25	0.14	0.05

*Table 27 Required pumps, amounts, power requirements per MWth installed, *only required for MSR*

Besides pumps there are also the fans that are required to maintain circulation flow for the gasses, these are shown in Table 28.

Purpose	Amount of pumps	Amount active in normal operation	Operating media	Pressure head (m)	Temperature difference (°C)	Mass flow total (kg/s)	Pump power total (kW)
Main coolant fan helium*	3	2	Helium	30	500	0.39	0.15
Secondary coolant fan helium (He reactor)	3	2	Helium		423	0.46	0.18
Secondary coolant fan helium (Salt reactor)	3	2	Helium		213	0.90	0.35

*Table 28 Required fans, amounts, power requirements per MWth installed, *only required for (V)HTR*

In addition to the pumps there will be a baseload as well for the control electronics, as well as the minor systems that regulate and monitor power on the reactor itself. These are considered at 1% of the delivered power, with the considered conversion efficiency this is 3.5 kW.

Not every pump is used in each layout, with the power requirement of the layouts differing by their reactor type, as is shown in Table 29.

Cycle/ reactor type	Open cycle Brayton (kW load per MWth installed)
(V)HTR	4.5
MSR	5.5

Table 29 Power required for pumps and control electronics per MWth installed

7.7.2 Battery technology

Battery technology has improved significantly over the past decades, with more uses in the maritime sector. Batteries can be used for a variety of purposes and installed sizes:

- Peak shaving, where the batteries “shave” a portion of the loading and redeploy this power when needed.
- Power source (supplemental), where the batteries act as a standalone power source for the vessel or dedicated components. Charging is required either by other machinery or from an external supply (shore power).
- Emergency use only, where the batteries act only as backup in case of failure.

With these three options being a consideration for implementation in a nuclear based propulsion and power generation plant. The use of batteries is highly dependent on the expected operations, requirements, available weight, space, and finally also the cost.

To give a brief overview, currently batteries can be assumed to be dischargeable over their lifetime as far as the so-called depth of discharge, this capacity diminishes over the lifetime down to the end-of-life capacity. An important consideration is the C-rate of the batteries, which is how fast the batteries can both deploy and charge as a factor of their capacity. Current commercially available batteries are used for this derivation, with the values shown in Table 30.

Property	Density (m^3/MW)	Weight (ton/MW)	Depth of discharge	C-rate	Cycle efficiency	end of life capacity
Value	20.23	6.7	100%*	1	98%	70%

*Table 30 Derived properties of commercially available battery package, data from [174], *indicating more installed capacity than stated to compensate for the depth of discharge allowance.*

Battery technology is a useful consideration for a supplemental power and peak shaving role. It was previously established that batteries can be added relatively easily in the electric layout. The batteries can be added to supplement the load response, as for the current developed reactors this is estimated to be limited at 5%/min. It was also established that vessels can encounter transients that are both larger (in magnitude) and faster (in time) than this (discussed in section 4.2.3). Batteries could help address these issues. Installing batteries for transients is possible in a way similar to the currently employed peak shaving. Consider the reactor and its turbine operating at a stable load, transient conditions such as heavy weather can cause a fluctuation of the loading in a relatively short time scale. This is visualized in Figure 76.

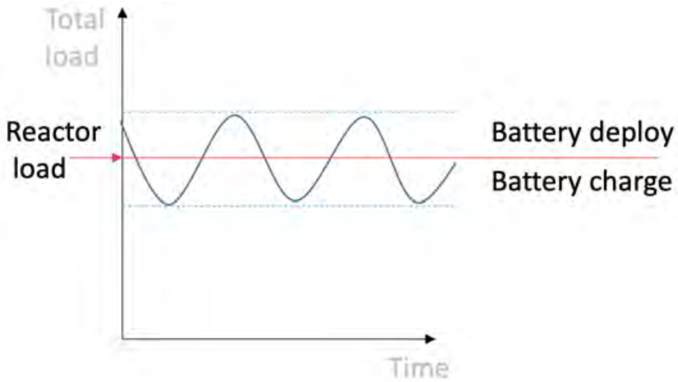


Figure 76 Peak shaving, battery deployment and charge

The required battery power is both a factor of the installed power, as well as from the expected transient loading (which can differ for ships, routes, weather, and intended purpose). If the general case is considered as a baseline, where the reactor load is at the centreline of the transient loading most of the time (and thus the batteries deploy and charge at relatively stable/equal rate). The power of the battery package ($P_{battery}$) can be determined from the amount of power installed on the vessel ($P_{installed}$) and the percentage expected transient loading ($r_{transient}$), the capacity of the battery package for a duration of one hour is equal to its deployable power in case of 1C batteries. This is when considering the power delivered the important factor, and not the duration.

$$P_{battery} = P_{installed} \cdot r_{transient}$$

For instance: on a vessel with 40MW installed power, transient loading is expected to be at most 15% due weather on the vessels route (similar to the values discussed in the research mentioned in section 4.2.3). This would indicate a power requirement of 6MW, which can be satisfied with a 6MWh battery package (1C batteries), considering the lifetime degradation to 70% would require 8.57MWh to be fitted initially (if the batteries from the manufacturer shown in Table 30 are used). This is a substantial battery pack although not unreasonable as similar sizes are already being fitted in other vessels at this moment [175]. It should be noted that when fitting more batteries an upper limit has to be considered from where the volume, weight and cost of the batteries becomes excessive.

The second option is to use the batteries only for transient loads that cannot be subdued or compensated for by conventional (and slower) load following. This is useful for components such as thruster tunnels and cranes, which can cause large power draw spikes. For these components the duration of use and the height of the spike has to be considered. However, the power draw is generally significantly lower than that of the main propulsion, with the time and amount of use also often being lower. In this case relatively minor battery systems can be used, capable of delivering the full power of the machinery, with the duration specified by the use. For instance: a 2MW bow thruster to be used during manoeuvring in port, for an expected use of one hour. For batteries with 1C discharge capacity, this would mean that the battery package has to be 2MWh at 100% depth of discharge, considering the lifetime degradation to 70% would require 2.86MWh to be fitted initially.

The final option of emergency use is interesting, although quite quickly becomes unfavourable from a weight, cost, and spatial perspective. Especially if emergency operation, and safe return to port is required for an extended duration. In this case batteries cannot compete with fuels, as the amount of stored power in a battery is not competitive.

7.8 Chapter conclusion

From the amount of options discussed it can be seen that there are many ways in which the nuclear-powered propulsion and power generation system can be integrated.

It is shown that shielding is the most significant size and weight contribution to the overall system, and this has to be considered as a major contribution to the overall design.

Turbine types were discussed: the most promising option is the open Brayton cycle, although this is a departure from the now common steam turbine used in nuclear power generation. The open Brayton cycle has some distinct benefits in size, load response capabilities and reduced complexity, although these come at the cost of a reduced efficiency.

For the heat exchanger the helical coil is selected as a moderately compact but well proven technology, over the smaller and more compact PCHE.

Using all these components the overall drivetrain layout was discussed, which is considered best suited to be an all-electric layout. In the all-electric layout, it is possible to supplement the power demand as well as allow for redundant emergency propulsion systems.

Finally, the balance of plant required was discussed, showing specific pumps as well as control electronics estimates that are important considerations for the power use of the overall system. A brief description was given on battery systems, as these are a common addition to current marine propulsion and power generation systems and should be considered as a useful supplement for the nuclear based setup as well.

8 IMPLEMENTATION OF REACTOR BASED MARINE PROPULSION AND POWER GENERATION SYSTEM

This chapter covers the sub question: what are the overall characteristics of an implementation of a marine propulsion and power generation system? Considering a preliminary assessment for vessels that are suitable and establishing a selection of conceptual reference vessels. Finally detailing the conceptual vessels on their: Fuel consumption, waste and emissions, expected cost, and their performance on the earlier established indicators of size, weight and load following.

8.1 Initial weight assessment suitable vessels

As the reactor is expected to fit within a vessel of relatively conventional design[22] it is important to consider the size and weight allowance. In the current situation the dominant weight and volume of the propulsion plant is the required fuel. The amount of fuel carried by vessels of different types and sizes can vary greatly. Using multiple publications, a dataset of over 700 vessels is constructed. The dataset consists of vessels delivered over the last two decades. Most of these vessels are lead vessels in a class of vessels, indicating that although they are only added as singular there are multiple sisterships of identical configuration. The vessels are separated in nine different ship types, with information on their fuel weight, volume, installed power (for propulsion), and deadweight.

Using this information, it is possible to determine a range where it becomes possible to install a reactor in the vessel without it intruding on the cargo carrying capacity in both weight and volume of the vessel. Although it should be considered that the reactor requires some care with its placement and cannot be divided similarly to fuel tanks.

A plot of all available values, compared to the earlier (in section 7.3) estimated upper and lower limit for the reactor shielding weight is shown in Figure 77. The comparison is shown between shielding weight and fuel weight as these are the dominant values in the weight and volume assessment[23].

[22] A full redesign would negate the effectiveness of the nuclear and conventionally fuelled comparison

[23] A more detailed weight and volume estimate is included in the upcoming section 8.5.2, showing the breakdown in greater detail.

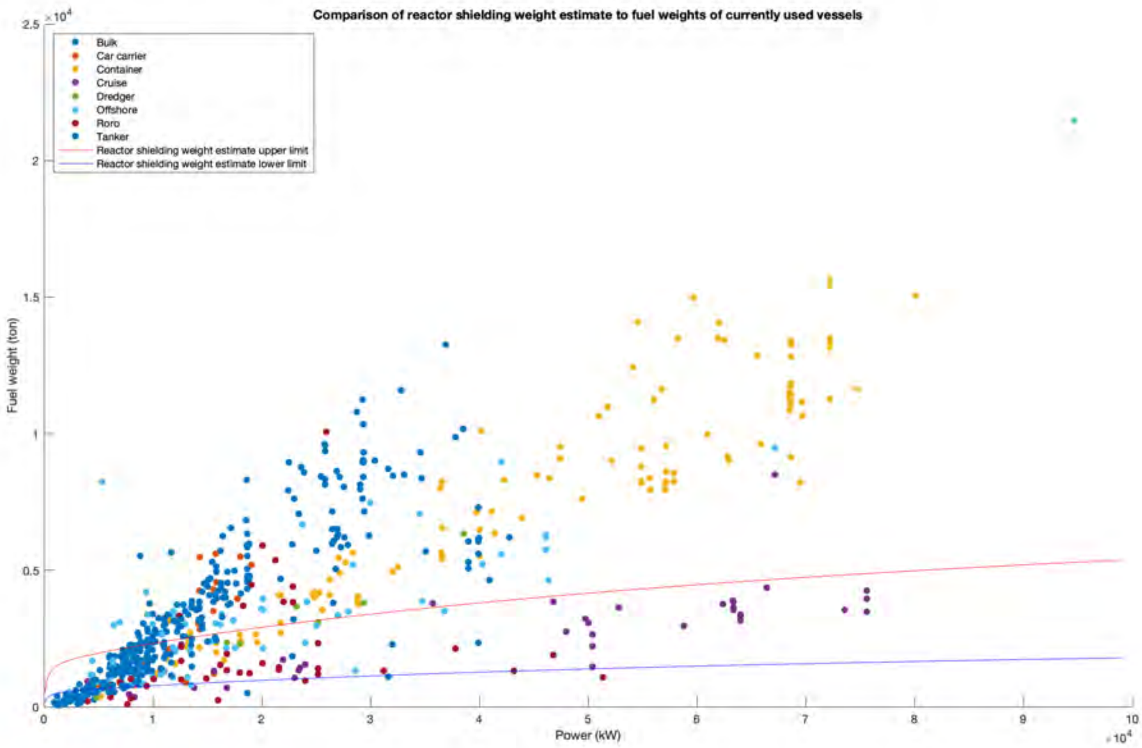


Figure 77 Plot of vessel fuel weights, plotted together with reactor weight estimate. Data from: [176], [177], [178], [179], [180], [181], [182], [183], [184], [185], [186], [187], [188], [189], [190], [191], [192]

From Figure 77 it immediately becomes apparent that there are a significant amount of ship sizes that could implement a reactor (above the red line) as their fuel weight currently exceeds, or far exceeds the weight of the shielding estimate. Some vessels fall in between the lower estimate (blue line) and upper estimate (red line), for these the application can intrude on the weight and size of the vessel used for cargo depending on how compact and light the shielding is constructed. Below the blue line the application will be challenging without accepting reduced cargo capacity or fundamentally changing the vessel. This is further visualized by showing the different ship types separate, with their DWT (deadweight tonnage) represented as plotted colour. The upper and lower bound of reactor shielding weight are shown, as well as a first-degree polynomial fit on the vessel type dataset.

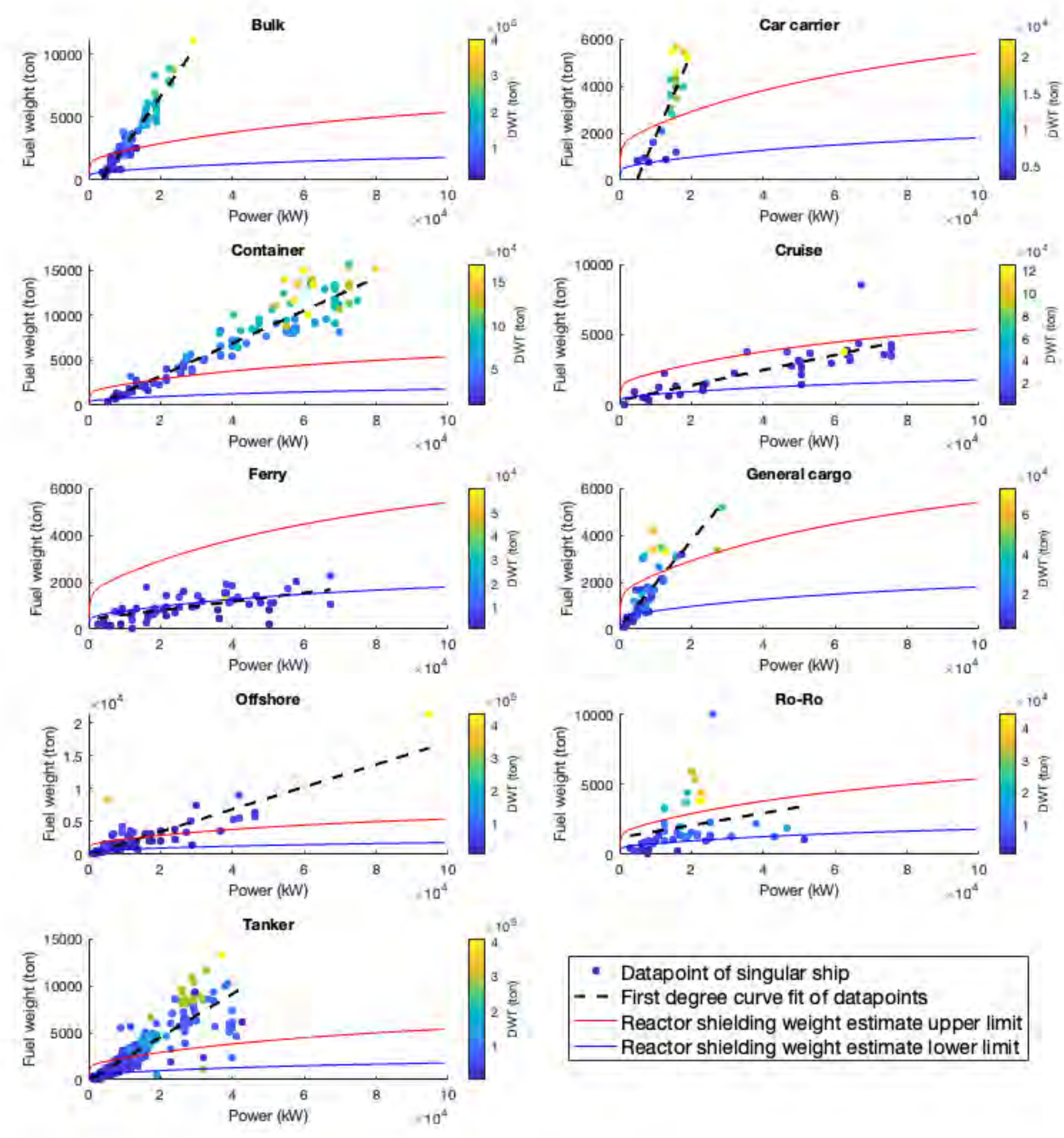


Figure 78 Datapoints from previous figure plotted separately for ship types

From the nine plots in Figure 78 it can be seen in more detail what vessels are suited for a nuclear-powered marine propulsion and power generation system. Large vessels are almost by definition an easier application as they tend to carry far greater amounts of fuel, this compares favourably to the marginal increase in reactor and shielding weight per kW. Smaller vessels (lower DWT) and reduced powers are a more difficult application. The specific vessel groups can be divided in groups that show the influence of the application.

- Ferry, cruise, and ro-ro vessels are difficult applications. These ship types either lie below or almost completely in the bounds of the reactor weight estimate over the complete range. These vessels in their current form will suffer from a cargo weight and possible volume reduction.

- Offshore, general cargo and car carriers are very dependent on the installed power, with the application becoming attractive at relatively large installed powers. Lower installed powers are difficult and require consideration or possible intrusion in the cargo capacity.
- Bulker, tanker, and container vessels are a very suitable application, at relatively low installed powers the reactor becomes competitive for weight and size already.

These observations also tie into the type of work the vessels are used in, with the vessels that are used on longer and more constant voyages having generally larger fuel capacity making them better applicable for a reactor implementation.

These considerations hold when we consider a like for like replacement of the reactor in the conventional ship. Adoption of this technology however could also mean rethinking the overall ship design which would open the door for broader application and deployment. This ties into the consideration of vessels operating on new fuels, options such as ammonia and methanol require significantly more volume and weight for the same energy as the diesel fuels they are replacing. This means that the reactor becomes more competitive from a weight and volume perspective compared to these new vessel designs, as these vessels would have an increased fuel weight to achieve their current endurance.

8.2 Establishing conceptual reference ships

Using the comparison made in the earlier Figure 78 is possible to establish conceptual ships that can be used for direct comparison to their fossil fuelled counterpart and to illustrate the concept in greater detail, the ships shown are:

- A bulker with an installed power of 20MW
- A tanker with an installed power of 30MW
- An offshore ship with an installed power of 40MW
- A containership with an installed power of 50MW

The speed, size and deadweight of these vessels is determined from the ship data of existing vessels as used earlier to determine the fuel weight. A selection of vessels is chosen that are close to (the offshore vessel) or above (bulker, tanker, and containership) the feasible range (as determined in section 8.1) for a nuclear based marine propulsion and power generation plant. The vessel choice in this case being based purely on the power requirement of the vessel.

Ship/ parameter	Unit	Bulker	Tanker	Offshore	Container
Service speed	Kn	15	15	12	22
Expected power for service speed (85% MCR)	kW	15800	22865	31280	38505
Deadweight (approximate)	t	180000	290000	31000	86000
Loa x breadth x draught	m	292 x 45 x 17	333 x 60 x 21	189 x 32 x 12	299 x 48 x 13

Table 31 Ship parameters reference vessels, from [185], [186], [189] & [191]

The installed power will then be delivered in the conceptual case with the earlier (chapter 7) selected components for the nuclear marine propulsion and power generation plant.

The reactors implemented are the earlier discussed (V)HTR and MSR, both suitable and shown due to their difference in TRL, in both layouts combined with open cycle Brayton turbines. For the heat exchangers the helical coil is shown, as the more conservative choice over the modern PCHE. Load following is handled using the load rejecting turbine arrangement, split over two turbines for redundancy reasons. a supplemental battery capacity is fitted to handle a 15% transient for up to one hour, intended for short load peaks and use of thrusters and other large machinery. The 15% is considered a relatively large battery pack, estimated to provide more than sufficient capacity for a generalized application. All components are combined in the double propeller fully electric layout as selected in section 7.6, offering a high level of redundancy and ensuring that the vessel remains operational in case of a single point failure. Finally, an emergency power system is fitted, which can provide power to attain half speed using diesel fuel in case the reactor must be stopped. Information on this system is added in: Appendix H: Emergency power system

The relevant information for each of the conceptual vessels is shown summarized in Table 32.

Ship/ parameter	Unit	Bulker	Tanker	Offshore	Container
Installed power	MW	20MW	30MW	40MW	50MW
Installed thermal power	kW	60606	90909	121212	151515
Margin reserve to expected power for heavy loading, balance of plant & hotel load.	%	27%	31%	29%	30%
Balance of plant power (Reactor systems)	kW	273	409	667	833
Reactor type	-	VHTR (With intermediate loop)	VHTR (With intermediate loop)	MSR (with intermediate loop)	MSR (with intermediate loop)
Reactor weight	t	250	250	250	250
Shield weight (lower-upper estimate)	t	970-2909	1131-3393	1268-3805	1387-4160
Reactor & shield size (spherical- cubic)	m^3	782-1493	942-1798	1078-2059	1195-2282
Layout option	-	Turbine electric, emergency engine electric	Turbine electric, emergency engine electric	Turbine electric, emergency engine electric	Turbine electric, emergency engine electric
Turbine type	-	Open Brayton recuperated	Open Brayton recuperated	Open Brayton recuperated	Open Brayton recuperated
Number of turbines	-	2	2	2	2
Turbine efficiency	%	33	33	33	33
Turbines weight	t	30	45	60	75
Turbines volume	m^3	60	90	120	150
Turbine ducting cross section	m^2	11	16.5	22	27.5
Shaft to shaft efficiency	%	90	90	90	90
Primary heat exchanger, helical	m^3	42	63	15	18
Intermediate heat exchanger, helical	m^3	35	55	19	24
Decay cooler	m^3	0.1	0.3	0.5	0.6
Emergency power system	kW	2773	4159	5667	7083
Emergency power system volume (engines + fuel)	m^3	30 + 100	46 + 150	62 + 204	78 + 255
Emergency power system weight (engines + fuel)	t	24 + 90	36 + 135	49 + 184	62 + 230
Transient load	%	15%	15%	15%	15%
Batteries fitted (capacity)	MWh	4.3	6.4	8.6	10.7
Batteries weight	t	29	43	57	72
Batteries volume	m^3	87	130	173	217

Table 32 Conceptual nuclear-powered vessels

The overall layout is shown schematically for each of the vessels (as all will use an identical layout) in Figure 79.

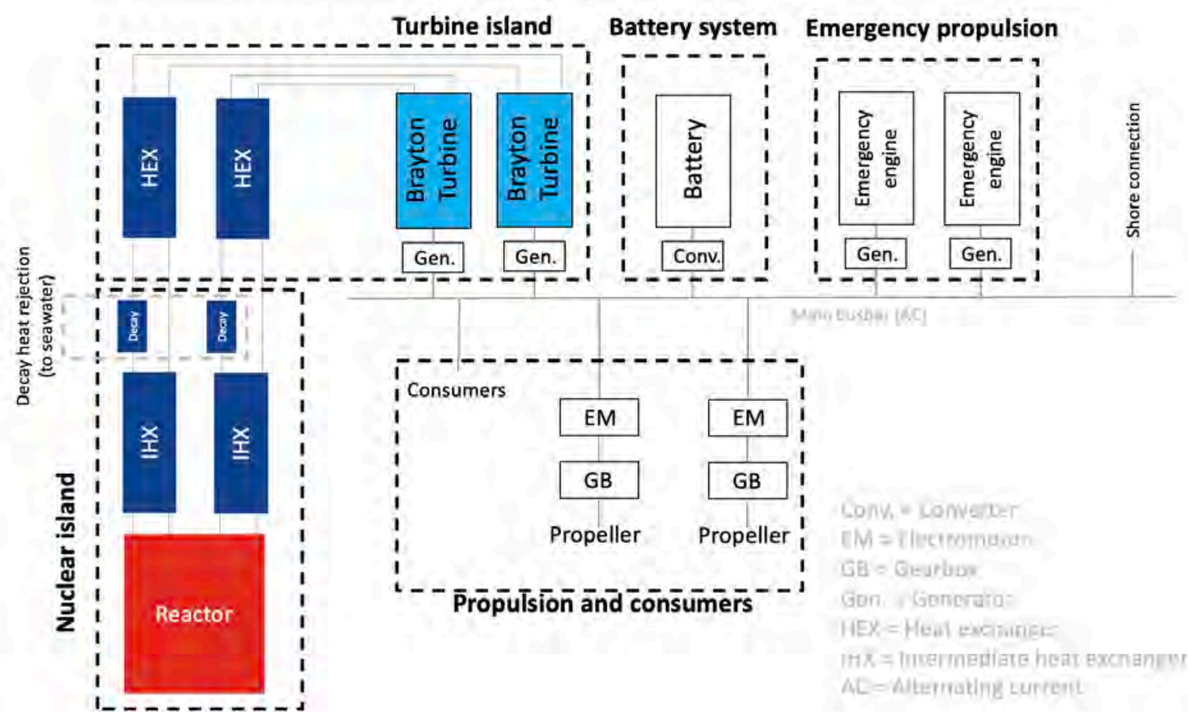


Figure 79 Schematic overview of full layout as used on the conceptual vessels

8.3 Environmental assessment of nuclear-powered concept ships

8.3.1 Consumption of nuclear fuel

A nuclear-powered marine propulsion and power generation system is distinctly different from a fuel perspective compared to the current fossil fuels. As already mentioned earlier nuclear fuel is neither burned nor exhausted, instead the fissile material slowly is depleted while remaining inside the reactor. Nuclear fuel in a reactor produces heat, so to determine the useful power (mechanical or subsequent electrical power) it is required to both know the type and performance of the reactor (the effectivity measure burnup) and the conversion efficiency of the drivetrain. Using this information, it is possible to determine a depletion per power produced figure, similar to the commonly used fuel consumption figures seen in use with fossil fuelled engines and turbines. The values used are shown in Table 33, with the burnup value being the lower of the earlier estimates as discussed in section 3.8. Large burnup improvements would result in significant efficiency gains over the complete fuel cycle.

Parameter	Value
Burnup	90 GWd/tHM
Peak conversion efficiency recuperated	33%
Load following (identical to capabilities determined in section 7.4.3)	≤50% load = 50% thermal loading >50% load = 10% allowance for load following

Table 33 Values for determining specific nuclear fuel usage curve

Using the information from Table 33 and the earlier determined load following constraints it is then also possible to determine a fuel consumption curve over the entire power spectrum of the ship. Ideally the curve is flat over the entire region of operation, but due to the turbine efficiency this is not the case. The burnup, which is given for the entire fuel load not only the fissile material, is first converted to kWh per gram, with 1 gigawatt day being $24 \cdot 10^6$ kWh, this results in 2160 kWh per gram of fuel used. In marine diesel performance it is common to determine the performance in the multiplicative inverse: the gram per kWh delivered, where the efficiency of conversion is considered as well. This is shown in figure Figure 80 and a zoomed in more readable version of the higher loading (where the turbine efficiency is in or in its near optimum) in Figure 81.

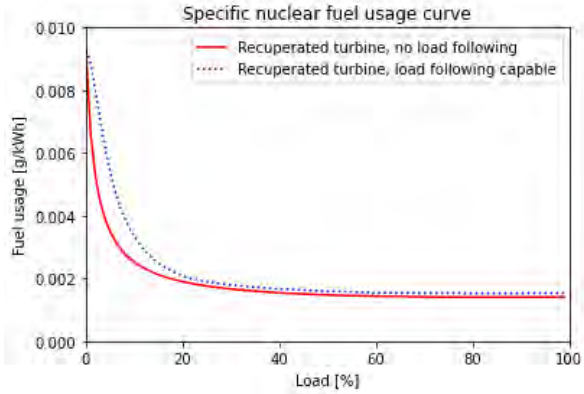


Figure 80 Specific nuclear fuel usage curve

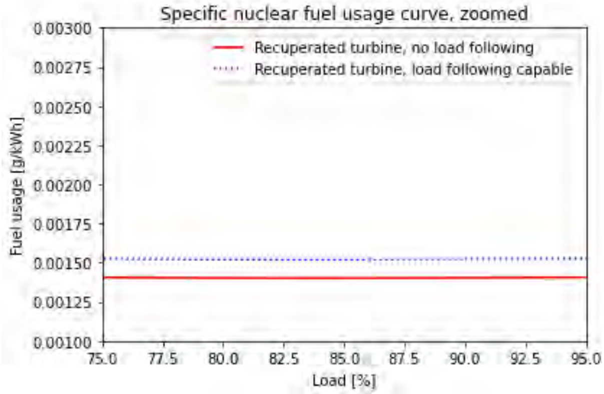


Figure 81 Specific nuclear fuel usage curve, zoomed

From Figure 80 & Figure 81 it can be seen that the reactor (and its turbine for conversion) requires only very small amounts of fuel per kWh produced. To put this value into perspective, a relatively average value for marine diesel engines running on diesel is 175 g/kWh (a difference of more than factor 10^5). The part load efficiency under 20% load is very poor, partly increased due to the proposed high thermal loading for the benefit of load following, with the turbine being very inefficient at these loads. Starting at 20% loading, fuel usage quickly approaches more acceptable levels.

The yearly consumption depends on three parameters: (design) installed power, the percentage that the vessel is in operation, and the amount of power used when in operation. These can all be seen together in a load profile, as discussed in section 4.2.3. For a conceptual vessel as the ones shown no load profile is available, however it can be shown for multiple loading scenarios. Four scenarios are established, with each having a portion of low load operation (50% of installed power used) and a "no load portion" which should be considered as in port and on shore power with no usage of nuclear fuel. Generalizing a load profile like this instead of exactly for a ship is not new, as a very similar methodology is also used for emission (NO_x) testing of marine diesel engines [193]. The scenarios are shown in Table 34.

Scenario	Time spent at full load	Time spent at part load	Time spent at no load
A	15%	10%	75%
B	40%	10%	50%
C	65%	10%	25%
D	90%	10%	0%

Table 34 Loading scenarios

If these scenarios are considered the yearly fuel usage can be shown either per MW of installed power (Table 35) or directly for the reference ships (Table 36). Each of the scenarios is evaluated for the recuperated turbine with load following capability.

Cycle/ scenario	Recuperated cycle with load following (kg/MW year)
A	3.4
B	6.8
C	10.1
D	13.5

Table 35 Nuclear fuel usage per year per MW (delivered) power, shown for the scenarios

Vessel/ Scenario	Bulker (kg/year)	Tanker (kg/year)	Offshore (kg/year)	Container (kg/year)
A	64	102	136	170
B	136	204	272	340
C	202	303	404	505
D	270	405	540	675

Table 36 Nuclear fuel usage per year, shown for the concept vessels, and each scenario

Table 36 shows that the mass of fuel consumed yearly by the nuclear-powered vessels is very limited, even for the larger vessels. This low fuel consumption contributes to the vessels significant operational range and the long refueling interval. This interval depends on the reactors fuel load and the refueling concept but can be considered as between 18 months, up to the reactor's lifetime (25+ years).

8.3.2 Generated nuclear waste

The nuclear fuel waste can be determined, and it can be shown how much has to be stored as long-lived waste. Similarly, the amount of intermediate level waste, low-level waste, tails, and other waste products can also be determined for the complete lifetime of the vessel.

The fuel cycle that is used for the reactor is an important consideration, the conventional "once-through" cycle is considered as the baseline. The use of a closed cycle can reduce the high-level waste by a factor of 1.5 up to 3 [2]. This is a significant additional improvement to consider for the reduction of high-level waste.

The high-level waste or spent nuclear fuel is given in mass, while for storage the volume is of greater interest. High level waste is with the current reactors mostly the spent nuclear fuel inside the complete fuel assembly. These complete fuel assemblies are already not as dense as the fuel itself, subsequently they are also casked for long term storage. Casks are storage vessels built from materials such as concrete and steel that are used for: Transport, interim storage, and long-term storage of high-level nuclear waste [2]. A commercially used cask, designed for complete PWR assemblies is shown in Figure 82. The amount of different casks is numerous, with specific casks for different purposes. The cask shown in Figure 82 is not an exact fit for the following problem but is used to give an indication.

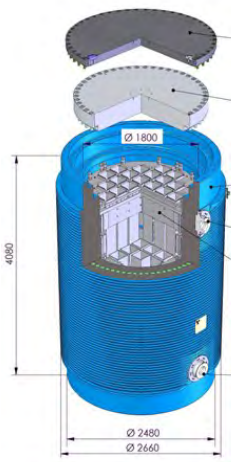


Figure 82 Nuclear fuel cask, in commercial use [194]

Considering that this cask holds 9 tons when filled, of which parts of the load would be fuel assembly as seen in Figure 82. Although specific casks would have to be used for items such as pebbles and waste fuel from the MSR. Considering that 9 tons of fuel assemblies fit inside a cask, and the cask is a cylinder of 2.66 meters in diameter and 4.08 meters in height, would mean that each ton of high-level waste requires 1.62m^3 of storage space. This is on the assumption that the weight of the fuel assemblies with fuel is identical to the weight of the stored fuel from a (V)HTR or molten salt reactor.

Besides the high-level waste there is also the production of tails, the waste product from enrichment. Depending on the fuel enrichment the amount of tails increases. This was already determined in the earlier Table 2 (from section 1.3.3), as 5% LEU produces 8.4 kg of tails per kg of fuel, and 20% LEU produces 37.75 kg of tails per kg of fuel.

Besides the high-level waste and the tails, low and intermediate level waste will be generated. This waste is given by volume and is between 50-100 m^3 per year for a shore-based plant of 1000MWe [195]. For the ship this amount will be significantly lower, considering its reduced amount of installed power. Scaling the shore-based reactor value (0.05-0.1 m^3 per MWe) gives the values shown in Table 37, which assumes that the low-level waste production is not significantly influenced by downtime of the reactor, as maintenance and occupancy are expected to continue at all times.

Vessel/waste production estimate	Bulker (m^3/year)	Tanker (m^3/year)	Offshore (m^3/year)	Container (m^3/year)
Low & intermediate level waste	1 - 2	1.5 - 3	2 - 4	2.5 - 5

Table 37 Low level and intermediate waste production per operating year for the reference vessels

The final consideration is that for decommissioning at the end of the lifetime there will be an additional amount of waste if the reactor is decommissioned. The reactor can theoretically be moved to another vessel instead of decommissioned, as reactor lifetime can exceed that of a ship. The question is if this move is practical, as large sections of the installation will have been irradiated at this point. Decommissioning of the reactor would generate additional low-level waste/intermediate level waste in the form of reactor parts, components in direct contact, along with parts of the shield that have to be stored.

Estimates of the waste of decommission can be given, based on the components that will be installed on the vessel. A high estimate is given where the reactor, the shield, and the components in direct contact with nuclear material all have to be stored at the end of the lifetime. The low estimate is based on the idea that the main components will have to be stored but the reactor shielding is mostly water and can be disposed after filtration and processing as also discussed in literature [195]. Based on the analytical estimate in section 7.3 it can be estimated, that 75% of the shields volume could be water indicating that only 25% of the shield would have to be stored. The reactor and the heat exchanger in contact with the coolant or salt are assumed to be casked and have a similar density as the spent fuel despite being of a lower-level waste category. The estimate is shown for the conceptual vessels in Table 38.

Vessel/decommissioning waste estimate	Bulker (20MWe, VHTR)	Tanker (30MWe, VHTR)	Offshore (40MWe, MSR)	Container (50MWe, MSR)
Lower estimate (m^3)	500	600	600	600
Higher estimate (m^3)	1100	1300	1400	1500

Table 38 Decommissioning waste, for the established reference ships

The aggregate waste production for the conceptual vessels for the entire lifetime is shown, considering that the reactor will be decommissioned at the end of the vessel’s lifetime (25 years), instead of re-used. The total is shown in Table 39.

Vessel/waste stream (25 years)	Bulker				Tanker				Offshore				Container			
Scenario	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Casked high level waste (closed cycle – once through cycle in m^3)	1 – 3	2 – 6	3 – 8	4 – 11	1 – 4	3 – 8	4 – 12	5 – 16	2 – 6	4 – 11	5 – 16	7 – 22	2 – 7	5 – 14	7 – 20	9 - 27
Tails produced 5-20% enrichment (m^3)	1 - 3	2 - 7	2 – 10	3 – 13	1 – 5	2 – 10	3 – 15	4 – 20	2 – 7	3 – 14	4 – 20	6 – 27	2 – 8	4 – 17	6 – 25	7 - 34

Vessel/waste stream	Bulker	Tanker	Offshore	Container
Low & intermediate level operational waste (low-high estimate in m^3)	30 - 50	40 - 80	50 - 100	60 - 130
Decommissioning waste (low-high estimate in m^3)	500 - 1100	600 – 1300	600 - 1400	600 - 1500

Vessel/waste stream	Bulker				Tanker				Offshore				Container			
Total (casked) high-level waste over lifetime (m^3)	1 – 3	2 – 6	3 – 8	4 – 11	1 – 4	3 – 8	4 – 12	5 – 16	2 – 6	4 – 11	5 – 16	7 – 22	2 – 7	5 – 14	7 – 20	9 - 27
Total low, intermediate level waste and tails over the lifetime (low-high m^3)	530 – 1150	530 – 1160	530 – 1160	530 – 1160	640 - 1390	640 - 1390	640 – 1400	640 – 1400	650 - 1510	650 - 1510	650 - 1520	660 - 1530	660 - 1640	660 - 1650	670 - 1660	670 - 1660

Table 39 Total reactor related waste over the lifetime of the reference vessels

The total waste stream of nuclear power can be generalized to two different streams (as seen in Table 39), first there is the stream of high-level waste that is significantly radioactive. This waste stream is significantly smaller than the other waste stream, however the waste in this waste stream is long-lived. The high-level waste must be stored securely for thousands of years, allowing for radioactive decay. The first decade of this period the waste is generally actively cooled, while afterwards it can be casked and stored long-term. This storage must be done in specially suited repositories [196]. The difference between operating on the closed cycle and the once through cycle is quite large, although even in the once-through cycle the high level remains in order of a few casks over the operational lifetime.

The secondary stream contains the material that is less radioactive, making it less complicated to handle and store. Low level waste can be stored in near surface repositories, for a period up to a few hundred years. Intermediate level waste is generally slightly more complicated to store, with a higher level of containment than can be achieved in near surface repositories. The period of storage is more than a few hundred years [197]. Tails can be considered the easiest to store, and they are generally stored in quarries and mines [198].

For added perspective the values for a conventional nuclear power plant are shown in Table 40, a conventional plant is shown as there is no historical information on lifetime waste for nuclear powered vessels available.

Waste type	Volume of waste (m^3)
Low and intermediate level waste	1250-2500
High level waste (spent fuel, casked)	1125-1375
Tails production (5% LEU assumed) [24]	330
Decommissioning waste	10000

Table 40 lifetime waste generation of a conventional 1000MWe reactor (for power generation), data from [195]

When comparing the vessel with the values for the full-size nuclear reactor from Table 40, waste production is comparable for the produced power. Low and intermediate level waste production is equal as the value for the vessel is derived from the same value. The conventional nuclear reactor however produces a larger amount of high-level waste relative to its power production, primarily due to a lower burnup, but also due to not operating on the closed fuel cycle.

8.3.3 Waste reduction when using thorium instead of uranium

The use of thorium, as discussed earlier in section 3.1.2, has many advantages over the uranium that is now commonly used. The proposed thorium cycle where the entire fuel cycle becomes fuelled with thorium and U233 (from breeding thorium) would result in a significant change in the overall waste generation of the nuclear fuel. Thorium is different from uranium as it can be fully used and does not require an enrichment process. Instead of enriching however, it has to be turned from fertile to fissile.

The total amount of thorium waste would depend on the burnup and efficiency of the reactor, however if these are considered to be similar to the uranium cycle this can be estimated to provide a significant reduction on two aspects: the long-lived wastes radioactivity as well as the amount of tails produced. Tails production would completely be stopped, which would reduce the overall waste stream by at most 2%. The benefit of reducing the radioactivity of the high-level waste is however quite large. Earlier in the report the figure (Figure 13) from the research by Hargraves and Moir [10] was shown, where the benefits of the use of the thorium cycle versus the uranium cycle are shown. The amount of radioactive material which remains radioactive for a long time is greatly reduced. Allowing for easier storage of most of the spent fuel, which is then in the order of magnitude of intermediate level waste (hundreds of years of storage instead of tens of thousands). A benefit is that only a very limited portion (0.1%) becomes plutonium [10], which when separated out can be reused for MOX fuel similar to that of the conventional uranium cycle. An additional benefit is that the stored waste would then have very limited value in the context of proliferation.

8.3.4 Harmful emissions over the lifetime

As already established earlier: the operation of a conventional nuclear power plant or a nuclear marine propulsion and power generation system will not produce harmful down the pipe emissions. The entire process is however not completely free of harmful emissions, due to emissions from reactor construction and the fuel production process. In a study by the IPCC [16] the CO_2 equivalent per kWh

[24] Based on the yearly fuel usage (30 tons per year [192]) a feed factor of 8.4 and a density of ≅19 t/m^3

was determined at 12 grams, to put this into perspective: this is similar to the emissions by wind power. This value is for conventional nuclear power plants and can be considered as pessimistic for nuclear power in the marine application. The marine application does not require the same size of construction effort (as it does not have a building) indicating that these emissions for purely the reactor are likely an overestimate. The values as calculated for the conceptual containership, in each scenario, are shown in Table 41.

Lifetime emissions /scenario	Container vessel emissions (kt CO_{2eq})
Scenario A	26.3
Scenario B	59.1
Scenario C	92.0
Scenario D	124.8

Table 41 Nuclear, CO_2 equivalent emissions over lifetime (shown for conceptual container vessel)

8.4 Economic assessment of nuclear-powered propulsion and power generation system

The economics of a nuclear-powered vessel are distinctly different when compared to the fossil fuel-based counterpart. In this assessment only the changes caused by the drivetrain are discussed, with the overall vessel design considered to be similar to conventional vessel design and not included in the price estimates.

8.4.1 Capital cost (CAPEX)

Capital cost of nuclear power has been mentioned before multiple times, as this is a considerable investment. Nuclear power price assessments general consider the location and the buildings to be built as well, this would be different for the nuclear-powered vessel. A cost breakdown of a detailed and recent estimate is available and is shown in Table 42.

Item	Percentage of total cost
Design, architecture, engineering, and licensing	5%
Project engineering, procurement, and construction management	7%
Construction and installation works:	
• Nuclear island	28%
• Conventional island	15%
• Balance of plant	18%
Site and development works	20%
Transportation	2%
Commissioning and first fuel loading	5%

Table 42 Breakdown of nuclear power plant construction cost, reproduced from [111]

With the cost per kW already discussed earlier in section 3.1.3 , two prices estimates were given: one lower estimate of 3782 $/kW which is a target for SMR developments. The other estimate is a slight increase of the current average price at 6922 $/kW. Both these estimates are for conventional power plants, similar to the breakdown shown in Table 42, which would indicate that a portion of this budget is used for site development and work that is not required for a vessel. This 20% can either be removed from the budget or altered as a way of relocating budget for the few components that are distinctly different from the shore-based installation. In the case of the marine propulsion and power generation system this would be the propulsion motors, gearboxes, emergency propulsion system, and the battery system. The margin of 20% for this is considered quite significant.

Besides the initial cost of the nuclear power system, it should also be considered that at the end of the operational lifetime the reactor has to be decommissioned. This decommissioning process is known to be rather costly for conventional nuclear power plants, with estimates based on historical decommissioning's in the order of 1 million dollars per MWe (2013 price estimate, for the complete plant and smaller sized reactors) [199] & [200]. The decommissioning costs of the commercial marine applications is not as well established, as there were only a few commercial applications, an estimate is however available for NS Savannah of 77 million dollars (price estimate from 2008) [201]. The naval application has seen many more successful decommissioning's, with an average cost of 23.6 million dollars (price estimate from 1990) for the complete inactivation, removal, and disposal of the submarine's reactor compartment at a naval shipyard [202].

Considering the values mentioned, an estimate of 2 million dollars per MWe is considered as an average between the lower costs for conventional plants and the higher costs for marine and naval applications.

The CAPEX estimates for each of the conceptual vessel's propulsion and power generation systems are shown in Table 43, including the decommissioning costs.

Vessel/price estimate	Bulker (20MW)	Tanker (30MW)	Offshore (40MW)	Container (50MW)
Lower estimate (M$)	116	173	231	289
Higher estimate (M$)	178	268	357	446

Table 43 CAPEX estimates nuclear power for concept vessels

8.4.2 Operational cost (OPEX)

The operational cost of the nuclear-powered concepts is comprised of two costs: the fuel and the associated cost of operation. The amount of fuel required can be determined from the earlier determined operation scenarios and fuel consumption, with the associated cost of operation a function of the total power generated.

The fuel cost of nuclear fuel can be calculated by determining: the raw material price, the amount of fuel required, and the cost to turn the raw material into usable nuclear fuel. In section 1.3.3 it was shown that the feed factor as well as the required SWU can be determined for enriching uranium. Using the earlier (in Table 2 of section 1.3.3) determined values and available prices it is then possible to determine the price of nuclear fuel per kg.

Item	Cost	Source
Uranium ($ per kg mined)	130 $	current[25] approximate spot price [203]
Conversion cost ($ per kg mined)	16 $	[111]
Enrichment cost ($ per SWU)	100 $	Average price in 2020 [204]
Fuel fabrication cost ($ per kg end product)	300 $	[111]

Table 44 Fuel fabrication process prices

The fuel fabrication cost is based on conventional fuel assemblies, there might be differences in price between conventional, (V)HTR, and MSR fuels although it is difficult to determine exactly what the cost will be, as both are not (yet) as common.

Using the values shown in Table 44 it is possible to determine the price of 5% LEU at 2560 $/kg, and 20% LEU at 10531 $/kg. Using the fuel price and the consumption in the scenarios it can then be

[25] April 2022

determined how much operational costs will be incurred for the fuel, again shown per year in Table 45. The full calculation is added in Appendix I: Nuclear fuel cost.

Vessel/ Scenario	Bulker		Tanker		Offshore		Container	
Enrichment (%)	5	20	5	20	5	20	5	20
A (M$/year)	0.16	0.67	0.26	1.07	0.35	1.43	0.43	1.79
B (M$/year)	0.35	1.43	0.52	2.15	0.70	2.86	0.87	3.58
C (M$/year)	0.52	2.13	0.77	3.19	1.03	4.25	1.29	5.32
D (M$/year)	0.69	2.84	1.04	4.27	1.38	5.69	1.73	7.11

Table 45 Yearly fuel cost for concept vessels and scenarios

Besides the fuel cost the nuclear power plant also has recurring maintenance and operation cost (including waste handling and storage), these are discussed in a recent report by the United States Energy Information Administration [57], showing specific values for SMR's (shown in Table 46). The cost are split as fixed cost (per kW installed) and cost that depend on the power delivered (per MWh). Again, these figures are intended for shore based SMR plants, but provide the closest match to the concept.

Maintenance cost/plant	Fixed operations and maintenance cost $/kW per year	Variable operations and maintenance cost $/MWh
Small Modular Reactor	95.48	3.02

Table 46 Fixed operation and variable operation and maintenance cost, data from [57]

8.4.3 Cost reduction when using thorium instead of uranium

Thorium as fuel is expected to be cheaper than uranium, this is because the full amount of thorium can be converted to fuel material. Normally with uranium there would be a waste stream addition of tails, which is caused by the requirements for the enrichment. As thorium requires no enrichment it does not suffer the same amount of wastage, with the raw material price accounting for nearly half the fuel cost this is a significant cost reduction. In 2019 thorium was approximately 72 $/kg [205], which at the time would be almost identical to the kilogram price of uranium [203]. Thorium would still have to be processed from its raw form to a usable fuel form, but without the significantly increased feed factor (reducing tails) and separative work (SWU). Finally, the usable thorium will have to be converted to usable fuel following a fuel fabrication process which is estimated to be similarly priced to the value shown in Table 44. Combining these estimates would indicate price reductions in the order of up to 80-90%, with the main issue that this would only create fertile material and not fissile material. The fertile material has to be used in a reactor where it can absorb neutrons and decay into fissile uranium. If it's assumed this process happens in the reactor it used in this would mean that the fuel cost remains low, if this has to be done separately it could add some additional cost. The raw fuel cost estimate to produce fertile thorium for fuel purposes is shown in Appendix I: Nuclear fuel cost.

8.4.4 Total cost of ownership

Using all the earlier derived information, it is possible to determine the total cost of ownership for the nuclear-powered marine propulsion and power generation system. The total cost depends on the scenario and the load expected, the estimate shows the total spread of cost of ownership for each of the conceptual vessels. With the low estimate being both a low loading scenario, as well as low CAPEX, and the high estimate being a high loading scenario and high CAPEX. This is shown visually in Figure 83 with the values used shown in Table 47.

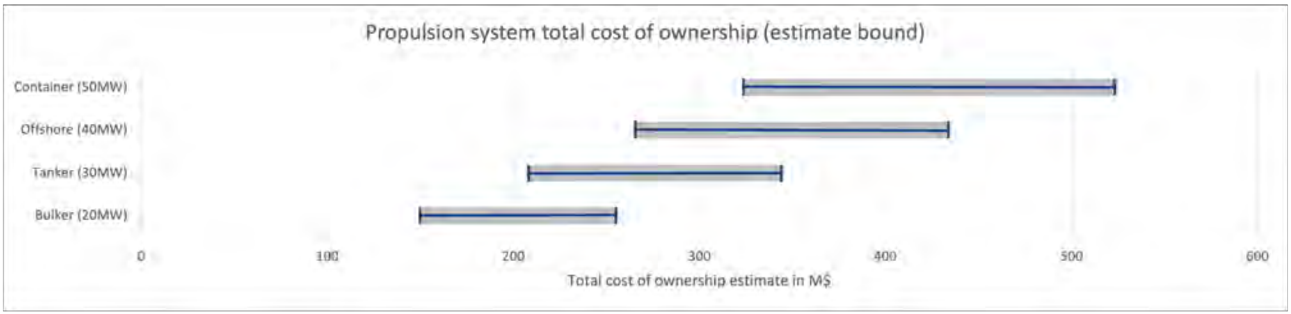


Figure 83 Nuclear marine propulsion and power generation system, total cost of ownership estimate bounds

Concept vessel/ total cost of ownership	Bulker (M$)	Tanker (M$)	Offshore (M$)	Container (M$)
Low estimate	149	207	265	323
High estimate	256	345	434	524

Table 47 Nuclear marine propulsion and power generation system, total cost of ownership, low and high estimate values

An interesting note on these total cost of ownerships is that the CAPEX cost of the installation are the biggest cost entry even in high loading scenarios over a lifetime of 25 years.

8.5 Size and weight assessment

For the conceptual vessels the overall size and weight of the complete plant can be estimated.

8.5.1 Volume estimate for complete layouts

With a combination of the earlier derived information (chapter 7) and commercially available components a volumetric estimate can be given for the complete layouts.

Component	Bulker (m^3)	Tanker (m^3)	Offshore (m^3)	Container (m^3)
Reactor	Inside shielding	Inside shielding	Inside shielding	Inside shielding
Shielding	1493	1798	2059	2282
Heat exchangers	77	117	34	42
Turbines	60	90	120	150
Generators *	36	53	71	89
Electromotors *	32	48	64	80
Gearboxes *	17	25	34	42
Switchboards*	44	44	44	44
Emergency power system	130	196	266	333
Batteries	87	130	173	217
Total	1976	2501	2865	3279

*Table 48 Volume of the nuclear-powered marine propulsion and power generation system for each of the conceptual vessels, * indicates that component data is elaborated in Appendix J: Volume and weight estimation of complete layout*

8.5.2 Weight estimate for complete layouts

With a combination of the earlier derived information (chapter 7) and commercially available components a weight estimate can be given for the complete layouts.

Component	Bulker (t)	Tanker (t)	Offshore (t)	Container (t)
Reactor	250	250	250	250
Shielding	2909	3393	3805	4160
Heat exchangers*	193	293	85	106
Turbines	30	45	60	75
Generators *	55	82	109	137
Electromotors *	49	74	98	123
Gearboxes *	31	47	63	78
Switchboards*	24	24	24	24
Emergency power supply	114	18	233	292
Batteries	28	43	57	72
Total	3683	4269	4784	5317

*Table 49 Weight of the nuclear-powered marine propulsion and power generation system for each of the conceptual vessels, * indicates that component data is elaborated in Appendix J: Volume and weight estimation of complete layout*

8.5.3 Visualization of size requirement

The discussed size requirement is shown visualized for the container vessel cross section in Figure 84. Here the entire power and propulsion system is located on the same location as where a conventional fuel-based engine and engine room would be fitted.

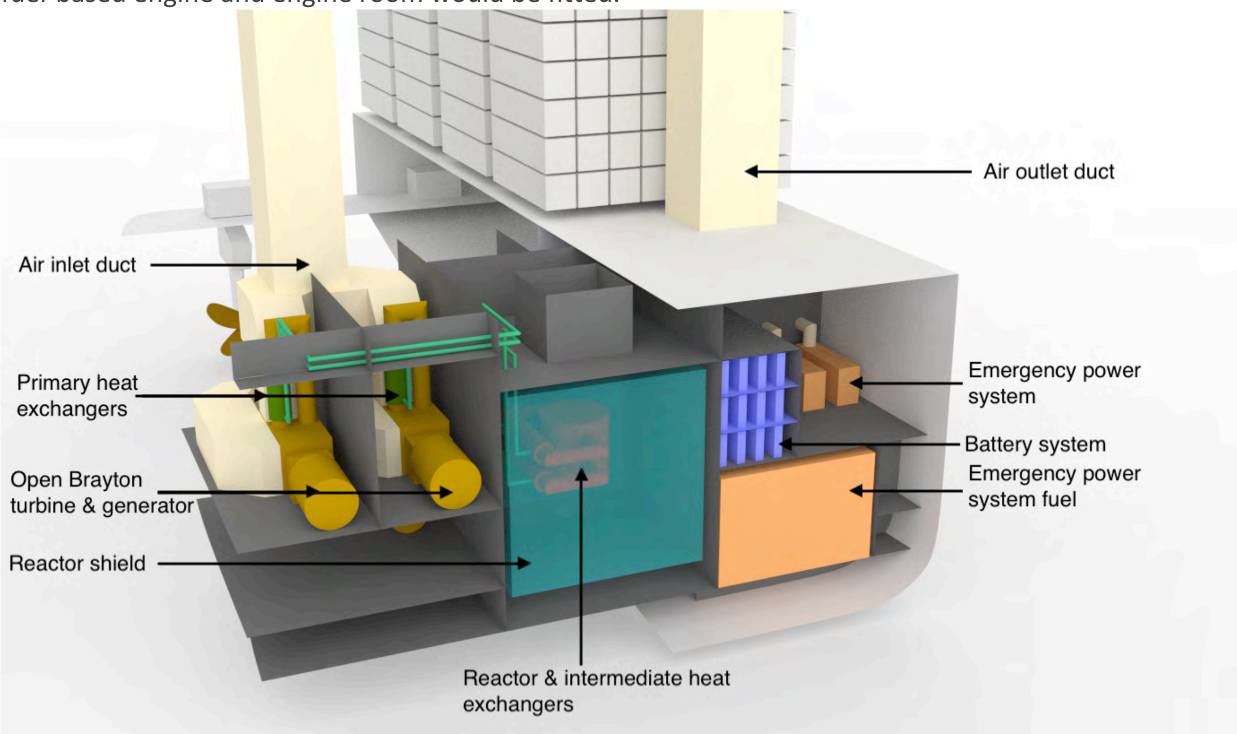


Figure 84 3d visualization of nuclear marine propulsion and power generation system in the conceptual container vessel

8.6 Load response and start-up

Load response capabilities can be shown for the vessels when evaluating the complete layout. The layouts are expected to operate using the earlier mentioned (section 7.4.3) open cycle Brayton turbine with heat rejection capabilities, alongside the use of batteries (as discussed in section 7.7.2). The load response strategy is shown in Figure 85 using a flowchart that reflects the rule-based nature of the load following.

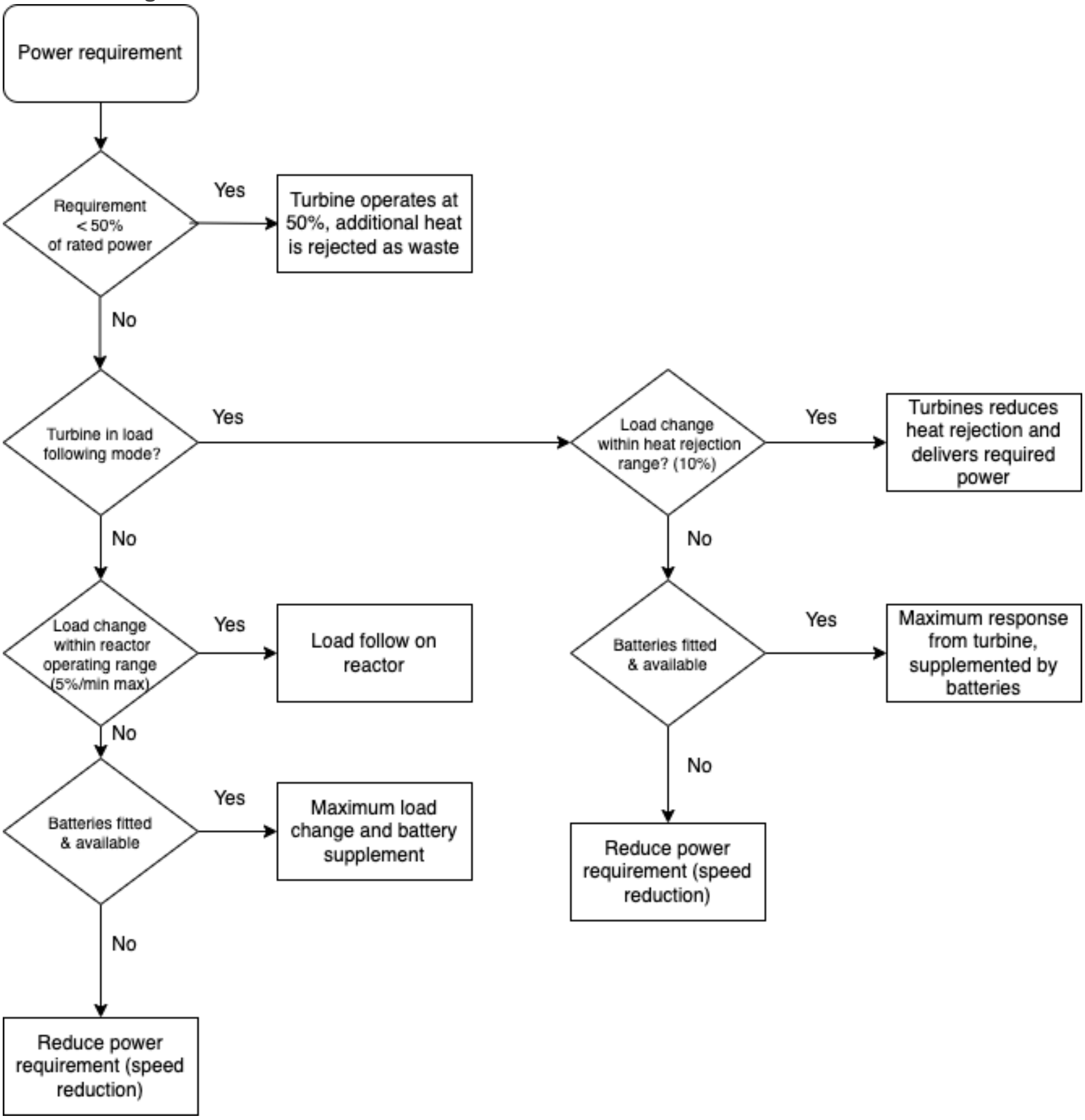


Figure 85 Load following layout with both a heat rejecting turbine and supplemental batteries, flowchart

To further visualize the capabilities of a vessel with this layout a varying load is simulated, in this case a generalized load is shown that shows a load requirement with increasing amplitude swings. This is shown for a load demand below 50% and a load demand closer to full power. The figures are shown split. In Figure 86 it is shown that below 50% load the demand can be met relatively easily (no discrepancies between demand and supplied power), although this occurs at a significant heat rejection. The heat rejection allows for operation far out of the conventional (earlier assumed 50% power lower limit) operating range of the nuclear reactor, this is at the cost of overall efficiency. A reactor with a wider operating range would see benefits here, as a greater operating range would reduce the amount of heat rejected. The use of heat rejection does allow for startup without additional difficulties, with the limiting factor being the startup time for the reactor to reach the assumed 50% thermal load (as from this point operations are possible with heat rejection).

Above 50% power demand the heat rejection is significantly less severe as is shown in Figure 87, The limited additional thermal loading (+10 %) is in this case also a less severe penalty to efficiency. The batteries are used only when the load following is exceeded, showing that the battery capacity is only used marginally for this load case.

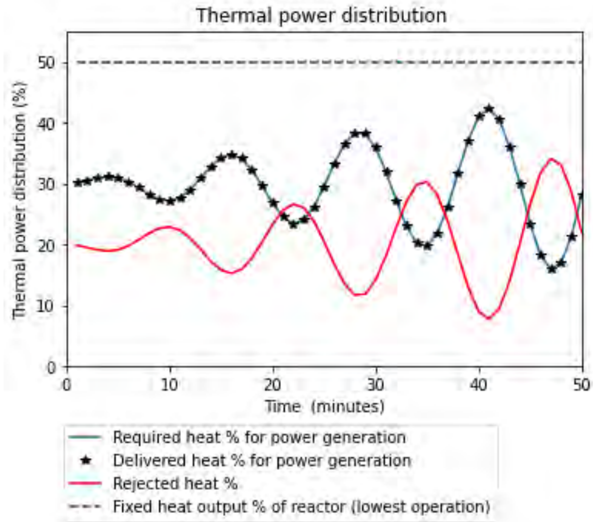


Figure 86 System, thermal power distribution, shown for variable load below 50%

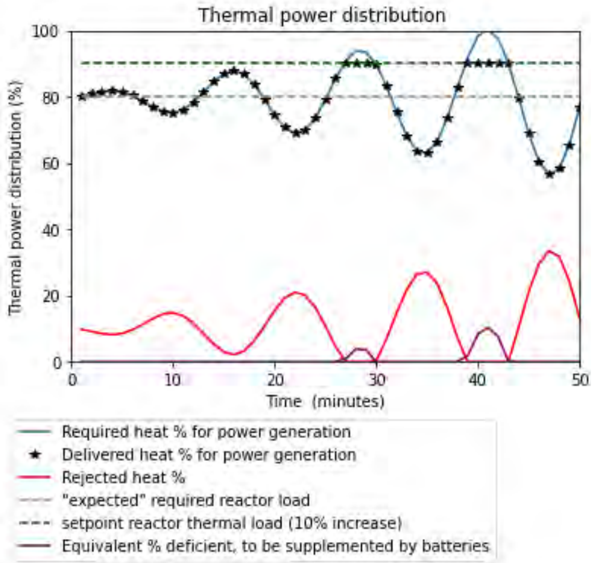


Figure 87 System, thermal power distribution, shown for variable load above 50%

Further optimalization regarding the distribution between load rejection and batteries for different load profiles would be beneficial, with significant reserve capacity in the shown case. The exact composition of battery capacity and reactor thermal load setpoint can be optimized on a vessel-by-vessel or load case basis.

From both Figure 86 & Figure 87 it can be concluded that the combination of heat rejection and batteries allow for a very capable load following plant. This load following capability however does come at the price of increased system complexity and reduced operating efficiency.

8.7 Chapter conclusion

In this chapter vessel types are grouped in a comparison of their dominant weights, highlighting that the application of nuclear power in the maritime environment will have some vessel type and size specific challenges. Four conceptual vessels were established that are used to relate the in chapter 7 derived parametric information to more relatable shipbuilding figures. The four vessels are evaluated on the established parameters of: Environmental impact, economics, size, weight, and load following. The nuclear reactor-based layout is distinctly different from conventional layouts in that its CO_{2eq} emissions are limited, but it does produce nuclear waste of different varieties. The economics are shown to be very frontloaded due to the high CAPEX cost associated with nuclear power, although the OPEX is low in comparison. The size and volume of the layouts is detailed on the component level and visualized. Finally, some details were discussed on the load response of the entire layout, which is shown to be very capable when making use of heat rejection and supplemental batteries.

9 COMPARISON OF REACTOR BASED SYSTEM AND CONVENTIONAL MARINE PROPULSION AND POWER GENERATION SYSTEM

This chapter covers the sub question: how does a nuclear propulsion and power generation system compare to a conventional marine propulsion system? Where the reactor-based propulsion systems as detailed for the conceptual vessels in the previous chapter are compared to their fuel-based counterparts for their respective: Environmental impact, economics, size, weight, and performance.

9.1 Environmental impact comparison

For environmental impact there are two distinctly different properties, solid waste, and emissions. The reactor produces mostly storable waste of different categories. Fossil fuels on the other hand produce waste that is not storable but goes into the atmosphere. The difference between the two can be shown in figures when comparing the conceptual vessel to its fuel based equal, operating in the same scenarios. From the scenarios the energy demand and subsequent emissions can be determined, as these are almost entirely a function of the fuel.

The emissions of the fuel can be split in the direct emissions from operations, generally referred to as tank-to-wake, and the emissions from the entire production and transport process, generally referred to as well-to-tank. The values change for the different types of fuel, two common types of fuel (VLSFO and MGO) the values are shown in Table 50. The values are in the commonly used grams CO_2 equivalent per kWh, which includes other greenhouse gasses besides CO_2 scaled to their equivalent contribution.

Fuel type/ emission	VLSFO (gram CO_{2eq} / kWh)	MGO (gram CO_{2eq} / kWh)
Well to tank	95	104
Tank to wake CO_2	568	550

Table 50 Emission data for commonly used fossil fuels, data from [206]

Using the available information, it is possible to determine the lifetime emissions for the fossil fuelled vessels in the different scenarios. It is also possible to show the emissions for nuclear power caused by the production process. This is shown in Table 51, with the values shown are for the conceptual containership, using VLSFO as fuel (figures for MGO are nearly identical).

Fuel-nuclear emissions /scenario	Fuel (kt CO_{2eq})	Nuclear (kt CO_{2eq})
Scenario A	1452.0	26.3
Scenario B	3266.9	59.1
Scenario C	5081.9	92.0
Scenario D	6896.9	124.8

Table 51 Fuel emissions over vessel lifetime, shown for conceptual container vessel, in kilotons

Alongside the emissions it is possible to show the solid waste stream of nuclear power (Table 52) as already discussed in section 8.3. Again, shown for the scenarios on the conceptual containership.

Waste type /scenario	High level waste (m^3)	Low, intermediate level waste & tails (m^3)
Scenario A	2 – 7	660 – 1650
Scenario B	5 – 14	660 – 1650
Scenario C	7 – 20	670 – 1660
Scenario D	9 - 27	670 – 1660

Table 52 Nuclear waste production over vessel lifetime, shown for conceptual container vessel, in m^3

The nuclear option reduces lifetime CO_2 equivalent emissions by more than 98%, alongside a total removal of other down the pipe (air pollution) emissions (SO_x, NO_x, particulate matter). This comes at the tradeoff that there is solid waste that must be stored. The evaluation of this tradeoff remains a statement of the values in this report, as there is no universally accepted way of comparing harmful emissions to solid nuclear waste.

9.2 CAPEX and OPEX comparison between nuclear and fuel

When comparing costs of the nuclear option against the conventional fuel-based option, first the CAPEX must be considered. Conventional fuel-based engines are significantly cheaper than the nuclear options (as discussed in section 8.4), with a common approximate for fuel-based being 400 $/kW installed. The estimate of 400 $/kW is almost a factor 10 difference with the lower of the nuclear power estimates. Considering some allowances, the estimate of 500 $/kW installed is used.

Secondly the OPEX must be considered, the operational cost of conventional vessels is for a large part comprised of the fuel cost. Fuel prices can vary wildly, with low fuel prices being 400 $/ton (approximate price of MGO and VLSFO from 2019 to 2021), and high fuel prices peaking at 1500 $/ton (March 2022) [207]. Additionally, CO_2 emissions can be taxed, adding additional cost. Currently this taxation is not yet in place, this could however add significant cost in the future, as the CO_2 emissions of combustion for a conventional fossil fuel are more than a factor three of the fuel mass consumed [208].

Besides the use of fuel, a conventional vessel also has operational costs strictly for its propulsion plant. Operational costs are based on the same source [57] as used earlier for the nuclear power plants variable and fixed maintenance cost, with the values shown in Table 53.

Maintenance cost/plant	Fixed operations and maintenance cost ($/kW per year)	Variable operations and maintenance cost ($/MWh)
Internal combustion engine	35.34	5.72

Table 53 Fixed operation and variable operation and maintenance cost for internal combustion engine in power generation, data from [57]

Considering the known costs, it is possible to show the total cost over the lifetime of the vessel, the figures shown are for the conceptual container vessel. With the nuclear operational cost having a distinction between low OPEX (5% enriched fuel + operations and maintenance) and the higher OPEX caused by more expensive fuel (20% enriched fuel + operations and maintenance). As well as a distinction for the low CAPEX estimate and the high CAPEX estimate as discussed in section 8.4.1. For the fuel-based system three values are chosen to reflect the broad range that represents the cost of fuel and possible upcoming taxation. Starting at the low estimate of 400 $/ton up to the high estimate of 1600 $/ton, with 1000 $/ton in between. The total price is of interest for the economic viability of the concept, indicating that the exact composition of this price (fuel price + CO_2 taxing) does not matter for the viability.

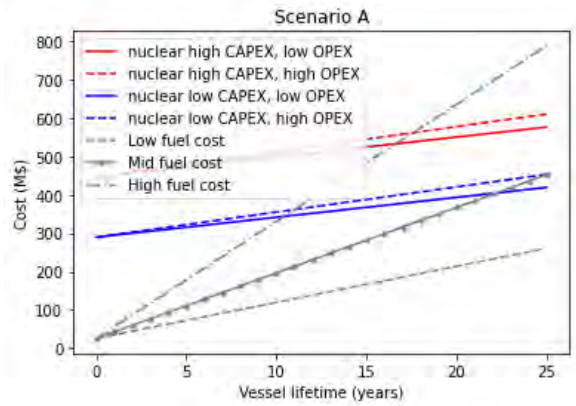


Figure 88 Scenario A, lifetime cost for container vessel

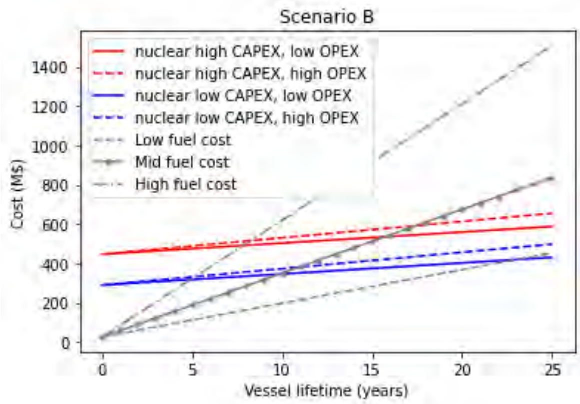


Figure 89 Scenario B, lifetime cost for container vessel

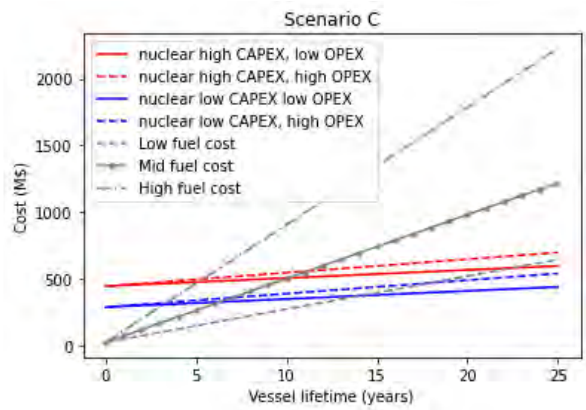


Figure 90 Scenario C, lifetime cost for container vessel

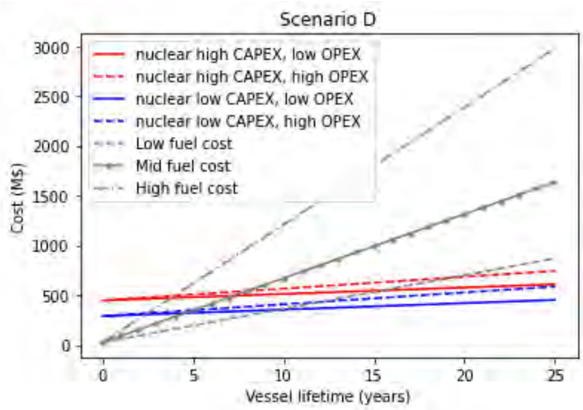


Figure 91 Scenario D, lifetime cost for container vessel

The figures shown are for the container vessel, with the other vessels shown in Appendix K: Graphs CAPEX – OPEX for conceptual vessels. Each of the graphs start at the CAPEX cost of the installation, where again the substantial difference between fuel and nuclear power is visible. For nuclear power the CAPEX is shown in two different lines, the high and the low estimate. In all scenarios the diesel fuel cost eventually exceeds the nuclear option, however the amount of years it takes to reach this breakeven point, and the required fuel costs are different. For scenario A, shown in Figure 88, breakeven happens relatively late at high fuel cost and low reactor pricing. Both scenario A, and scenario B (Figure 89) never reach a breakeven point if fuel costs are low over the lifetime and the reactor is bought at the more expensive high estimate. Both scenario C (Figure 90) and scenario D (Figure 91) have relatively quick breakeven points, with even the lowest fuel cost in some cases breaking even before the end of the lifetime. Indicating that high uptime and loading scenarios are favourable for nuclear power, similar to its non-marine application.

The high CAPEX of the nuclear power plant is shown to be the largest influence for the economic viability of the concept, indicating that cost reductions could be a substantial benefit. If the high CAPEX remains a concern leasing constructions can also be considered, however these are not discussed in this report. For the operational cost of the nuclear reactor, it can be seen that the nuclear fuel price is of limited influence for the total viability. Showing also that the reduction that could be achieved from the use of thorium as fuel is not of significant influence for the economic viability of the concept. The benefit of this low sensitivity to fuel price is the stability this gives compared to the fluctuations that are seen in fossil fuels.

The OPEX difference between nuclear and fossil fuelled is dominated by the difference in fuel cost. The nuclear option being significantly cheaper in overall OPEX despite having fixed operational costs that are approaching triple that of the fuel-based system.

9.3 Size and weight

As each of the conceptual vessels is based on reference vessels it is possible to determine their competitiveness in size and weight to their conventionally fuelled counterpart.

The weight and volume of the conventional marine propulsion and power generation system is estimated in Table 54 & Table 55. In these estimates the propulsion system as well as the auxiliary plant for power generation is considered. The fuel is shown based on the actual volume and weight of the fuel from these concept vessels. Each of the vessels (except for the offshore vessel) is shown with a main engine, auxiliary engines, and without power take-off shaft generators as these are not fitted on the actual vessels that are used for comparison. The offshore ship uses eight generator sets [186] for its complete propulsion and power generation system, which is also why a larger amount of electrical cabinets are estimated for this vessel.

Component	Bulker (m^3)	Tanker (m^3)	Offshore (m^3)	Container (m^3)
Fuel	5819	8600	3900	8500
Main engine	556	833	†440	1389
Auxiliary gen.	22	33		55
Electrical components	17	17	27	17
Total	6414	9483	4367	9961

*Table 54 Volume of the conventional fueled marine propulsion and power generation system for each of the conceptual vessels, * indicates that component data is elaborated in Appendix J: Volume and weight estimation of complete layout, † indicates that the offshore vessel uses generator sets instead of a single main engine.*

Component	Bulker (t)	Tanker (t)	Offshore (t)	Container (t)
Fuel	5842	8631	3510	8475
Main engine	769	1154	†348	1923
Auxiliary gen.	17	26		43
Electrical components	8	8	15	8
Total	6636	9819	3873	10449

*Table 55 Weight of the conventional fueled marine propulsion and power generation system for each of the conceptual vessels, * indicates that component data is elaborated in Appendix J: Volume and weight estimation of complete layout, † indicates that the offshore vessel uses generator sets instead of a main engine.*

These values allow for a direct comparison between the conventional and the nuclear option (that was estimated earlier in section 8.5), the differences are shown in Table 56. Indicating that the weight and volume is reduced in nearly every situation where the nuclear propulsion and power generation system is fitted. Only for the offshore vessel there is a weight addition instead of reduction, which can be attributed to the relatively low fuel load for its installed power and the relatively compact electric propulsion system. This could also have been expected earlier as this is the only one of the conceptual vessels that is close to the border region of the weight estimate (shown in the earlier Figure 78).

Component	Bulker	Tanker	Offshore	Container
Volume difference	-69%	-74%	-34%	-67%
Weight difference	-44%	-57%	**+24%**	-49%

Table 56 Volume and weight difference when comparing the nuclear option to the conventional option in %

Table 56 also confirms the earlier assumption where only shielding and fuel weight are compared (as was seen in section 8.1) as this shows to be quite representative for the complete system in a first estimate.

9.4 Performance of the vessel

A basic comparison of the vessel's performance can also be given, which is purely a comparison on the differences. As the vessels are expected to sail the same speed with the same installed power.

9.4.1 Load response

Conventional vessels operate differently than the discussed conceptual vessels. Their propulsion is handled using large 2-stroke diesel engines (except for the offshore vessel, where this is handled electrically), with the electrical grid generally handled using 4-stroke diesel generator sets. For load following this means that the electrical grid is very capable, capable of large power deviations in timespan of a few minutes [209]. For the main engine the loading capabilities are generally lower, with large loading differences quickly requiring 30 minutes to hours in time to attain [210].

The nuclear propulsion and power generation capabilities were shown in section 8.6, which are very capable. These capabilities are realized by the balance of plant, where the systems chosen to complement the reactor (the turbine, its layout, and battery system) are important to make the nuclear based propulsion and power generation plant equally or more capable than its fossil fuelled counterpart.

The requirements for load response are something that can differ on a vessel-by-vessel basis and is important to consider for designs that are made.

9.4.2 Range

The conventional vessels operating on fuel have fuel capacity for a few voyages, with fuel bunkering operations expected relatively often (week/month timescale). The nuclear vessels have significantly more operational range on a single fuelling, with refuelling intervals of years up to a single fuelling for the lifetime. The downside is that the nuclear refuelling operations are more time consuming and more complex.

9.5 Chapter conclusion

When comparing the nuclear-powered concept vessels to their conventionally fuelled counterparts there are significant differences. The most important difference is the potential for a 98% CO_{2eq} emission reduction over the lifecycle, with the only emissions of nuclear power stemming from the fuel and production process. The main trade-off being the nuclear waste that is produced, with both streams shown in a comparison. Most of the waste of nuclear power is of the low and intermediate level variety. The high-level waste, or "spent nuclear fuel" is only a small portion of the total waste stream. This total amount of high-level waste can be further reduced in both quantity and longevity using methods such as the closed fuel cycle and more importantly the use of thorium.

The economics of nuclear power are shown, showing the estimates for the capital cost (CAPEX) and operational costs (OPEX) over the lifetime. Breakeven points can be achieved against conventional fuel in different operating scenarios, although the optimal economic scenarios are seen for vessels that are under power for a significant portion of their lifetime. The relatively high CAPEX of nuclear power is shown, with cost reductions being very favourable for economic viability.

The size and weight of the reference vessels were compared, indicating that both substantial volume and weight reductions are possible for vessels, although this depends on the type and installation size of the vessel.

Finally, the comparison is made regarding performance and operations of the vessel, where it is seen that in a like-for-like replacement the vessel brings some operational improvements with regard to range and load response.

10 CONCLUSION

To answer the main research question: “what is the potential of nuclear reactor-based propulsion systems for the decarbonisation of shipping?” a variety of different aspects have been discussed.

Nuclear energy has seen widescale adoption for commercial power generation and naval purposes, however only a limited number of commercial ships have used the technology. Research into the subject has been ongoing, with most of it focused on the older PWR design. Most of this research has been on relatively simple shipboard applications, despite many vessels offering significantly more challenging situations and loading conditions.

A significant number of developments have been ongoing in the past decades, of which many are of interest to a marine application: Generation IV reactors for their increased safety, proliferation resistance and higher burnup. The thorium cycle for securing the future fuel supply and reduction of long-lived waste. Small modular reactors for their size and cost reduction. These developments are however predominantly focused on land-based applications, with the marine application receiving significantly less interest in research. This is a concern as the nuclear reactors generally are suited for scenarios of high loading and only moderate load following, which does not perfectly correspond to the requirements of vessels.

Nuclear power is a strictly regulated matter, with regulations for new reactors already extensive for conventional land-based reactors. The rules and regulations for marine applications are significantly outdated and fragmented, which combined with the international character of the maritime industry makes this one of the largest hurdles in the successful deployment of nuclear power for the marine application. These tie into the societal concerns with nuclear power, such as the waste problem and the safety perception, which have already influenced the historic applications of marine nuclear power and thus should also be addressed adequately for new applications to be successful.

For the marine application two reactor types were identified as promising: the (very) high temperature gas-cooled reactor, for near-term deployments due to its high TRL, passive safety measures and high achievable burnup and temperatures. For the long-term the molten salt reactor (which is currently at a lower TRL level) is identified as most promising, as it offers even better burnup, more possibilities for the fuel cycles and the option to use the thorium cycle. Multiple methods were discussed for converting the reactors thermal power to mechanical/electrical energy. Although currently the highest efficiencies are possible with steam cycles, the open Brayton cycle is selected. The open Brayton cycle is less efficient but offers reduced complexity and the benefit of greater load response when operated in an arrangement with heat rejection capabilities. The integration in the overall ship layout then follows the conventional options for marine propulsion systems, with the selected option being an all electrically driven layout for its favourable redundancy and the option to implement battery power.

Using four concept vessels of different installed powers the layouts were evaluated, considering the established important aspects: Lifetime environmental impact, economic viability, size, weight, and load response. These were assessed and compared to the conventional fuel-based counterpart. Showing that the system is suitable for larger vessels (due to the size constraint if no significant redesign is desired) operating at relatively high duty (attractive for economic feasibility). The environmental impact is a 98% CO_2 equivalent reduction over the lifetime, which comes as a trade-off to the produced nuclear waste stream. For this waste stream multiple reduction options are available in both amount and longevity (closed cycle and thorium cycle). The size and weight of a nuclear plant is vessel dependent but can generally be smaller if compared to the fossil fuelled conventional plant including fuel. The load response of the layout can be made very capable by selecting suitable balance of plant components, allowing the capabilities to be equal to or surpass those of conventional fuelled vessels.

Considering the significant CO_2 reduction achieved by the conceptual vessels, it can be concluded that nuclear power can be a significant contribution to the emission reduction goals of the maritime sector. Other benefits such as size, weight and increased range are a bonus, while other issues such as load response and cost are shown to be manageable.

11 RECOMMENDATIONS

This report touched on a significant amount of topics were further detail could be added, some of considerable interest are mentioned in the recommendations.

11.1 Environmentally related

Perhaps the most important recommendation is to start considering how CO_2 and its equivalents can be compared to the waste generated by nuclear power. In this report values are shown, with large CO_{2eq} reductions, that come at the trade-off of nuclear waste production. Establishing an acceptable way of comparing these would allow for a more objective comparison.

A second environmentally related recommendation is further and more detailed research on the total lifecycle of nuclear power. In this report the lifetime aggregate waste of power production together with decommissioning is estimated. Further detail and refinement could be added, as well as evaluating additional concerns such as additional infrastructure requirements and further refined decommissioning costs.

11.2 Nuclear power related

On the topic of nuclear reactors, the two most important developments that should be considered for the application are an improved operating range for the reactor and cost reduction. For the operating range 50% is used as the conservative estimate in this report, however improvements and greater operating range and load response is theoretically possible (especially for the MSR). Evaluating the operating range and response speed of the reactor further could open the door for increased part load efficiencies and significantly easier load response handling.

The other developments that were shown in this report, such as the interest in thorium and higher burnup, are not exclusive interests to the marine application but very promising developments overall. The maritime industry should consider “tagging along” in these developments and seeing where solutions are available that can be applied. This is generally best practise as it makes sense to prove the functionality and reliability of a reactor on shore before applying it at sea. Following this it should also be considered to re-evaluate assumptions made in this report when new developments and information becomes available.

For the shielding, the shield estimate in this report is an initial and unrefined estimate. The estimate is based on a selection of assumptions, such as materials, reactor power density and full-time ship occupancy. Further evaluation of more detailed concepts with more detailed parameters for specific reactors would be beneficial. First to validate the initial estimate, and secondly to improve the accuracy of the estimate.

For the use of heat exchangers multiple types and options were shown, further optimalization regarding different operating media, mass flows, temperatures, and pressure losses is however still recommended.

In this report the cost breakdown and cost of ownership of a nuclear reactor for different scenarios is shown, these are based on the cost breakdown for a conventional nuclear plant. More detailed marine design considerations, new fuel cost calculations, and generally further refined estimates would be valuable additions in this regard. In a similar sense different financing constructions can be established as a way of dealing with the relatively high CAPEX cost of nuclear power.

11.3 Marine engineering related

Further research is required into the open Brayton cycle and its load following capabilities with significant heat rejection. Considerations such as efficiencies with coolers, possibilities for increased recuperation efficiency and increased detail in turbine design are of interest.

Tying into the previous: Improving the distribution of battery systems in combination with heat rejection for turbines is something to consider, further research can define these requirements and installation sizes on a vessel type basis instead of a general application. Although this will always be a topic dependent on many factors that should be considered in detail for each individual application.

The final and largest topic for further research is a complete redesign of the vessel, in this thesis the viability on multiple aspects was shown when a reactor based marine propulsion and power generation plant is added to a "conventional" ship design. Redesigning the ship could mean reconsidering parameters such as vessel speed and allow for more space efficient placement of the reactor and balance of plant components. Besides this it is also possible to completely reconsider the lifetime of the vessel, as in the like for like replacement case the conventional 25 years of vessel lifetime is considered. However, as reactor lifetimes can commonly be 40 years, the overall vessel lifecycle could be completely reconsidered as well.

11.4 Legislation related

The legislation was identified as one of the largest hurdles for nuclear power in the marine application. For a successful application it is important to at least update the outdated legislation, to also encompass the new reactor types, although preferably completely renew it. Nuclear power for the marine application is something that has to be addressed in both the international environment as well as at the national level, especially due to the national involvement in nuclear power production and waste handling. A renewed legislation programme could also aid in removing some of the uncertainties on the implementation for all involved stakeholders (including but not limited to: Equipment manufacturers, ship designers & builders, classification societies & nuclear regulators, shipowners & operators, ports & local governments). Some classification societies have picked up nuclear power as a development already, however further involvement on all levels of legislation would be required.

BIBLIOGRAPHY

[1] Physicsbuzz, “Podcast NS savannah,” 05 2014. [Online]. Available: http://physicsbuzz.physicscentral.com/2014/05/podcast-ns-savannah.html.

[2] E. De Sanctis, S. Monti and M. Ripani, Energy from nuclear fission, An introduction, 1st ed., Springer International publishing, 2016.

[3] J. Gilleland and C. Ahlfeld, “Novel Reactor Designs to Burn Non-Fissile Fuels,” in *Proceedings of ICAPP ‘08*, Anaheim, 2008.

[4] J. Lamarsh and A. J. Baratta, Introduction to nuclear engineering, 3rd edition, international edition ed., Essex: Pearson education limited, 2014.

[5] D. Leblanc, “Molten salt reactors: A new beginning for an old idea,” *Nuclear engineering and design,* p. 6, 2010.

[6] US Nuclear Regulatory Commission, *Fuel rod,* 2016.

[7] J. Powers, “Fully Ceramic Microencapsulated Fuel in FHRs: A Preliminary Reactor Physics Assessment,” Oak Ridge National Laboratory, Oak Ridge, 2014.

[8] N. Tsoulfanidis, The nuclear fuel cycle, Illinois: American Nuclear society, 2013.

[9] IAEA, “Status and advances in MOX fuel technology,” *Technical reports series no. 45,* 2003.

[10] R. Hargraves and R. Moir, “Liquid Fluoride Thorium Reactors: An old idea in nuclear power gets reexamined,” *American Scientist,* pp. 304-313, July-august 2010.

[11] IAEA, “Nuclear Power Proves its Vital Role as an Adaptable, Reliable Supplier of Electricity during COVID-19,” 21 June 2021. [Online]. Available: https://www.iaea.org/newscenter/news/nuclear-power-proves-its-vital-role-as-an-adaptable-reliable-supplier-of-electricity-during-covid-19.

[12] N. J. Carron, An Introduction to the Passage of Energetic Particles through Matter, CRC press, 2006.

[13] P. Tsvetkov, A. E. Waltar and D. Todd, “Introductory Design Considerations,” in *Fast spectrum reactors*, Springer, 2012, pp. 23-38.

[14] IAEA, “PRIS (Power Reactor Information System),” IAEA, [Online]. Available: https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByType.aspx. [Accessed 7 Feb 2022].

[15] I. Pioro, “Introduction: Generation IV International Forum,” in *Handbook of generation IV nuclear reactors*, Woodhead publishing, 2016, pp. 37-54.

[16] S. Schlömer, T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith and R. Wiser, “Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,” Cambridge University Press, Cambridge, 2014.

[17] IAEA, Non-baseload operation in nuclear power plants: load following and frequency control modes of flexible operations, Vienna: IAEA publishing section, 2018.

[18] K. Kosowski and F. Diercks, “Quo Vadis, Grid Stability? Challenges Increase as Generation Portfolio Changes,” *Major trends in energy policy and nuclear power,* pp. 16-26, march 2021.

[19] Nuclear Energy Agency, “Technical and Economic Aspects of Load Following with Nuclear Power Plants,” OECD, Paris, 2011.

[20] IAEA, “Nuclear power plant outage optimisation strategy,” International Atomic Energy Agency, Vienna, 2002.

[21] IAEA, “Indicators for management of planned outages in nuclear power plants,” International Atomic Energy agency, Vienna, 2006.

[22] M. A. Rosen, “Nuclear Energy: Non-Electric Applications,” *European Journal of Sustainable Development Research,* vol. 5(1), 2021.

[23] Generation IV international forum (GIF), “Technology Roadmap Update for Generation IV Nuclear Energy Systems,” OECD Nuclear Energy Agency, Paris, 2014.

[24] M. Ragheb, “Nuclear naval propulsion,” in *Nuclear Power - Deployment, Operation and Sustainability*, Intech open, 2011.

[25] A. Zrodnikov, G. Toshinsky, O. Komlev, V. Stepanov and N. Klimov, “SVBR-100 module-type fast reactor of the IV generation for regional power industry,” *Journal of nuclear materials 415,* p. 8, 2011.

[26] M. Rawool-Sullivan, P. D. Moskowitz and L. N. Shelenkova, “Technical and Proliferation-Related Aspects of the

Dismantlement of Russian Alfa-Class Nuclear Submarines," *The non proliferation review,* pp. 161-171, 2002.

[27] L. O. Freire and D. A. de Andrade, "Historic survey on nuclear merchant ships," *Nuclear engineering and Design,* pp. 176-186, 2015.

[28] Rosatom - Atomflot, "atomnye-ledokoly," [Online]. Available: http://rosatomflot.ru/flot/atomnye-ledokoly/.

[29] E. Schröder, W. Jager and H. Schafstall, "Nuclear merchant ship propulsion," in *International conference on nuclear power and its fuel cycle*, Salzburg, 1977.

[30] United states general accounting office, "Cost of operating the nuclear merchant ship Savannah," Maritime administration, department of commerce, Washington, 1970.

[31] H. Schøyen and K. Steger-Jensen, "Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications," *Journal of cleaner production,* pp. 152-160, 2017.

[32] J. Carlton, R. Smart and V. Jenkin, "The nuclear propulsion of merchant ships: Aspects of engineering, science and technology," *Journal of Marine Engineering & Technology,* pp. 47-59, 2011.

[33] J. Carlton, R. Smart and V. Jenkins, "The Nuclear Propulsion of Merchant Ships: Aspects of Risk and Regulation," in *Lloyds Register Technology Days 2010*, London, 2010.

[34] S. Hirdaris, Y. Cheng, P. Shallcross, J. Bonafoux, D. Carlson, B. Prince and G. Sarris, "Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion," *Ocean engineering,* pp. 101-130, 2014.

[35] J. Jacobs, "Nuclear short sea shipping," Delft, 2007.

[36] J. A. Vergara and C. B. McKesson, "Nuclear propulsion in high-performance cargo vessels," *Marine Technology,* pp. 1-11, 2002.

[37] Institution of Mechanical Engineers, "Public perceptions: Nuclear power," Institution of Mechanical Engineers, London, 2020.

[38] H. Ritchie and M. Roser, "Energy," 2020. [Online]. Available: https://ourworldindata.org/nuclear-energy#citation.

[39] United States nuclear regulatory commission, "International Nuclear and Radiological Event Scale (about emergency preparedness)," 28 august 2017. [Online]. Available: https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/emerg-classification/event-scale.html.

[40] International Nuclear Safety Advisory Group, "DEFENCE IN DEPTH IN NUCLEAR SAFETY," International Atomic Energy Agency (IAEA), Vienna, 1996.

[41] IAEA, "IAEA Safety glossary," International Atomic Energy Agency, Publishing section, Vienna, 2019.

[42] CORDEL Working group of the World Nuclear Association, "Facilitating International Licensing of Small Modular Reactors," World Nuclear Association, London, 2015.

[43] Licensing & Permitting Task Force of the World Nuclear Association, "Licensing and project development of new nuclear plants," World Nuclear Association, London, 2015.

[44] United states department of energy, "Energy Research Abstracts: Volume 4, Issues 1-9381," Technical Information Center, U.S. Department of Energy, Springfield, 1979.

[45] IMO, *Resolution A.491(XII),* 1981.

[46] United Nations, *United nations convention on the law of the sea,* Montego Bay, 1982.

[47] IAEA & IMCO, "Safety Considerations in the Use of Ports and Approaches by Nuclear Merchant Ships," International Atomic Energy Agency, Vienna, 1968.

[48] Australian Radiation Protection and Nuclear Safety Agency, "Nuclear powered warships visit planning," [Online]. Available: https://www.arpansa.gov.au/research/radiation-emergency-preparedness-and-response/visits-by-nuclear-powered-warships.

[49] International Maritime Organization, "International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on board Ships (INF Code)," [Online]. Available: https://www.imo.org/en/OurWork/Safety/Pages/INF-Code.aspx.

[50] IAEA, "Applicability of Design Safety Requirements to Small Modular Reactor Technologies Intended for Near Term Deployment," IAEA publishing section, Vienna, 2020.

[51] A. Papanikolaou, Risk-based ship design, methods tools and applications, Berlin Heidelberg: Springer, 2009.

[52] IAEA, Nuclear fuel cycle and materials section, "Thorium fuel cycle — Potential benefits and challenges," International Atomic Energy Agency, Vienna, 2005.

[53] E. v. Vaerenbergh, "China shows us the path to the nuclear future," 12 October 2021. [Online]. Available: https://www.europeanscientist.com/en/features/china-shows-us-the-path-to-the-nuclear-future/.

[54] L. Boldon and P. Sabharwall, "The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy AllianceINL/EXT-14-32616Revision 0Small Modular Reactor: First-of-a-Kind(FOAK) and Nth-of-a-Kind (NOAK) Economic Analysis," Idaho National Laboratory, Idaho falls, 2014.

[55] IAEA, Advances in Small Modular Reactor Technology Developments, Vienna: IAEA, 2020.

[56] Energy Options Network, "What will advanced nuclear plants cost," EIRP (Energy Information Reform Project), Arlington, 2017.

[57] U.S. Energy Information Administration, "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2021," U.S. Energy Information Administration, 2021.

[58] IAEA, "ARIS (Advanced Reactor Information System)," [Online]. Available: https://aris.iaea.org/. [Accessed 7 Feb 2022].

[59] European Commission, "Horizon 2020 - Work programme 2014-2015 Annex G," European Commission, 2014.

[60] IAEA, "Management of high enriched uranium for peaceful purposes: Status and trends," Nuclear Fuel Cycle Materials Section, Vienna, 2005.

[61] IAEA, "Passive safety systems and natural circulation in water cooled nuclear reactor power plants," International Atomic Energy Agency publishing section, Vienna, 2009.

[62] L. X. Yan, "Very high-temperature reactor," in *Handbook of generation IV nuclear reactors*, Duxford, Woodhead publishing, 2016.

[63] A. Ougouag, J. Ortensi and H. Hiruta, "PBR, Analysis of an Earthquake-Initiated-Transient in a," in *International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009)*, Lagrange park, 2009.

[64] F. Wols, J. Kloosterman, D. Lathouwers and T. van der Hagen, "Conceptual design of a passively safe thorium breeder Pebble Bed Reactor," *Annals of Nuclear energy,* pp. 542-558, 2015.

[65] Generation-IV International Forum Risk and Safety Working Group, "Very high Temperature Reactor (VHTR)," Paris, 2015.

[66] F. Reitsma, "The Pebble Bed Modular Reactor Layout and Neutronics Design of the Equilibrium Cycle," in *PHYSOR 2004 -The physics of fuel cycles and advanced nuclear systems: Global Developments*, Lagrange park, 2004.

[67] L. X. Yan, Sato, T. Y. Hiroyuki, K. Kunitomio and R. Hino, "Evaluation of high temperature gas reactor for demanding cogeneration load follow," *Journal of Nuclear Science and Technology,* pp. 121-131, 2012.

[68] T. J. Pederson, "Copenhagen Atomics waste burner," in *Molten Salt Reactors and Thorium Energy*, Sawston, Woodhead publishing, 2017, pp. 599-607.

[69] R. L. Murray and K. E. Holbert, Nuclear energy, Elsevier, 2015.

[70] P. Tsvetkov, A. Waltar and A. Todd, "Sustainable Development of Nuclear Energy and the Role of Fast Spectrum Reactors," in *Fast spectrum reactors*, Springer, 2012, pp. 3-22.

[71] IAEA, "Status of Fast Reactor Research and Technology Development," International Atomic Energy Agency (IAEA), Vienna, 2012.

[72] J. Sackett, "General Safety Considerations," in *Fast spectrum reactors*, Springer, 2012, pp. 417-432.

[73] C. Gao, P. Wu, W. Liu, Y. Ma and J. Shan, "Development of a bypass control strategy for supercritical CO2 Brayton cycle cooled reactor system under load-following operation," *Annals of nuclear energy,* 2021.

[74] C. Smith and L. Cinotti, "Lead-cooled fast reactor," in *Handbook of Generation IV Nuclear Reactors*, Woodhead publishing, 2016, pp. 119-155.

[75] H. Oshima and S. Kubo, "Sodium-cooled fast reactor," in *Handbook of Generation IV Nuclear Reactors*, Woodhead publishing, 2016, pp. 97-118.

[76] P. Tsvetkov, "Gas-cooled reactors," in *Handbook of Generation IV Nuclear Reactors*, Woodhead publishing, 2016, pp. 91-96.

[77] K. Weaver, "Gas-cooled fast reactors," in *Fast spectrum reactors*, Springer, 2012, pp. 489-511.

[78] J. Engel, W. Grimes, B. H.F., M. E.H., D. J.F. and R. W.A., "Conceptual design characteristics of a denatured molten-salt reactor with once-through fueling," Oak ridge national laboratory, Oak ridge, 1980.

[79] Core Power, "Maritime applications," [Online]. Available: https://corepower.energy/maritime-applications. [Accessed 9 Feb 2022].

[80] Seaborg Technologies, "The reactor," [Online]. Available: https://www.seaborg.com/the-reactor. [Accessed 09 Feb 2022].

[81] J. Serp, M. Allibert, O. Benes, S. Delpech, O. Feynberg, V. Ghetta, D. H. D. Heuer, V. Ignatiev, K. J.L., L. Luzzi, E. Merle-Lucotte, J. Uhlír, R. Yoshioka and D. Zhimin, "The molten salt reactor (MSR) in generation IV: Overview

andperspectives," *Progress in Nuclear Energy,* no. 77, pp. 308-319, 2014.

[82] R. Yoshioka and M. Kinoshita, "Liquid fuel, thermal neutron spectrum reactors," in *Molten Salt Reactors and Thorium Energy*, Woodhead Publishing, 2017, pp. 281-373.

[83] A. Laureau, M. Aufioro, P. Rubiolo, E. Merle-Lucote and D. Heuer, "COUPLED NEUTRONICS AND THERMAL-HYDRAULICS TRANSIENT CALCULATIONS BASED ON A FISSION MATRIX APPROACH: APPLICATION TO THE MOLTEN SALT FAST REACTOR," in *Joint international conference on mathematics and computation*, Nashville, 2015.

[84] J. Uhlír, "Chemical processing of liquid fuel," in *Molten Salt Reactors and Thorium Energy*, Sawston, Woodhead publishing, 2017, pp. 209-230.

[85] R. Geertsma, R. Negenborn, K. Visser and J. Hopman, "Design and control of hybrid power and propulsion systems for smart ships: A review of developments," *Applied Energy,* pp. 30-54, 2017.

[86] L. van Biert, M. Godjevac, K. Visser and P. Aravind, "A review of fuel cell systems for maritime applications," *Journal of power sources,* no. 327, pp. 345-364, 2016.

[87] H. Klein Woud and D. Stapersma, Design of propulsion and electric power generation systems, Witherby publishing group ltd, 2019.

[88] E. K. Dedes, D. A. Hudson and S. R. Turnock, "Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping," *Energy policy,* pp. 204-218, 2012.

[89] A. Ritari, J. Huotari, J. Halme and K. Tammi, "Hybrid electric topology for short sea ships with high auxiliary power availability requirement," *Energy,* 2020.

[90] T. Lauvdal, "Power management systems with fast acting load reduction for DP vessels," in *Dynamic positioning conference*, 2000.

[91] IMO, "RESOLUTION MEPC.203(62)," IMO, London, 2011.

[92] A. A. Mclean, "A simulation approach to the evaluation of operational costs and performance in liner shipping operations," in *Proceedings of the 2008 Winter Simulation Conference*, Miami, 2008.

[93] T. E. Notteboom and B. Vernimmen, "The effect of high fuel cost on liner service configuration in container shipping," *Journal of Transport Geography,* no. 17, pp. 325-337, 2009.

[94] T. Tanuma, "Introduction to steam turbines for power plants," in *Advances in Steam Turbines for Modern Power Plants*, Woodhead publishing, 2017, pp. 3-9.

[95] S. McBirnie, Marine, Steam Engines, and Turbines, Boston: Butterworth publishers, 1980.

[96] X. Yan and L. Lidsky, "Design of closed-cycle helium turbine nuclear power plants," in *International Gas Turbine and Aeroengine Congress and Exposition*, Cincinatti, 1993.

[97] B. Zohuri, "Advanced Nuclear Open Air-Brayton Cycles for Highly Efficient Power Conversion," in *Molten salt reactors and integrated molten salt reactors*, Academic Press, 2021, pp. 171-196.

[98] S. T. Revankar, "Chapter four - Nuclear hydrogen production," in *Storage and hybridization of nuclear energy*, Academic press, 2019, pp. 49-117.

[99] A. Ohji and M. Haraguchi, "Steam turbine cycles and cycle 2 design optimization: the Rankine cycle, thermal power cycles, and IGCC power plants," in *Advances in Steam Turbines for Modern Power Plants*, Woodhead publishing, 2017, pp. 11-40.

[100] TLV, "Types of steam," [Online]. Available: https://www.tlv.com/global/TI/steam-theory/types-of-steam.html#toc_6.

[101] H. Ol and K. Tanigaki, "The ship design of the first nuclear ship in Japan," *Nuclear engineering and design,* pp. 211-219, 1969.

[102] The Royal Institution of Naval Architects, "Significant ships of 2016," *Significant ships,* February 2017.

[103] W.-K. Tien, "Theoretical analysis of cogeneration system for ships," *Energy conversion and management,* pp. 1965-1974, 2007.

[104] J. Spelling, M. Jöcker and A. Martin, "Thermal Modeling of a Solar Steam Turbine With a Focus on Start-Up Time Reduction," *Journal of Engineering for Gas Turbines and Power,* 2012.

[105] M. Angel Gonzalez-Salazar, T. Kirsten and L. Prchlik, "Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables," *Renewable and Sustainable Energy Reviews,* pp. 1497-1513, 2018.

[106] N. Funahashi, "Steam turbine roles and necessary technologies for stabilization of the electricity grid in the renewable energy era," in *Advances in Steam Turbines for Modern Power Plants*, Woodhead publishing, 2017,

pp. 521-537.

[107] G. Darie, H. Petcu, G. Negreanu and V. Gherghina, “Sliding pressure operation of large conventional steam power unit,” in *5TH IASME / WSEAS INTERNATIONAL CONFERENCE ON HEAT TRANSFER, THERMAL ENGINEERING AND ENVIRONMENT*, Athens, 2007.

[108] A. Karakurt and Ü. Günes, “Performance analysis of a steam turbine power plant at part load conditions,” *Journal of Thermal Engineering,* pp. 1121-1128, 2017.

[109] V. Roeder and A. Kather, “Part load behaviour of power plants with a retrofitted post-combustion CO2 capture process,” in *Energy procedia*, Trondheim, 2013.

[110] A. Rivera-Alvarez, M. J. Coleman and J. C. Ordonez, “Ship weight reduction and efficiency enhancement through combined power cycles,” *Energy,* pp. 521-533, 2015.

[111] World Nuclear Association, “Economics of nuclear power,” September 2021. [Online]. Available: https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx. [Accessed 6 April 2022].

[112] J. Latcovich, T. Åstrom, P. Frankhuizen, S. Fukushima, H. Hamberg and S. Keller, “Maintenance and overhaul of steam turbines,” in *International Association of Engineering Ensurers*, Moscow, 2005.

[113] P. Wu, Y. Ma, C. Gao, W. Liu, J. Shan, Y. Huang, J. Wang, D. Zhang and x. Ran, “A review of research and development of supercritical carbon dioxide Brayton cycle technology in nuclear engineering applications,” *Nuclear engineering and design,* 2020.

[114] V. Dostal, “A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors,” Cambridge, 2004.

[115] A. Razak, Industrial gas turbines, Cambridge: Woodhead publishing, 2007.

[116] J. Lee, J. I. Lee, H. J. Yoon and J. E. Cha, “Supercritical Carbon Dioxide turbomachinery design for water-cooled Small Modular Reactor application,” *Nuclear engineering and design,* pp. 76-90, 2014.

[117] A. Gad-Briggs, P. Pilidis and T. Nikolaidis, “Analyses of the Load Following Capabilities of Brayton Helium Gas Turbine Cycles for Generation IV Nuclear Power Plants,” *Journal of Nuclear Engineering and Radiation Science,* 2017.

[118] S. A. Wright, R. F. Radel, M. E. Vernon, G. E. Rochau and P. S. Pickard, “Operation and analysis of a supercritical CO2 Brayton cycle,” Sandia National Laboratories, Albuquerque, 2010.

[119] J. Lee, “Performance Characteristics of Indirect-Fired Gas Turbine/Cogeneration Cycles,” in *Turbo Expo: Power for Land, Sea and Air*, London, 1982.

[120] B. Sørensen and G. Spazzafumo, Hydrogen and Fuel Cells, Emerging Technologies and Applications, Academic press, 2018.

[121] I. Dinger and C. Zamfirescu, Sustainable hydrogen production, Elsevier, 2016, pp. 163-308.

[122] K. Zeng and D. Zhang, “Recent progress in alkaline water electrolysis for hydrogen production and applications,” *Progress in energy combustion and science,* pp. 307-326, 2010.

[123] A. Hauch, S. D. Ebbesen, S. H. Jensen and M. Mogensen, “Highly efficient high temperature electrolysis,” *Journal of materials chemistry,* 2008.

[124] A. Mohammadi, M. Shioji, Y. Nakai, W. Ishikura and E. Tabo, “Performance and combustion characteristics of a direct injection SI hydrogen engine,” *International journal of hydrogen of energy,* pp. 296-304, 2007.

[125] P. Chiesa, G. Lozza and L. Mazzocchi, “Using hydrogen as gas turbine fuel,” *Transactions of the ASME,* pp. 73-80, 2005.

[126] C. Bourne, T. Nietsch, D. Griffiths and J. Morley, “Application of fuel cells in surface ships,” DTI, 2001.

[127] M. Alibert, M. Aufiero, M. Brovchenko, S. Delpech, V. Ghetta, D. Heuer, A. Laureau and E. Merle-Lucotte, “Molten salt fast reactors,” in *Handbook of Generation IV Nuclear Reactors*, Woodhead publishing, 2016, pp. 157-188.

[128] H. Klein Woud and D. Stapersma, Design of auxiliary systems, shafting and flexible mounting, 2016, pp. 375-427.

[129] O. Chag H., K. Eung S. and M. Patterson, “Design Option of Heat Exchanger for the Next Generation Nuclear Plant,” *Journal of Engineering for Gas turbines and power ,* 2010.

[130] IAEA, “Design of the Reactor Coolant System and Associated Systems for Nuclear Power Plants,” IAEA publishing section, Vienna, 2020.

[131] R. Hill, C. Hodge and T. Gibbs, “The potential of the molten salt reactor for warship propulsion,” in *Conference paper inec*, Portsmouth, 2012.

[132] L. O. Freire and D. A. de Andrade, “Economically feasible mobile nuclear power plant for merchant ships and remote clients,” *Nuclear technology,* pp. 766-780, 2019.

[133] Jurewicz, Jacob M., “Design and Construction of an Offshore Floating Nuclear Power Plant,” Massachusetts Institute of Technology, Cambridge, 2015.

[134] Electric Power Research Institute, “Rethinking Deployment Scenarios for Advanced Reactors, Scalable nuclear energy for zero-carbon synthetic fuels and products,” Electric Power Research Institute, Palo Alto, 2021.

[135] Chegg, “Penetrating power,” [Online]. Available: https://www.chegg.com/learn/physics/introduction-to-physics/penetrating-power.

[136] Sayres and associates corporation, “N.S. Savannah, Updated final safety analysis report,” U.S. Department of Transportation Maritime Administration, 2017.

[137] A. Yamaji and K. Sako, “Shielding design to obtain compact marine reactor,” *Journal of nuclear science and technologoy,* pp. 510-520, 1994.

[138] Y. Kawai and I. Kataoka, “SHIELDING EXPERIMENT FOR THE FIRST NUCLEAR SHIP IN JAPAN,” *Nuclear engineering and design,* pp. 169-186, 1969.

[139] United States Department of Transportation, Maritime Administration, Office of ship disposal, “N.S Savannah, Updated Final Safety Analysis Report,” United States Department of Transportation, 2011.

[140] American Bureau of Shipping, “Guidance notes on ship vibration,” American Bureau of Shipping, Spring, 2021.

[141] DNV-GL, “Rules for Classification,” DNV-GL, 2015.

[142] F. Traverso, T. Gaggero, G. Tani, E. Rizzuto, A. Trucco and M. Viviani, “Parametric Analysis of Ship Noise Spectra,” *Journal of Oceanic Engineering,* 2016.

[143] M. R. Pradipta, “Noise Considerations for Propulsion System Evaluation,” TU Delft, Delft, 2018.

[144] E. Miasnikov, “The Future of Russia's Strategic Nuclear Forces Discussions and Arguments,” Center For Arms Control, Energy And Environmental Studies Moscow Institute of Physics and Technology, Moscow, 1995.

[145] Ohio University, “Properties of various ideal gasses,” [Online]. Available: https://www.ohio.edu/mechanical/thermo/property_tables/gas/idealGas.html. [Accessed 22 March 2022].

[146] R. Romatoski and L. Hu, “Fluoride salt coolant properties for nuclear reactor applications: A review,” *Annals of Nuclear energy,* vol. 109, pp. 635-647, 2017.

[147] United States Nuclear Regulatory Commision, “Radiation,” 13 May 2021. [Online]. Available: https://www.nrc.gov/about-nrc/radiation/around-us/calculator.html. [Accessed 2022 March 22].

[148] S. Köse and I. Kiliç, “Investigation of neutronic and thermal-hydraulic performance for HTR-10 under normal operating conditions,” *Turkish journal of nuclear sciences,* pp. 1-18.

[149] U.S. Nuclear Regulatory Commission, “Basic health physics,” 5 July 2011. [Online]. Available: https://www.nrc.gov/docs/ML1122/ML11229A721.pdf. [Accessed 4 May 2022].

[150] New York Shipbuilding Corporation, “NS Savannah Nuclear Reactor Isometric Profile,” 1968. [Online]. Available: https://www.loc.gov/resource/hhh.dc1047.sheet/?sp=10. [Accessed 21 March 2022].

[151] A. Kimmenaede, Warmteleer voor technici, Groningen/houten: Noordhoff, 2010.

[152] W. Fröhling, H. Unger and Y. Dong, “Thermodynamic assesment of plant efficiencies for HTR power conversion systems,” Jülich.

[153] J. D. Kumana, “Essentials of steam turbine design and analysis,” AIche, August 2018. [Online]. Available: https://www.aiche.org/resources/publications/cep/2018/august/essentials-steam-turbine-design-and-analysis#:~:text=Steam%20turbines%20typically%20rotate%20at,steam%20quality%20of%2097%25).. [Accessed 25 March 2022].

[154] C. R. Martin, “About Pyromat,” [Online]. Available: http://www.pyromat.org/about.html#license. [Accessed 24 March 2022].

[155] Mitsubishi heavy industries, LTD, “Steam Turbine generator,” [Online]. Available: https://pdf.nauticexpo.com/pdf/mitsubishi-heavy-industries-ship-ocean/steam-turbine-generator/32135-10532.html. [Accessed 23 March 2022].

[156] N. Connor, “What is Turbine Bypass System (TBS),” Thermalengineering.org, 22 May 2019. [Online]. Available: https://www.thermal-engineering.org/what-is-turbine-bypass-system-turbine-steam-dump-system-definition/. [Accessed 5 April 2022].

[157] N. Polikhronidi, R. Batyrova, A. Aliev and I. Abdulagatov, “Supercritical CO2: Properties and Technological Applications - A Review,” *Journal of Thermal science,* vol. 28, no. 3, pp. 394-430, 2019.

[158] C. Martin, “Five keys intelligent sea water cooling,” Circor, 2018.

[159] J. Syblik, L. Vesely, E. Slavomir, J. Stepanek and V. Dostal, “Analysis of supercritical CO2 Brayton power cycles in

nuclear and fusion energy," *Fusion engineering and design,* no. 146, pp. 1520-1523, 2019.

[160] L. Hu, D. Chen, Y. Huang, L. Li, Y. Cao, D. Yuan, J. Wang and L. Pan, "Investigation on the performance of supercritical Brayton cycle with CO2-based binary mixture as working fluid for an energy transportation system of a nuclear reactor," *Energy,* no. 89, pp. 874-886, 2015.

[161] G. Xiao, T. L. H. Yang, D. Ni, M. l. Ferrari, M. Li, Z. Luo, K. Cen and M. Ni, "Recuperators for micro gas turbines: A review," *Applied energy,* no. 197, pp. 83-99, 2017.

[162] General Electric, "Datasheet 25MW," Febuary 2018. [Online]. Available: https://www.geaviation.com/sites/default/files/datasheet-25mw.pdf. [Accessed 14 March 2022].

[163] D. Stapersma, Lecture notes WB4408A, Diesel Engines volume 2 Turbocharging, Delft: Delft University of Technology, 2010.

[164] F. Mura, R. W. De Doncker, B. Persigehl, J. Peter and K. Hameyer, "Analysis of a gearless medium-voltage variable speed gas turbine," VGB, Essen, 2011.

[165] ARHSE, "Types of heat exchangers," 2 August 2020. [Online]. Available: https://www.arhse.com/tag/types-of-heat-exchangers/. [Accessed 23 March 2022].

[166] S. Bahremand and A. Abbassi, "Heat transfer and performance analysis of nanofluid flow in helically coiled tube heat exchangers," *Chemical engineering research and design,* no. 109, pp. 628-637, 2016.

[167] Y.-S. Lin, Q. Jing and Y.-H. Xie, "Numerical investigation on thermal performance and flow characteristics of Z and S shape PCHE using S-CO2," Wuhan, 2019.

[168] C. Oh H., E. Kim S. and M. Patterson, "Design Option of Heat Exchangerfor the Next Generation NuclearPlant," *Journal of engineering for gas turbines and power,* no. 132, 2010.

[169] J. R. Lines, "Helically Coiled Heat Exchangers Offer Advantages".

[170] MIT, "Printed circuit heat exchanger PCHE," MIT, [Online]. Available: https://ase.mit.edu/projects/printed-circuit-heat-exchanger-pche/. [Accessed 7 April 2022].

[171] Alfa Laval, "Alfa Laval PCHE, The printed circuit heat exchanger," [Online]. Available: https://www.alfalaval.com/globalassets/documents/products/heat-transfer/plate-heat-exchangers/pche/printed-circuit-heat-exchanger_product-leaflet_en.pdf. [Accessed 24 March 2022].

[172] Wartsila, "Dispelling the myth of high losses in electrically enhanced propulsion systems," 2021 November 2021. [Online]. Available: https://www.wartsila.com/insights/article/dispelling-the-myth-of-high-losses-in-modern-electrically-enhanced-propulsion-systems. [Accessed 23 March 2022].

[173] Sulzer, "Molten salt circulation pump," Sulzer, 2021. [Online]. Available: https://www.sulzer.com/en/shared/applications/molten-salt-circulation-pump. [Accessed 31 March 2022].

[174] Tesvolt, "TPS-E power storage," [Online]. Available: https://www.tesvolt.com/_media/05%20SERVICE/03%20Downloads/Produkte/TPS%20E/RD.TI.017.E.ENG_Datasheet_TPS-E_v.D.01.pdf. [Accessed 24 March 2022].

[175] Corvus Energy, "Projects Aida Perla," Corvus Energy, 2022. [Online]. Available: https://corvusenergy.com/projects/aida-perla/. [Accessed 23 May 2022].

[176] Royal Institution of Naval Architects, "Significant ships of 2000," Royal Institution of Naval Architects, London, 2001.

[177] Royal Institution of Naval Architects, "Significant ships of 2001," Royal Institution of Naval Architects, London, 2002.

[178] Royal Institution of Naval Architects, "Significant ships of 2002," Royal Institution of Naval Architects, London, 2003.

[179] Royal Institution of Naval Architects, "Significant ships of 2003," Royal Institution of Naval Architects, London, 2004.

[180] Royal Institution of Naval Architects, "Significant ships of 2004," Royal Institution of Naval Architects, London, 2005.

[181] Royal Institution of Naval Architects, "Significant ships of 2005," Royal Institution of Naval Architects, London, 2006.

[182] Royal Institution of Naval Architects, "Significant ships of 2006," Royal Institution of Naval Architects, London, 2007.

[183] Royal Institution of Naval Architects, "Significant ships of 2007," Royal Institution of Naval Architects, London, 2008.

[184] Royal Institution of Naval Architects, “Significant ships of 2008,” Royal Institution of Naval Architects, London, 2009.

[185] Royal Institution of Naval Architects, “Significant ships of 2009,” Royal Institution of Naval Architects, London, 2010.

[186] Royal Institution of Naval Architects, “Significant ships of 2010,” Royal Institution of Naval Architects, London, 2011.

[187] Royal Institution of Naval Architects, “Significant ships of 2011,” Royal Institution of Naval Architects, London, 2012.

[188] Royal Institution of Naval Architects, “Significant ships of 2012,” Royal Institution of Naval Architects, London, 2013.

[189] Royal Institution of Naval Architects, “Significant ships of 2013,” Royal Institution of Naval Architects, London, 2014.

[190] Royal Institution of Naval Architects, “Significant ships of 2014,” Royal Institution of Naval Architects, London, 2015.

[191] Royal Institution of Naval Architects, “Significant ships of 2015,” Royal Institution of Naval Architects, London, 2016.

[192] Royal Institution of Naval Architects, “Significant ships of 2016,” Royal Institution of Naval Architects, London, 2017.

[193] International Maritime Organization, “Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines,” IMO, London, 2008.

[194] GNS, “Castor 440 84 MVK,” GNS, [Online]. Available: https://www.gns.de/language=en/29921/castor-440-84-mvk. [Accessed 6 April 2022].

[195] European Commision, “The present situation and prospects for radioactive waste management in the European Union,” European Union, Brussels, 1999.

[196] Canadian Nuclear Safety Commission, “High level radioactive waste,” Canadian Nuclear Safety Commission, 4 May 2021. [Online]. Available: http://nuclearsafety.gc.ca/eng/waste/high-level-waste/index.cfm. [Accessed 11 April 2022].

[197] Canadian Nuclear Safety Commission, “Low and Intermediate level radioactive waste,” Canadian Nuclear Safety Commission, 4 May 2021. [Online]. Available: http://nuclearsafety.gc.ca/eng/waste/low-and-intermediate-waste/index.cfm. [Accessed 11 April 2022].

[198] Canadian Nuclear Safety Commission, “Uranium mills and mine waste,” Canadian Nuclear Safety Commission, 15 November 2021. [Online]. Available: http://nuclearsafety.gc.ca/eng/waste/uranium-mines-and-millswaste/index.cfm. [Accessed 11 April 2022].

[199] OECD Nuclear Energy Agency, “Cost of decommissioning nuclear power plants,” OECD, Paris, 2016.

[200] World Nuclear Association, “Decommissioning Nuclear Facilities,” World Nuclear Association, May 2022. [Online]. Available: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx#:~:text=For%20US%20reactors%20the%20expected,to%20%241.22%20million%20per%20MWe.. [Accessed 13 June 2022].

[201] Sayres and Associates corporation, “N.S. Savannah Post shutdown decommissioning activies report,” U.S. Department of Transportation Maritime Administration, office of ship disposal programs, Washington, 2008.

[202] United States general accounting office, “Nuclear submarines, Navy efforts to reduce inactivation costs,” United States General accounting office, Washington, 1992.

[203] Trading economics, “Commodity Uranium,” Trading economics, [Online]. Available: https://tradingeconomics.com/commodity/uranium. [Accessed 6 April 2022].

[204] U.S. Energy Information Administration, “Uranium marketing annual report,” U.S. Energy Information Administration, 20 May 2021. [Online]. Available: https://www.eia.gov/uranium/marketing/#:~:text=Fourteen%20million%20separative%20work%20units,price%20of%20%24109.54%20per%20SWU.. [Accessed 6 April 2022].

[205] United States Geological Survey, “Mineral Commodity Summaries,” United States Geological Survey, January 2020. [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-thorium.pdf. [Accessed 11 April 2022].

[206] E. Lindstad, B. Lagemann, A. Rialland, G. Gamlem and A. Valland, “Reduction of maritime GHG emissions and the

potential role of E-fuels," *Transportation research,* vol. Part D, no. 101, 2021.

[207] Ship & Bunker, "World Bunker Prices," Ship & Bunker, 2022. [Online]. Available: https://shipandbunker.com/prices. [Accessed 11 April 2022].

[208] D. Stapersma, Lecture notes WB4408B, Diesel engines volume 4, Emissions and heat transfer, Delft: Delft University of Technology, 2010.

[209] Wartsila, "Combustion engine vs Gas turbine: Ramp rate," Wartsila, [Online]. Available: https://www.wartsila.com/energy/learn-more/technical-comparisons/combustion-engine-vs-gas-turbine-ramp-rate. [Accessed 5 May 2022].

[210] MAN Diesel, "Service Letter SL09-503/JAP," [Online]. Available: https://www.man-es.com/docs/default-source/service-letters/sl2009-503.pdf?sfvrsn=2b95b1dc_4. [Accessed 5 May 2022].

[211] G. Haratyk, K. Shirvan and M. Kazimi, "Compact steam generator for nuclear application," Centre for Advanced Nuclear Energy Systems, Chicago, 2015.

[212] General Electric, "Steam product catalog," November 2019. [Online]. Available: https://www.ge.com/content/dam/gepower-new/global/en_US/downloads/steam-new-site/products/aqcs/Steam-Product-Catalog.pdf. [Accessed 28 March 2022].

[213] MAN Energy solutions, "MAN 175D genset," 2021. [Online]. Available: https://www.man-es.com/docs/default-source/marine/man-es_l3_factsheets_4p_man_175d_genset_n5_201119_low_new.pdf. [Accessed 12 April 2022].

[214] AMETEK, "Shell-and-Tube heat exchangers 30-series," 2010. [Online]. Available: https://www.bannerindustries.com/wp-content/uploads/2015/02/AMETEK-Shell-and-Tube-Heat-Exchangers-30-Series-10-Inch-Shell.pdf. [Accessed 26 April 2022].

[215] ABB, "High voltage induction motors, technical catalog for IEC motors," 2011. [Online]. Available: https://www.jjloughran.com/sites/default/files/ABB%20HV_Induction_motors_technical_IEC_catalog_.pdf. [Accessed 25 April 2022].

[216] Wartsila, "Wartsila solutions for marine and oil & gas markets," 2022. [Online]. Available: https://www.wartsila.com/docs/default-source/marine-documents/segment/brochure-marine-solutions.pdf. [Accessed 25 April 2022].

[217] Siemens, "Switchboards, selection and application guide," 2020. [Online]. Available: https://s3.amazonaws.com/dcc-data-extract/new-delta/asset/Compas/daily/Compas/2020-04-07/Selection%20Application%20Guide/SIE_Selection_And_Application_Guide_Dist_Switchboards.pdf. [Accessed 29 April 2022].

[218] MAN Diesel & Turbo, "MAN B&W S60ME-C8.2," 2014. [Online]. Available: https://man-es.com/applications/projectguides/2stroke/content/epub/S60ME-C8_2.pdf. [Accessed 26 April 2022].

[219] T. Dolan, Molten Salt Reactors and Thorium Energy, Duxford: Woodhead publishing, 2017.

[220] Clarksons, "World fleet register," [Online]. Available: https://www-clarksons-net.tudelft.idm.oclc.org/wfr/fleet.

[221] C. Gao, P. Wu, W. Liu, Y. Ma and J. Shan, "Development of a bypass control strategy for supercritical CO2 Brayton cycle cooled reactor system under load-following operation," *Annals of Nuclear Energy,* no. 151, 2021.

APPENDIX

Appendix A: Nuclear power plant generations

This appendix section gives further detail and adds to the earlier Table 3.

Generation I

The first generation of nuclear reactors were the first large scale prototype power reactors, all constructed in the beginning of nuclear power developments. Most notable are Fermi 1, Magnox, Dresden and Shippingport. With Shippingport being notable as it was built on naval (PWR) nuclear technology.

Generation II

The second generation of nuclear reactors are developments of technology from the first generation. Multiple different types were and are still in use, this also marked the start of deployment and development in other countries (beyond the United States).

- The PWR (pressurized water reactor) is still the most used reactor and covered in chapter 3.4.
- The BWR (boiling water reactor) is a reactor that instead of transferring heat via heat exchangers utilizes the properties of water to form steam directly in the reactor. This results in the steam turbine/power conversion loop being directly integrated in the primary coolant loop. Although this saves partly in system complexity, it increases the spread of radiated coolant through the facility. Which is not ideal.
- CANDU (Canada deuterium uranium) is a reactor that uses heavy water as coolant, the benefit of this is that the reactor does not require enriched uranium but can operate on natural uranium.
- VVER, Russian reactor design, translation: water-water energetic reactor. This reactor is the equivalent to the PWR reactor as developed in the US during the time of the Soviet Union (now in use in Russia).
- RBMK, Russian reactor design, translation: High power channel-type reactor. This Soviet Union design used graphite as moderator and water as coolant.

Generation III and III+

The third generation of power plants builds on the idea of the second-generation power plants with improvements regarding safety, efficiency, and cost reduction. Similarly with generation III+ which is a development of this technology. This term includes the ABWR (Advanced boiling water reactor), which is a progression of the BWR reactor and the EPR (European pressure reactor), which is a development on the PWR platform.

Generation IV

The fourth generation of reactors is different in that it are mostly novel designs. The applicable designs were identified by the generation-IV international forum (GIF) and are all currently still in development.

- VHTR, covered together with the HTGR in chapter 3.5 .
- MSR, covered in chapter 3.7 .
- SCWR (Supercritical water reactor), which is a combination of a PWR and BWR reactor that utilizes supercritical water as its coolant and moderator. This reactor is not covered in this report due to its size. This reactor is currently only being developed in the large commercial power scale and does not fit for the ship concept.
- GFR, SFR, LFR covered together in chapter 3.6

Appendix B: Calculation shielding

Values used for attenuation coefficient

Substance	Group	value
Water	1	0.0966
	2	0.0493
	3	0.0339
	4	0.0275
Concrete	1	0.0870
	2	0.0445
	3	0.0317
	4	0.0268

Table 57 Attenuation values for shield materials, data from [4]

Taylor Form buildup factor

For the buildup factor B_p the Taylor form is used, this enables a programmed solution to work without requiring the manual input from lookup tables. The Taylor form is shown below, with the values used shown in Table 58. With A being A_1 and A_2 being 1-A .

$$B_p = A_1 e^{-\alpha 1 \mu r} + A_2 e^{-\alpha 2 \mu r}$$

Substance	Energy (MeV)	A	$-\alpha_1$	α_2
Water	0.5	100.845	0.12687	-0.10925
	2.0	12.612	0.05320	0.01932
	4.0	11.163	0.02543	0.03025
	6.0	8.385	0.01820	0.04164
Concrete	0.5	38.225	0.14824	-0.10579
	2.0	18.089	0.04250	0.00849
	4.0	11.460	0.02600	0.02450
	6.0	10.781	0.01520	0.02925

Table 58 Parameters for the Taylor form for exposure buildup, data from [4]

Values used for mass absorption coefficient of air

Substance	Group	value
Air	1	0.0297
	2	0.0238
	3	0.0194
	4	0.0172

Table 59 Mass absorption coefficient for air, data from [4]

Appendix C: Shield curve fit

Below the curve fit and its parameters are shown for the shielding calculation. The curve fit is the centreline used in the calculations and is derived from the original calculation. The curve fit is used as it is easier to implement in other calculations (easier than using the original calculation).

Curve	$f = (p1x^3 + p2x^2 + p3x + p4) / (x^3 + q1x^2 + q2x + q3)$
p1	6001
p2	3.306e+08
p3	-1.895e+05
p4	-190.3
q1	2.943e+05
q2	1.904e+08
q3	2.452e+05

Table 60 Curve fit for reactor shielding

Appendix D: Calculation Rankine (steam) turbine

Calculating the Rankine cycle efficiency relies mostly on the T-s diagram, as well as some relationships for the steam cycle that are established in literature [151]. The most important relationship being the standard temperatures and their respective steam pressures. The T-s diagram as shown earlier for the cycle with superheat is shown again in Figure 92, although now all points have been given an index, as this is more convenient when determining all their properties. In this assessment the feedwater pumping work is ignored, and the water is simply expanded to steam from point 1 to 2.

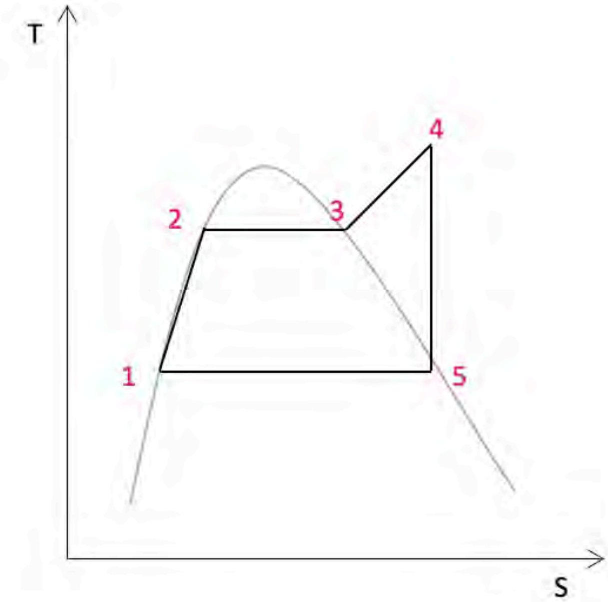


Figure 92 T-s diagram Rankine cycle (ideal with superheat)

Information on each of the points in the cycle can be determined, their values are taken from the Pyromat database [154] (multiphase water) in a programmed solution, this is however identical to looking up these values from a book of steamtables. The diagram is important as it is required to determine/know the moisture content at each point. The temperatures at each point can be determined either from the other properties or predetermined. Similarly, pressures associated with the steam are predetermined from literature [99], as not every temperature is achievable at every pressure. Each of the points is shown in Table 61.

Point	Pressure	Temperature “T”	Entropy “s”	State
1	Condenser pressure	Determined from pressure relation	Determined from pressure relation	Water
2	Predetermined from literature	Determined from pressure relation	Determined from pressure relation	Water (heated)
3	Isobaric from 2	Determined from pressure relation	Determined from pressure relation	Saturated steam
4	Isobaric from 3 (and thus 2)	predetermined from achievable temperature	Calculated	Superheated steam
5	identical to 1	Determined from pressure relation and state	Identical to 4, in ideal cycle	Part steam, part water. Calculated

Table 61 Relationship between points of the Rankine cycle

At two points a calculation is required first for the entropy of the superheated steam at point 4, the values for the used constants $c_w = 4.2$ & $c_p = 2.2$, r is the heat of evaporation, and this is determined for the temperature using Pyromat.

$$s4 = c_w Ln\frac{T3}{273} + \frac{r}{T3} + c_p Ln\frac{T4}{T3}$$

Secondly for the water content (steam quality) at the end of the turbine expansion, as this was mentioned earlier in section 7.4.1 as something that has to be considered in the design.

$$x = (s4 - c_w Ln(\frac{T1}{273}))/(\frac{r}{T1})$$

With all these points determined it is then also possible to determine the heat input, the work, and the cycle efficiency. This can be done for the ideal cycle, but also for the cycle with losses if we consider the isentropic efficiency.

$$\eta_{ideal} = W_{out}/Q_{in}$$
$$\eta_{th} = (W_{out} \cdot \eta_{isentropic})/Q_{in}$$

Again, all these calculations can be repeated for the cycle with re-heating. The difference being that in reheating a secondary heating stage is added. This secondary heating stage is added in identical fashion, considering the pressure drop after expansion.

Appendix E: Sizing Rankine cycle additional components

For the Rankine (steam) cycle some additional components are required besides the turbine to complete the cycle. The largest of these components: The steam generator and the condenser should be considered for the layout as these are a significant size contribution.

Based on studies for competitively sized steam generators it is possible to determine the relative size by scaling conceptual versions. These are shown in Table 62. Scaling of a commercial unit is considered over calculation as a steam generators functionality is based on a phase change, which Is more difficult to accurately calculate compared to heating or cooling without phase change.

Steam generator type/media	Helical coil (m^3)	PCHE* (m^3)
Steam	0.45	0.011

*Table 62 Steam generator sizing (m^3) per MWth, based on [211] * indicates theoretical only*

For the steam condenser again a commercial unit scaled, this is done for the same reason as for the steam generator as the condenser relies on a phase change. The condenser is sized proportionally to its power, shown in Table 63.

Steam condenser type/media	Bundle type, for seawater use (m^3)
Steam	4.3

Table 63 Steam condenser sizing (m3) per MWth, based on commercially available unit, data from [212]

From the values in Table 62 & Table 63 it can be concluded that the steam layout is significantly larger than the additional components of the Brayton cycle sized in section 7.5.

Appendix F: Calculation Brayton turbines

Calculating the Brayton cycle efficiency in either open or closed form relies on the T-S diagram, as shown in Figure 93. In the diagram both the ideal cycle, as well as the isentropic loss lines are shown (in red, a deviation from the ideal cycle).

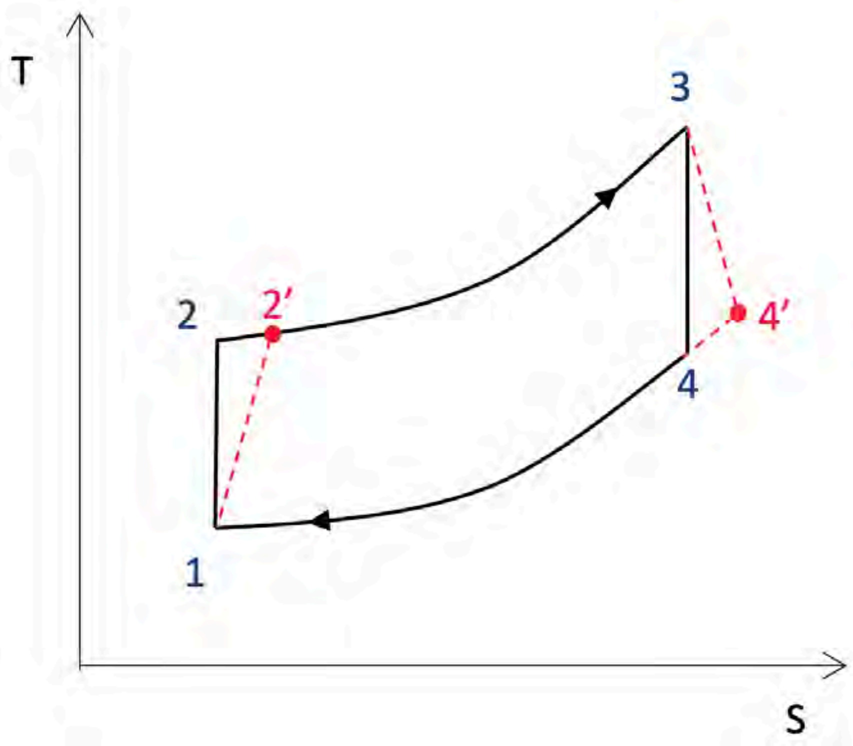


Figure 93 T-S diagram Brayton cycle, with isentropic efficiency lines

Calculation is identical for both closed and open cycle Brayton turbines; the difference is in part 4-1, where in closed Brayton a cooler is fitted, while in open Brayton the heat is exhausted at 4 and fresh air taken in at 1. Both ways reject heat, only the method is different. The relationship between the points is as follows, with *k* being the heat capacity ratio:

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k}$$

$$T_4 = T_3 \left(\frac{P_4}{P_3}\right)^{(k-1)/k}$$

With the pressures related to each other by the compression ratio ε, when the isentropic losses are considered, these are related as follows (with c = compressor, t = turbine):

$$\eta_{i,C} = \frac{T_2 - T_1}{T_2{}' - T_1}$$

$$\eta_{i,T} = \frac{T_3 - T_4{}'}{T_3 - T_4}$$

The power taken by the compressor and delivered by the turbine can also be derived:

$$P_c = -\dot{m}_c C_p (T_2 - T_1)$$

$$P_t = \dot{m}_c C_p (T_3 - T_4)$$

With useful power following from the sum of the negative compressor power and the positive turbine power. The total thermal power added can be determined, when considering losses as follows:

$$Q_{2'-3} = \dot{m}_c C_p (T_3 - T_2{}')$$

With this information the thermal efficiency can be determined for the entire installation as following (note that compressor power is negative as derived earlier, therefore added not subtracted).

$$\eta_{th} = \frac{P_c + P_t}{Q_{2\prime-3}}$$

As both close to conventional open cycle turbines, as well as relatively modern closed cycle turbines are discussed some details that are important in the execution of the programmed solution should be noted:

- Properties and values of the media are different if either air or for instance helium and sCO_2 are used. These properties are taken from the Pyromat library [154] in the programmed solution.
- Compression ratio ε can be different for the different turbines and their media, the optimal ratio is determined by evaluating the efficiency while varying the compression ratio and choosing the maximum efficiency.
- While the theoretical cycle has no difference when comparing heat rejection (open Brayton) and a heat exchanger (closed Brayton) pressure losses can occur here. These are not considered.
- As mentioned in the section on open cycle Brayton turbines (section 7.4.3) the open cycle has inlet and outlet ducting, these impose additional losses, these are considered as these are a well understood part in the comparable marine gas turbine application.
- Pressure related losses can also occur in the heat exchanger for the heat addition (2-3), these are not considered in this evaluation.

The recuperator is discussed, which is an addition to the cycle that preheats the media coming out from the compressor using the exhaust gasses. After this step the normal cycle proceeds, with the heat added being slightly reduces as the starting temperature is higher. Recuperator effectiveness was established at 80%, from which the temperature after the recuperator can be determined. The maximum temperature difference between the two mediums is the difference between T_4 and T_2, with an effectiveness of 80 percent the temperature after the recuperator (referred to as T_5) becomes:

$$T_5 = \varepsilon(T_4 - T_2) + T_2$$

Appendix G: Calculation heat exchangers

Heat exchanger sizing depends heavily on the type of heat exchanger used (and type associated properties) and the temperature difference between the media. The properties of the heat exchangers used are shown in in Table 20. For each heat exchanger the effectivity of ε = 0.95 is assumed.

For each of the heat exchangers the temperatures of both fluids are determined, from this the LMTD or logarithmic mean temperature difference is determined using the following equation [128]:

$$LMTD = \frac{\Delta\theta_0 - \Delta\theta_1}{ln\frac{\Delta\theta_0}{\Delta\theta_1}}$$

With the values and the results for each of the heat exchangers shown in Table 64.

Reactor/turbine	**He cooled reactor** LMTD (°C)	**Salt cooled reactor** LMTD (°C)
To air (direct)	38.8	n/a
To He (Intermediate)	20.6	80.7
To air (He to air intermediate)	18.0	101.7

Table 64 LMTD values for heat exchangers

This can then be used to determine the required surface area of the heat exchanger, by using the heat transfer coefficient as determined in the earlier mentioned Table 65. This then gives the amount of surface area required in the heat exchanger.

	He cooled reactor			**Salt cooled reactor**		
Reactor/turbine	Tubular (m^2)	Helical coil (m^2)	PCHE (m^2)	Tubular (m^2)	Helical coil (m^2)	PCHE (m^2)
To air (direct)	51.6	25.8	12.9	n/a		
To He (Intermediate)	96.9	48.5	24.2	24.7	12.4	6.2
To air (He to air intermediate)	111.0	55.5	12.9	19.7	9.8	4.9

Table 65 Heat exchanger surface area values

Using the surface density of the heat exchanger type, it is then possible to determine the size of the heat exchanger (which were presented in section 7.5). This calculation does not consider pressure losses or the option to run one coolant faster and at a larger temperature delta than the other, the calculation serves purely as a first indication of effectivity and size.

Appendix H: Emergency power system

The backup engines used for emergency power in the layouts are sized according to the information in Table 66, which is based on a commercially available marine generator set. The system is fitted with a fuel reserve for 7 days, delivering enough power to attain half speed and maintain the balance of plant of the reactor. The amount of diesel generator sets depends on the amount of power required and the redundancy requirements.

Parameter	Power density (kW/m^3)	Weight (kW/t)	Fuel consumption (g/kWh)
Value	91	115	193

Table 66 Backup engine information, based on commercially available marine diesel generator set [213]

Appendix I: Nuclear fuel cost

Nuclear fuel cost is determined using the estimates and available costs of materials and production steps. These values are given in the earlier Table 2 & Table 44. The complete calculation is shown in Table 67 & Table 68,based on the calculations demonstrated in the publication by Tsoulfanidas [8], with the yellow sections showing the variables.

Cost breakdown

Uranium cost	130	dollar	kg	Current approx spotprice (April 2022)
Conversion cost	16	dollar	U	
Enrichment cost	100	dollar	SWU	
Fuel fab cost/kg	300	dollar	kg	For conventional fuel rods

Material requirements

				Equation from Tsoulfanidas, ch 3.6			
Feed factor							
xp = requested enrich	5	%		0,05			
xf = content of 235 in natural uranium	0,711	%		0,00711			
xw = content 235 in waste stream	0,2	%	also known as tails assay	0,002			
feed factor	9,39334638						
Total needed	1	kg end product		Fill in			
Total needed	9,39334638	kg u308					
Separation potentials						Cost	
vxf	4,868883386						
vxw	6,187755671		48%		Uranium (mined)	1221,135029	dollar
vxp	2,649995081		6%		Conversion	150,2935421	dollar
			35%		Enrichment	885,0863618	dollar
Swu factor			12%		Fuel fab	300	dollar
	8,850863618	SWU/kg					
	8,850863618	SWU			Total cost	2556,514933	dollar

Table 67 Calculation fuel price 5% enrichment

Material requirements

				Equation from Tsoulfanidas, ch 3.6			
Feed factor							
xp = requested enrich	20	%		0,2			
xf = content of 235 in natural uranium	0,711	%		0,00711			
xw = content 235 in waste stream	0,2	%	also known as tails assay	0,002			
feed factor	38,74755382						
Total needed	1	kg end product		Fill in			
Total needed	38,74755382	kg u308					
Separation potentials						Cost	
vxf	4,868883386						
vxw	6,187755671		48%		Uranium (mined)	5037,181996	dollar
vxp	0,831776617		6%		Conversion	619,9608611	dollar
			43%		Enrichment	4574,709581	dollar
Swu factor			3%		Fuel fab	300	dollar
	45,74709581	SWU/kg					
	45,74709581	SWU			Total cost	10531,85244	dollar

Table 68 Calculation fuel price 20% enrichment

For thorium the same calculation can be made, although for thorium there is no enrichment step or additional feed required. This results in the price being only the raw material price, the conversion step (which is expected to be different for thorium but estimated to cost the same as for uranium). And no enrichment cost. Resulting in the price shown in Table 69. The main downside of thorium being that it is fertile instead of fissile.

Raw material price	72 $
Conversion step	16 $ (estimated at similar kg price as uranium)
Fuel fabrication cost	300 $ (estimated at similar kg price as uranium)
Total:	**388 $/kg**

Table 69 Calculation production cost thorium

The price shown for fertile thorium is significantly lower than the price for fissile uranium fuel. A reduction of 85-96% in price.

Appendix J: Volume and weight estimation of complete layout

For the volume and weight estimate of a nuclear based marine propulsion and power generation system some additional component size and weights were estimated. The components estimated are not unique for nuclear power and were estimated using available data from commercially available similar systems.

Heat exchangers:
For the heat exchangers the volume was determined in section 7.5, with the weight estimated at 3 tons per m^3 based on manufacturer data on conventional heat exchangers [214].

Electromotors:
For the electromotors the volume and weight is based on a commercially available unit that is scaled proportionally for the application. The derived values from the commercially available unit [215] are 562 kW/m^3 and 366 kW/t.

The electromotors used on the conceptual vessels are sized for delivering up to 90% of the installed power.

Generators:
As generators operate on the same principle they are sized similarly to the electromotors, with the same values used and scaled proportionally to the power requirement. Each of the used generators is sized for 100% of the turbines power output.

Gearboxes
For the gearboxes values are based on a commercially available unit [216] that is scaled proportionally for the application. The gearbox selected is single input and output with the complete size being the boxed size of the gearbox. The values derived for the calculation are 1075 kW/m^3 and 575 kW/t.

The gearboxes are sized to fit the electromotors used for the propulsion.

Electrical components:
The electrical components of the power grid such as the busbar, breakers and converters are estimated based on the volume of a cabinet (0.94 m^3 from manufacturer dimensions [217]) and an estimated weight (0.5 tons per cabinet). For conventional systems the estimate is three cabinets per machinery component, with electric systems being doubled to six cabinets per component. A baseline of 5 cabinets is added for the “standard” hotel components of the vessels.

Conventional plant: Marine diesel engine
To compare the conventional plant the size and weight of the marine diesel engine is estimated as well. The conventional diesel engine used for the propulsion system is considered to be a 2-stroke diesel. With the 4-stroke diesel generator sets that are required for the balance of plant and hotel load as additional. The 2-stroke marine diesel at 36 kW/m^3 and 26 kW/t [218], the 4-stroke diesel generator set at 91 kW/m^3 and 115 kW/t [213].

Appendix K: Graphs CAPEX – OPEX for conceptual vessels

Bulker, shown for scenario A to D

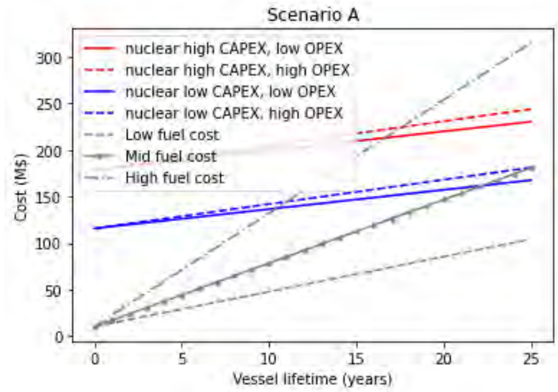


Figure 94 Bulker scenario A

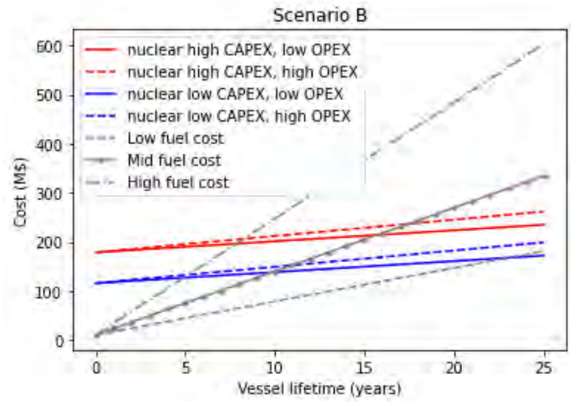


Figure 95 Bulker scenario B

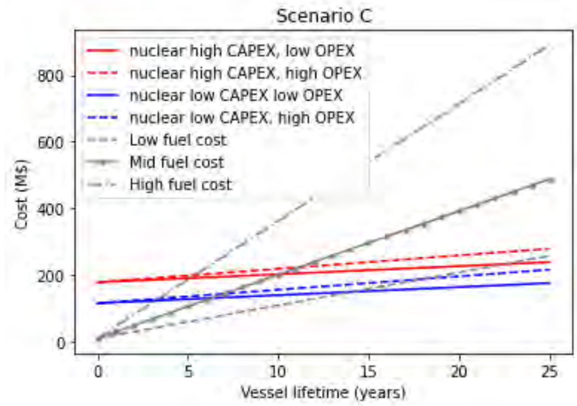


Figure 96 Bulker scenario C

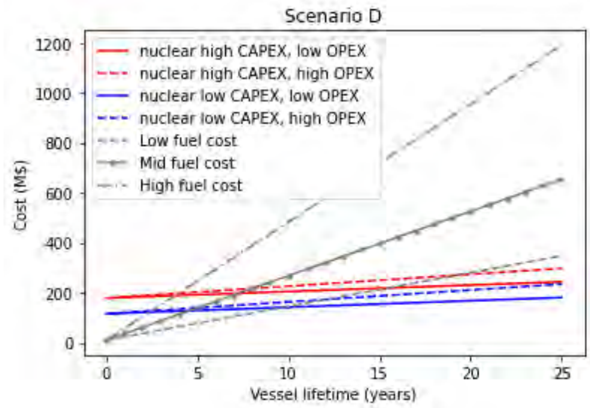


Figure 97 Bulker scenario D

Tanker, shown for scenario A to D

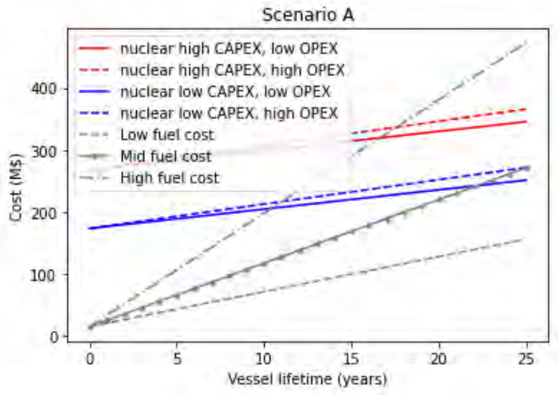


Figure 98 Tanker scenario A

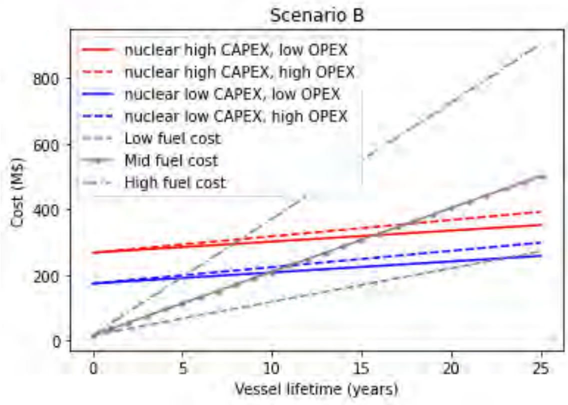


Figure 99 Tanker scenario B

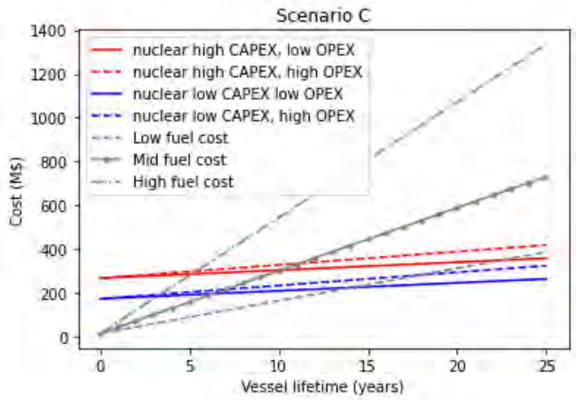


Figure 100 Tanker scenario C

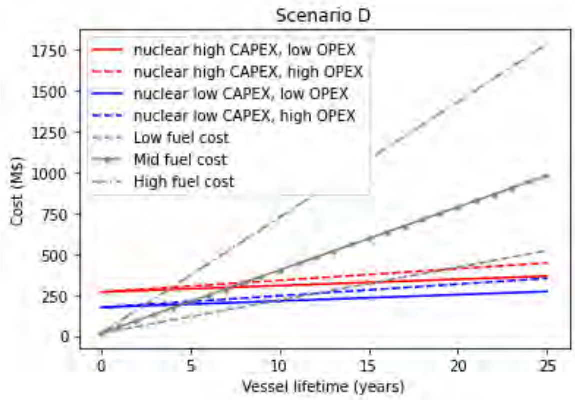


Figure 101 Tanker scenario D

Offshore, shown for scenario A to D

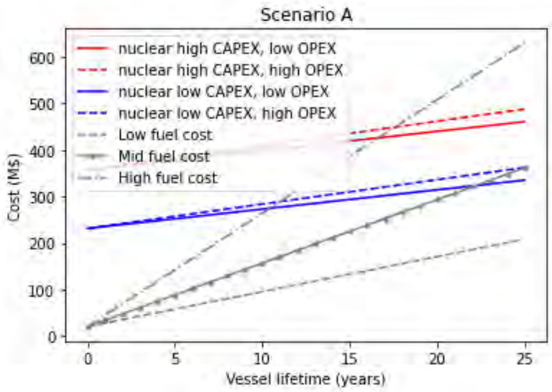


Figure 102 Offshore scenario A

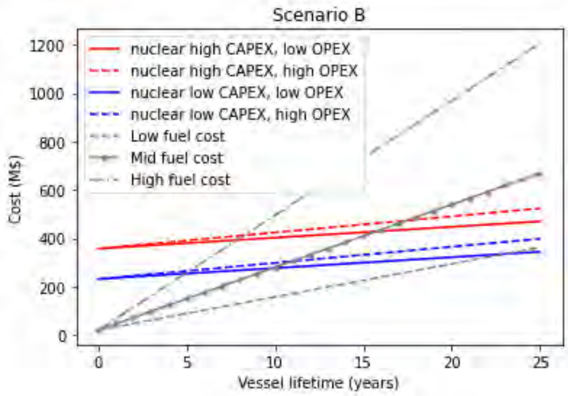


Figure 103 Offshore scenario B

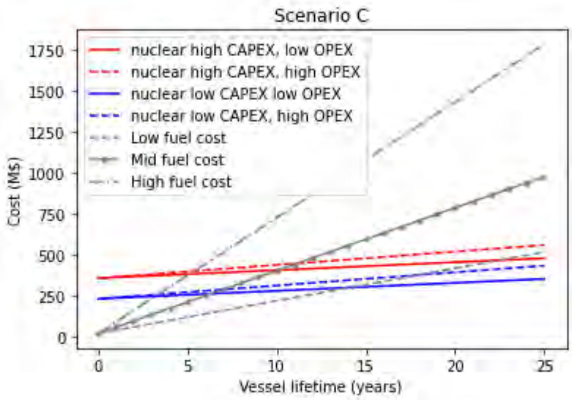


Figure 104 Offshore scenario C

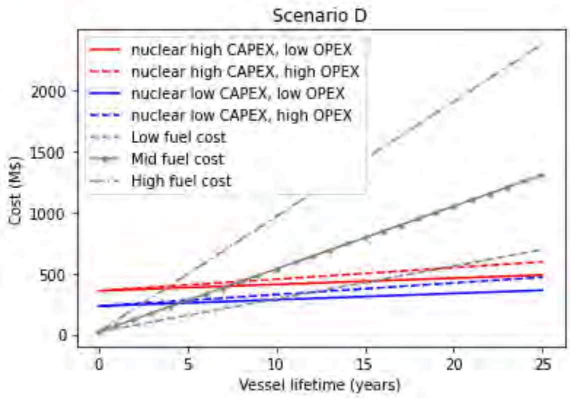


Figure 105 Offshore scenario D