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Selection of nuclear reactor and its system features for PC1 nuclear icebreaker

Department of Mechanical and Material Engineering

Master’s thesis

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13.6.2026
Turku

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Subject: Mechanical engineering

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Title: Selection of nuclear reactor and its system features for PC1 nuclear icebreaker

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Number of pages: 71 pages

Date: 13.6.2026

A nuclear-powered icebreaker concept ship titled IBELO is under development at Elomatic. The ship targets to meet PC 1 ice class, requiring year-round operation in all polar waters. Nuclear power offers high power, a fuel with high energy density and reduction in the refueling time, responding well to operational requirements of the concept ship. Development of the emerging generation 4 reactors would offer beneficial features related to nuclear power implementation to commercial ships. Lack of regulatory and more practical standards are main barriers for nuclear power adaptation to commercial ship.

This thesis aims to find most suitable options and solutions for concept ship machinery arrangement. Axiomatic design process is utilized to determine the suitable system features, starting from functional requirement and resulting most suitable system feature determination. Electrical propulsion system was selected because of its load following capabilities and flexibility. Converting nuclear thermal energy to electricity with turbines is considered most suitable, with turbine features for reheating and at least three pressure cylinders.

Reactor validation was performed utilizing the analytical hierarchy process (AHP) method and initial screening. Validation process found Lead-cooled fast reactor (LFR) Sealer-55 with 55 MW electrical power to be the most suitable option for the concept ship.

Keywords: nuclear power, nuclear-powered ship, icebreaker, small modular reactor, Generation 4, analytical hierarchy process

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1 Introduction

Floating vessels which use nuclear reactors for propulsion is not a new concept, as around 700 nuclear reactors have been operating on various ships since the 1950s [1]. First prototype of pressurized water reactor (PWR) for naval fleet was used on the USS Nautilus, which traveled 62000 miles on the sea trial 1955 with its first core loading. Nowadays over 200 small modular reactors (SMR) are used as a propulsion for over 160 ships, mostly relying on PWR technologies. These reactors are mainly on use at navies and are not suitable for civilian application due to the International Atomic Energy Agency (IAEA) limit of U253 enrichment under 19.75%[2]. [3]

The further problem is the implementation of reactor propulsion to different types of vessels, to ensure for example passenger and crew safety. This is also affected by the social concerns related to nuclear technology. Currently there is no active commercial ships or offshore platforms with nuclear facilities[4]. [5]

Regulations on limiting greenhouse gas emissions on shipping makes nuclear powered ships an attractive choice. Nuclear Power has low carbon emissions during its whole lifetime and zero-emission at operation [6]. For instance, nuclear fuel used on 12500TEU container vessel at route of 3500 nautical miles a reduction of 4850 tons of CO2 emissions can be achieved [7]. At EU, nuclear energy has been recognized as a sustainable energy source to assist achieving net-zero emission target, which makes it eligible for green sustainable financing [6]. [5]

Nowadays there is many different actors interested about nuclear energy at ships. In 2022 UK initiated to participate on Nuclear Code, which is one of few international legal instruments considering nuclear power at commercial shipping. Also, Chinese and South Korean shipbuilding companies have shown their interest and expertise at merchant nuclear shipping. [4]

The timeline of nuclear reactor development starts from 1940, and its different development paces are called as generations. Starting from Generation 1 early prototypes to Generation 4, which are now under development. The ongoing development, advanced reactor technologies in terms of SMR, Generation 4 reactors and possibility to use Thorium as a fuel increases the potential of commercial nuclear ship applications, with increased safety factors and resistance of nuclear fuel proliferation. [8] Progress is made with integration of Generation 4 reactors and SMRs. This development might improve safety, enable shorter construction times with higher standardization. Operational efficiency, stronger business model and requirements related to crew might be improved with more developed nuclear power. [4]

1.1 Nuclear powered concept ship IBELO

Finnish design and consulting company Elomatic is currently developing a nuclear-powered icebreaker concept ship called IBELO. The ship is targeted to meet Polar class level 1. International association of classification societies (IACS) established polar class [9], classifies ships strength and operational capability. There are seven different polar classes, were polar class 1 (PC 1) is the highest and described as “year-round operation in all polar waters”. PC requirements are divided to structural requirement and machinery requirements, which is mainly focusing on propulsion blades and shafts, with main machinery related intakes of air and sea water and ice protection.

Polar water refers to Arctic-and Antarctic-sea areas. Area of sea ice at late winter at Arctic is approximately 15,5 million square kilometers and at Antarctic 18,5 million square kilometers. At Antarctic, sea ice is seasonal ice, which melts and reforms annually, making it less thick when compared to Arctic sea ice. At Arctic, sea ice stays at the arctic area and continue thicken at the cold environment. At both regions ice thickness varies significantly, with Antarctic sea ice being typically 1 – 2 m thick and Arctic sea ice typically 2 – 3 m thick. [10]

Following ice chart presented at Figure 1 presents the thickness of Arctic sea ice in March of 2025. The chart is plotted from Earth Observation Climate Information Service (EOCIS) [11]. The data at the chart is generated with radar altimetry measurements from ESA CryoSAT-2 satellite. Mean sea ice thickness distribution derived by Hroshi Sumata et. al. [12] is presented on Figure 2, with plotted averages at two periods, 1990 – 2006 resulting approximately 2,7 m and 2007 – 2019 resulting approximately 1,7 m.

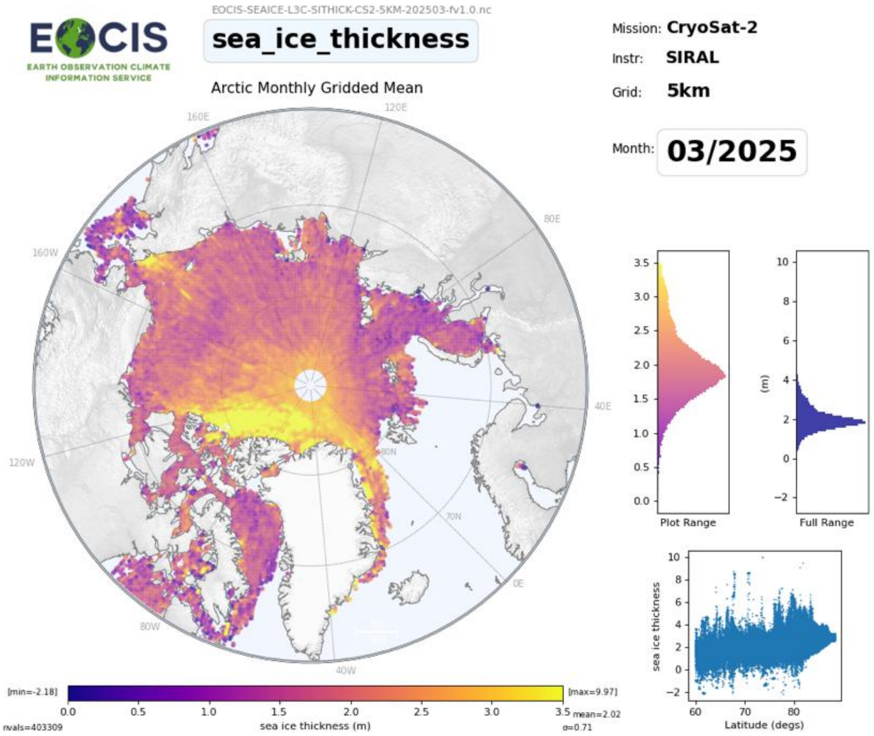

Figure 1. Arctic sea ice thickness at 2025 March

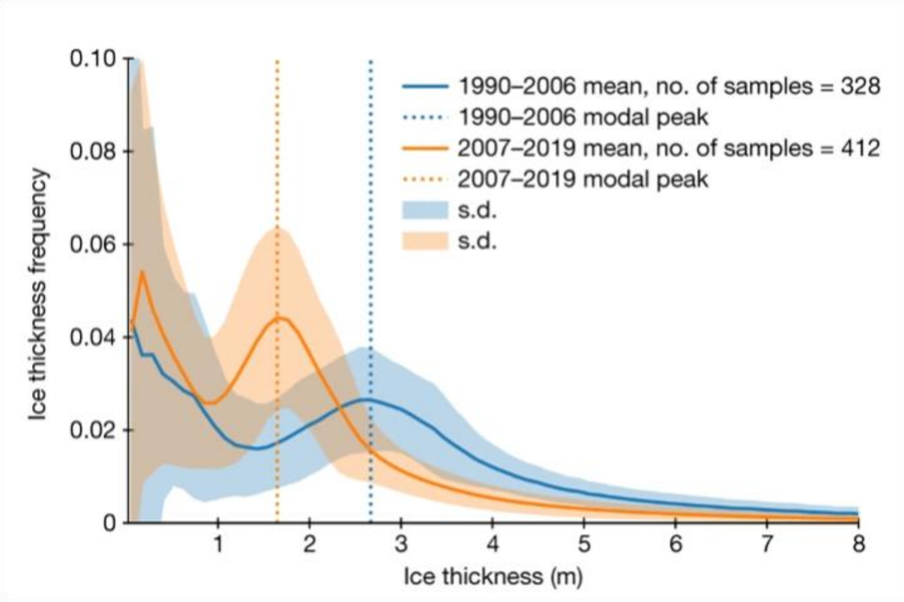

Figure 2. Mean sea ice thickness distribution. [12]

Intended use of IBELO targets to multipurpose ship with crew size of 130 person. Propulsion system at IBELO contain two shaft line thruster, two Azipod thrusters and 3 bow thrusters. IBELO’s main dimensions are presented on Table 1.

Table 1 Main dimensions of IBELO

Length (overall)	210,525 m
Length (between perpendiculars)	201,2 m
Beam	40 m
Draught (max)	13 m
Draught (min)	10,3 m
Depth	19,5 m

According to Arctic sea ice thickness analysis and PC1 class requirement of operation on all polar water, required propulsion power were calculated to ice thicknesses from 1 m to 4 m, with speed of 3 kn. Required propulsion power for IBELO were determined outside this study and presented in Figure 3 below. These values are used only as an input value at this study. The required propulsion power at 3 kn speed varies a lot, from 10,3 MW at 1 m thick ice to 153,5 MW at 4 m thick ice.

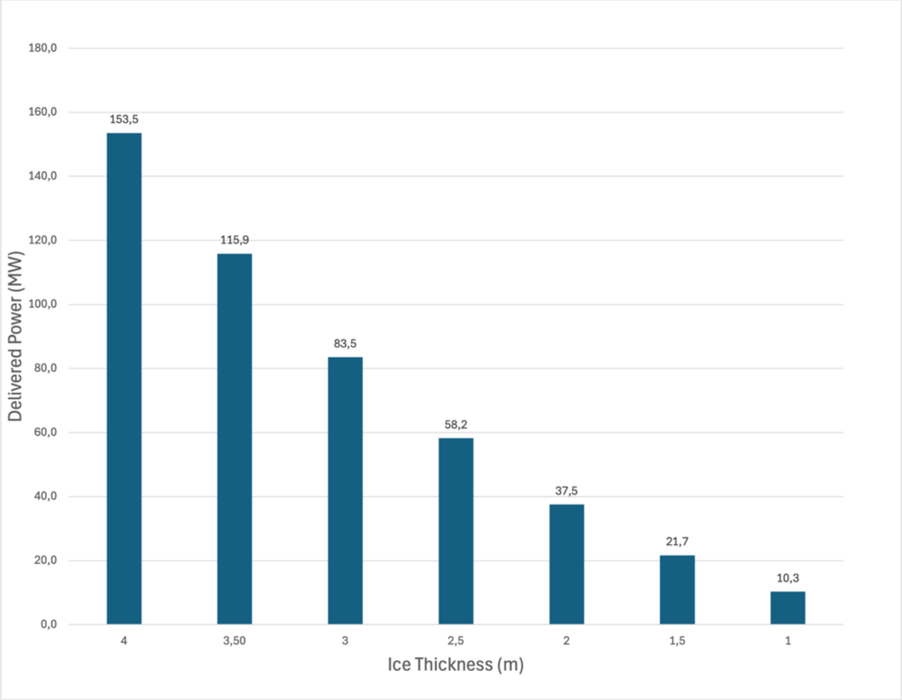

Figure 3. Required delivered propulsion power (MW) at 3 kn speed, for different ice thicknesses.

1.2 Research approach

At this study, main characters related to nuclear powered ship main machinery system are studied with literature review. Target is to find most suitable options and solutions at different machinery arrangement level and so one put together most suitable system responding to concept ship needs. This will include well picked nuclear reactor, most suitable power conversion option and propulsion type.

At the start of the study, following research questions have been posed: Why nuclear power is used, and how it can be used on maritime industry? Which Generation 4 SMR technology would be commercially and technically most suitable option for concept ship? What possible benefits and challenges there is when considering different nuclear reactors and machinery arrangement? How nuclear power is implemented and designed to ice breaker machinery system?

Approach of this study applies roughly axiomatic design process. Initial determination was done to the topic, that Generation 4 reactor technology will be used. Axiomatic design theory was developed by Nam P. Suh around 1990s. It is two-dimensional design framework, featuring specific domains and hierarchy. [13] Axiomatic design hierarchy and domains determined at this study are presented on Figure 4 below, starting from customer needs and going through functional domain, physical domain and process domain. With this method it is ensured that all features are determined in design beneficial order, resulting best overall solution.

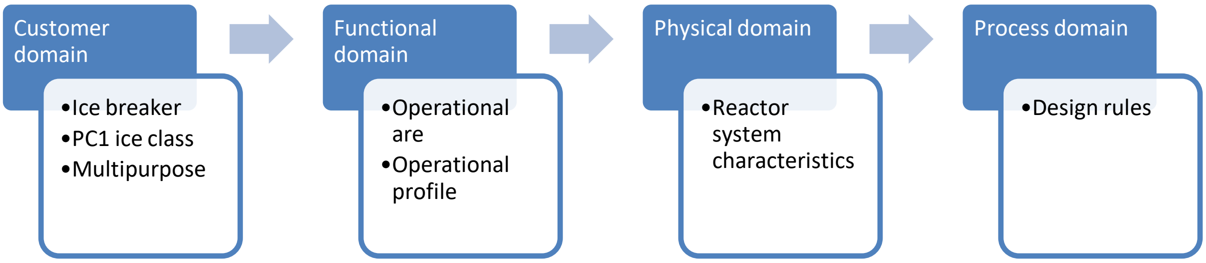

Figure 4. Axiomatic design hierarchy and its domains.

2 Regulatory framework

Installing nuclear power to different vessels requires both, maritime and nuclear regulatory framework. International organizations such as International maritime organization (IMO), International atomic energy agency (IAEA), and the European union (EU) have set international rules providing comprehensive legal and political framework for decarbonization and safety usage of nuclear power at ships [5]. IMO and IAEA must lead the effort of the standard development. Standards relating to ship construction, fuel management and operational protocol for commercial maritime nuclear industry needs to be covered with international regulatory framework. This needs to be transferred to more detailed and practical technical and operational standards to be implemented to specific vessels [5]. Beside international organizations, classification associations play critical role with enabling global regulatory adoption to practical standardization. Coordination across jurisdictions might be needed with regulatory roadmap and licensing. The classification society integration of regulations and class-based standards is crucial for Generation 4 reactors to be gradually adapted to ships[5]. [4]

Figure 5 below presents M. Drosińska-Komor et. al. [5] determined implementation roadmap for Generation 4 nuclear propulsion. It goes though international framework, classification society standards and harmonization to practical deployment at shipowner-level.

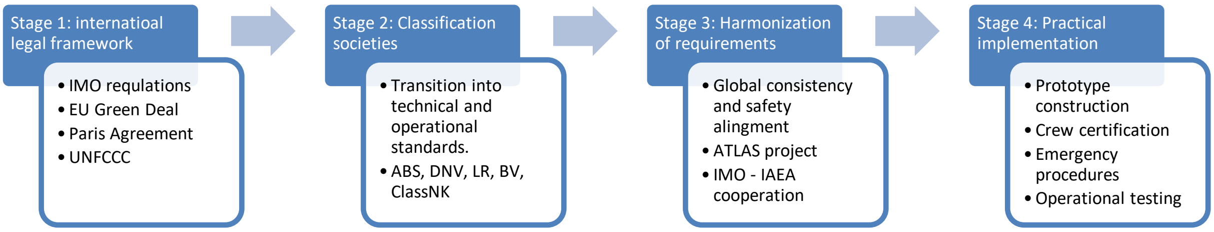

Figure 5. Generation 4 nuclear propulsion implementation roadmap, where: UNFCCC – United Nations Framework Convention on Climate Change, ABS – American Bureau Veritas, ClassNK – Nippon Kaiji Kyokai, LR – Lloyd's Register, DNV – Det Norske Veritas, ATLAS – Atomic Technology Licensed for Applications at Sea. [5]

There is lack of updated analyses of existing regulatory framework risks and adequacy relating to nuclear-powered ships. To create and update the regulatory framework strong ‘partnership’ would be required. Collaboration between industries, nations and international regulatory authorities is essential. [6]

International association of classification societies (IACS) has recognized nuclear powered propulsion as option to improve maritime operational efficiency and as an opportunity to improve marine decarbonization. They have recognized several key issues when nuclear power is adapted to commercial shipping, which will require multi-stakeholder collaboration and harmonized alignment with international frameworks. IACS is working together with International atomic energy agency (IAEA), International maritime organization (IMO) and flag states to improve nuclear energy solutions to safer and more transparent direction. IACS consider that nuclear power will introduce significant regulator challenges with political and public perception of nuclear energy. Technical challenges on safety operation and waste disposal with insurance and port state access are also challenges which will need lot of collaboration. [14]

EMSA recognizes that substantial amount of work will be needed to fulfill regulatory of nuclear power usage on merchant vessels. The regulatory framework might require modernization to fulfill all safety, environmental, technology integration and liability regimes. All nations do not support nuclear energy equally, even thought it could provide major benefits to meet emission-reduction goals. Affecting to improve the public opinions around of nuclear energy would be essentially important at areas with already low tolerance for nuclear applications. This would require precise regulatory and international oversight, also helping flag administrations smooth and coordinated actions as a whole. [6]

Public concern is one limitation of nuclear-powered ship operation, which relates to possibility of failures and so-one environmental contamination. Because of this, ports can prohibit nuclear vessels entrance to their territory, which again rises the need of clear regulations of nuclear-powered ship construction are important. [6]

2.1 Nuclear

Existing nuclear power related regulations are often focusing on land-based facilities, but at some cases also covering all activities, including marine [5].

‘Safeguard’ system administered by IAEA continuously oversights all nuclear fuel material to prevent proliferation. Any nuclear fuel at land and sea constitutes significant safety risk, which oversight response is at national regulatory. National regulatory is also responsible of risk and release of radiation, yard and port related emergency preparedness measures. National and international regulations need to be well coordinated to achieve internationally recognized nuclear installation, which is essential for achieving a commercially viable nuclear-powered ship. DNV considered preferred safety properties of maritime nuclear installation at international and national framework are listed on Table 2 below [4]. [5]

Table 2. DNV preferred safety properties of maritime nuclear installation at international and national framework. [4]

Main design properties	**Important aspect related to nuclear powered ship**	**Note**	**Reference to relevant regulatory system**
Safey	Modern safety levels, inharent safety, passive measures. No significant consequences when sinking at any environment. (Gen 3, Gen 4)		National reguirement, IMO requirements, IAEA recommondations
Emergency preparedness	Oversight and communication at all relevant situations.		National reguirement, IMO requirements, IAEA recommondations
Safeguards	Establish of international system for control and accountancy.	Requirements of monitoring from IAEA	IAEA requirements and national regulations
Security	Limited or no acces to reactor facilities, fresh and spent fuel when at sea.	Seurity and safety related possible conflict needs to be evaluated.	IAEA recommondations and national regulations
Non-proliferation	Fuel compositions and material not attractive for proliferation.	Enrichment limit 20 % of U235. Detailed assesment needed for fuel chain.	IAEA recommondations and national regulations

The nuclear energy maritime organization (NEMO) was recently established to support nuclear and shipping regulators when developing standards and regulations for construction, operation and decommissioning of nuclear installations. International regulatory framework by most areas is coordinated by IAEA. IAEA focus mainly to land based nuclear applications but also includes maritime nuclear installations, as all peaceful applications belongs under IAEA defined scope. IAEA's one main role is to monitor quantities of fissile materials spent in reactors and remaining as a fresh fuel. It promotes nuclear energy, set standards to minimize hazards and protect health and provides support services for commissioning nuclear energy. How to establish nuclear energy licensing for ships needs to be clarified by nuclear regulatory with shipping authorities and classification associates. [5]

As IAEA is organization of united nations (UN) it recommends responsibilities, tasks and principles. For detailed assessments and approvals come from national framework. This national responsibility includes for example security, safety, non-proliferation and licensing process. As national preference and practice need to be used when implementing recommended measures, a major unresolved issue of harmonization of regulations rises. This complicates international scaling of nuclear power plants. [5]

Beside new regulatory framework under development the globalization, geopolitical, digitalization and cyber security challenges rise. These are all making operational landscape of shipping stakeholders more complex, which is already even more dependent on new more effective propulsion, fuel and energy solutions to address strengthened global maritime demands. [7]

2.2 Existing regulatory framework

For maritime industry there is existing a well-functioning system with clear roles including, international organization, national governments, classification societies, shipowners and shipyards. For nuclear ship constructing and operation this background might be suitable starting point. [5]

Comprehensive rights and obligations of nuclear-powered ships were established in 1982 at the United Nations conventional law at the sea (UNCLOS). International convention of safety of life at sea (SOLAS) address safety management and emergency readiness. International convention for the prevention of pollution from ships (MARPOL) address measures for environmental protection. These are applicated also to nuclear-powered ships. So, in practice nuclear-powered ship has same right as conventional ships to innocent voyages and freedom of navigation in territorial seas, straits and high seas. However, at SOLAS only one specific reactor type provisions are considered at civil nuclear shipping, the PWR reactor, which is also the case with 1981 established code of safety for nuclear merchant ships (CSNMS). CSNMS provides design, construction, operational and certification guidance for nuclear-powered vessels. [5]

Also, several international and regional instruments exist. For example, international framework for co-operation between governments, local administrations, shipping and port industries is established in international ship and port facility security code (ISPS). This is done to identify security threats for ships or ports at international trade. [5]

At national and government level an important obligation lies with flag-, costal- and port states. For flag states several basic requirements are lied down in the SOLAS convection, including example safety certificates for nuclear passenger- and cargo ships. Coastal states on the other hand may set non-discriminatory requirements to safety and regulate own accessibility. This also includes emergency readiness if they have seen it necessary. Beside these port states plays important role related to verifying security, international compliance and with environmental standards. There are regional and international agreements targeting to uniform inspections and treatment of ships. Independent third-party organization role is fulfilled by classification societies. They work together with shipowner and shipyard with design, construction and operation, which support internationally uniform enforcement of safety framework of shipping. [5]

2.3 Environment

Global shipping needs to reduce GHG emissions, in particular carbon dioxide [15]. Traditionally ship propulsion systems emit GHG gases and other environmentally harmful pollutions [16]. According to data released by IMO, at 2020 ships were responsible of 457,000 tons of pollution. This highlights the criticality of changes towards environment friendly propulsion systems. [5]

International maritime organization (IMO) agreed in 2018 to reduce shipping GHG emissions to be aligned with UN's Paris agreement goals. This includes to reduce GHR emissions annually at least 50% by 2050, compared to 2008. This strategy was renewed in 2023, and the goal was set to reach net-zero GHG emissions by around 2050. This more ambition target would provide the impetus of transition towards international alternative energy sources. IMO's technical and financial measures have not yet been decided but as typical maritime vessel have lifetime more than 20 years, transition and progress need to be made quickly to new fleets. [7]

At Europe the European union package 'Fit for 55' was aimed to reduce GHG emissions by at least 55% at 2030, when comparing to 1990 [17]. This target was furthermore tightened up to reach climate neutrality by 2050. This was done with different initiatives such as the European green deal and 2030 climate target plan. These targets affect to all sectors, including marine, which all need to contribute to fulfill the targets. [6]

A solution for limiting emissions of shipping or at least to reach net-zero is to use renewable energy sources at ship propulsion system with zero emissions, such as nuclear energy[18].

2.4 Port, costal and flag states

Flag-, port- and costal states plays critical role in certification and its execution. Maritime nuclear fuel cycle demands specialized infrastructure, with yards and ports needed to be prepared to execute needed nuclear operations. [4]

Vessels that are operating internationally with possibility of no regular route between countries sets flag administrators and port states operational challenges because lack of uniform international regulation of nuclear-powered ships. Non-uniform safety standards between ship and port state might create accessibility challenges and delays, impacting ship efficiency on voyages. Additionally to possible decreased voyage efficiency it has been noticed that nuclear-powered ships might be better equipped for emission regulation related costs. [6]

2.5 Classification societies

The growing pressure of ship industry to adapt new propulsion technologies to improve energy efficiency and environmental performance is critical transition. Classification societies play critical role at this, to ensure innovative propulsion systems meet demanding requirements at technical, operational and environmental aspects. They just don’t inspect and certificate technical integrity of vessels but also works with developing the safety standards.[5]

Currently no governing uniform international standards exist related to civil nuclear-powered shipping. The safe introduction of nuclear technology to shipping is done by IAEA and their initiate of atomic technologies licensing for applications at sea (ATLAS) established in 2025. ATLAS with IMO aims to create comprehensive international framework for nuclear application usage in civil shipping. [5]

Classification societies play critical role of nuclear-powered vessels certification compliance. However, each third parti classification societies are developing their own guidelines and procedures. This is often done with collaboration of national nuclear regulators and flag administrators [19]. This is an issue of implementing nuclear power to commercial vessels, as there is discrepancies in classification society requirements [20]. Lack of harmonization between classification societies were identified according to key areas, such as operational safety, radiological protection of crew, environment and waste management. Also, differences at crew training, certification and international qualification recognition were obtained. M. Drosińska-Komor et. al. [5] complied comparison of classification societies and their approach to nuclear propulsion is presented on Table 3 below. [5]

Table 3. comparison of classification societies and their approach to nuclear propulsion.

BV – Bureau Veritas, FNPP – Floating nuclear power plant.

Classification society	**Regulatory framework for nuclear propulsion**	**Specific guidelines /standards**	**Cooperation with state authorities**	**Specific challenges/remarks**
DNV	No dedicated framework, work of guidelines in progress.	Case studies, reports, predictions	Yes	Need for new international regulations and harmonization of rules
LR	Assessment of existing regulatory, studies	Regulatory assessment studies, nuclear code	Yes	Legal change required, adaptation to new technologies, close cooperation with flag administration and regulatory bodies
ABS	Detailed requirements for FNPP and offshore units	ABS rules for FNPP	Yes	Cooperation with nuclear regulators, need to integrate classification requirements with national and international regulations
BV	Technology analysis, participation on pilot projects	Guidelines for new technologies, innovation qualification	Yes	Qualification of new solutions, assessment of compliance with international and local standards
ClassNK	General guidelines, development monitoring	Guidelines for alternative fuels, Energy efficiency design index	Yes	Adaptation of national regulations, need to update guidelines for nuclear propulsion

3 Functional requirements of maritime nuclear reactor

Safety is one critical aspect for marine reactors. For example, a passive cooling system working for extended periods without external power is required. Furthermore, maritime reactors need to handle extreme environmental conditions, such as harsh weather and extreme cold, especially at arctic areas and icebreakers. Maritime reactors and its systems also need to tolerate different ship movement. Shocks and vibrations from ship hull and to be resistance to possible collision. [5]

At 1981 established IMO Code of safety for nuclear merchant ships (CSNMS) [21] following requirements for design class 1 ships movements are defined. Static list of 30°, rolling up to 45°, inclination up to 10° either to fore or aft direction. Ship should also tolerate all combinations of previous angles within those limits.

Maritime reactors operating remote areas also needs long operational autonomy without need of refueling. Modern reactors have shown to operate up to 20-30 years without refueling and Loyd's Register predicts that hull lifetimes could extend up to 50 years if nuclear propulsion becomes widespread. [5]

Compared to land-based nuclear reactors maritime reactors need to be significantly smaller and lighter to fit different types of vessels and small compartments. [5] Marine reactors differ lot from land-based applications with different power demands. land-based applications are typically operating with constant power demand and relatively low versatility on output. Marine reactors will face different power demand during operation. This would occur for example maneuvering, docking and different ice conditions, demanding rapid load following. At nuclear reactors there is two ways for load following. First is to rely nuclear reactor specific characteristics and second possibility is to implement appropriately sized energy storage between reactor system and load. The storage could be electricity, heat or mechanical energy, which might be needed to different loads such as varying propulsion demand. First option of reactor power adjustment is important for load following but extra energy storage bring more flexibility to the whole system, which usage might also avoid short-term reactor power adjustments. [6]

4 Motivation for nuclear power at concept ship

Nuclear power at ships features with several benefits, such as long refueling interval, very long range and it has no emissions during operation [8]. Nuclear power usage on operation enables possibility for higher speed with more feasible economic, even with larger vessels [4]. Nuclear power and in particularly SMR's would be suitable for vessels with need of long refueling intervals, high operational autonomy and high-power demand [22].

4.1 Nuclear power compared to conventional energy sources

When comparing nuclear power to conventional fossil fuel-based propulsion its main benefit relates to different fuel properties. Its fuel is very dense reducing conventional fuel cargo space, with long refueling periods [23]. This would offer possibility to power long voyages without refueling [24]. Refueling times are varying from 18 months up to whole reactor lifetime more than 20 years. The energy autonomy could offer higher speed even with larger vessels and possibility to produce hydrogen for usage at fuel cell. [8]

Nuclear-powered propulsion is potential way to improve decarbonization at shipping, bypassing other green fuels, which production could be energy intensive. Nuclear propulsion produces almost no well-to-wake (WTW) emissions. As it uses fission reaction without fossil fuels and combustion, nuclear reactors have zero GHG tank-to-wake emissions during operation. Also, the emissions produced during uranium extraction, processing and transportation, so called upstream well-to-tank (WTT) emissions are relatively low. This offers significant environmental benefits and works as additional incentive for investments with possibility to improve public acceptance. [6]

M. Drosińska–Komor et.al [5] presented how Generation 4 rector at marine usage would respond to SDG targets set by UN. They concluded that using Generation 4 reactors are in line with sustainable development for both, environmental and socio-economic context. Although Generation 4 technologies have high initial cost, they also described the economic benefits highlighting increased ship cargo space, nuclear fuel price stability and possibility of selling green certificates. Although the technology has high initial costs, it will allow improvement of energy availability, environmental protection and emission reduction.

Emissions of nuclear power comes only from the production process. When comparing nuclear power to fossil fueled vessels the difference of CO2 emissions per kWh is over 98 % lower for nuclear power, which comes from the trade-off of nuclear power producing high-level, intermediate or low-level nuclear waste. At nuclear power no air pollutions are made when comparing to fossil fuel-based power sources. Possibility of using Thorium as a nuclear fuel can be large benefit at reducing waste longevity and its tails. Houtkoop et. al. [8] presented Table 4 below shows environmental impact differences between conventional and nuclear power. It should be noted that there is no generally accepted way to compare emissions and nuclear waste. [8]

Table 4. Environmental impact differences between conventional and nuclear power. [8]

	Conventionally fueled		**Nuclear power based**	
CO2 equivalent	Well-to-tank	95 g CO2 / kWh	Production process	12 g CO2 / kWh
	Tank-to-wake	568 g CO2 / kWh		
Air pollution	SOx and NOx particles		No	
Solid waste	No		High level waste	
			Low / intermediate level waste	
			Mining by-products	
			Decommissioning waste	

Nuclear power with relatively stable fuel cost and long refueling interval offers well aligned financial structure over whole ship lifetime, especially with advanced reactors such as SMRs. Although nuclear power has high upfront costs CAPEX, lower OPEX can be achieved over time as oil prices and carbon taxes increases. It has potential to become most cost-effective zero direct emission solution for shipping [5]. At DNV case study [4] it is considered that nuclear power can outperform other conventional technologies at both low and high fuel price scenarios. [6]

Nuclear-powered vessels have high upfront costs CAPEX, with many estimations to vary from US 3800 to 6900 per kW installed [25], [26]. This is roughly 10 times higher than conventional marine power plants. Nuclear power OPEX is lower than conventional power because significantly lower fuel cost. Houtkoop et. al. [8] presented Figure 6 below shows total lifetime costs for 30MW installed conventional and nuclear power. Nuclear fuel price was estimated to be between USD 2500 and USD 10000 per kg, which would response between USD 0.005 and US 0.02 per kWh [26]. Conventional fuel was estimated to vary from USD 0.07 to US 0.28 per kWh. Other fixed lifetime costs, without considering fuel costs for nuclear power were estimated to be 3 times higher than conventional combustion power [26]. It should be noted that nuclear-powered ship crew sizes are higher to ensure nuclear safety onboard, also effecting to operation costs of the ship [23]. [8]

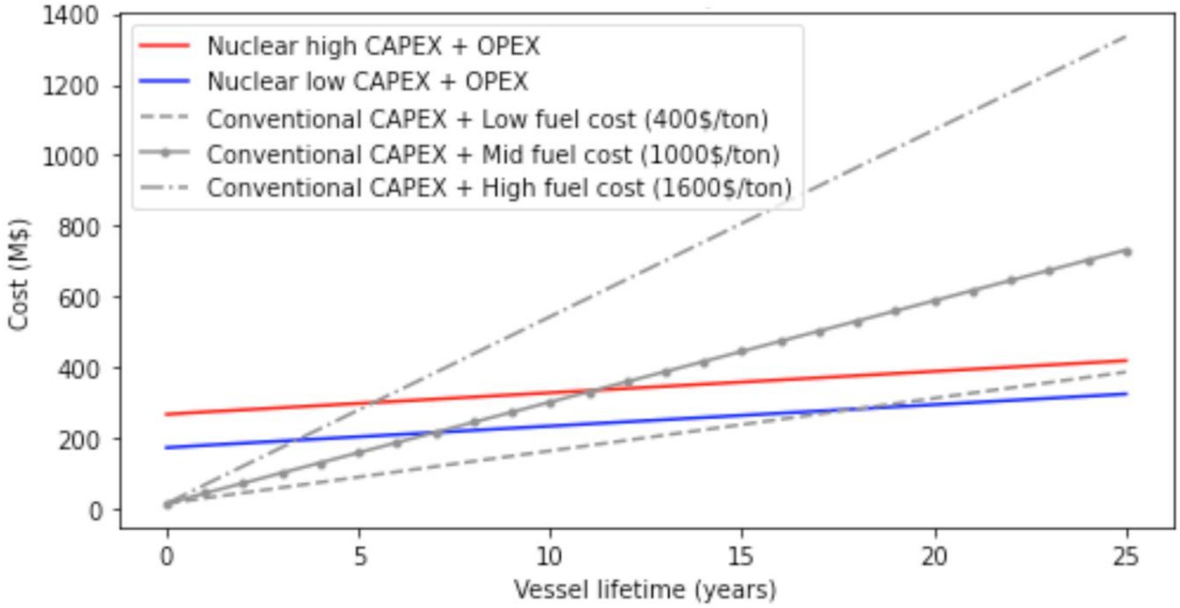

Figure 6. Comparison of lifetime cost between conventional and nuclear power. [8]

M. Drosińska-Komor et. al. [5] presented other estimation of total lifecycle coats for 25-year lifetime ship using conventional, nuclear and green synthesis fuel, is presented on Figure 7 below. Conventional and nuclear power were estimated to be approximately same (USD 500 million), with conventional fuel price at USD 600/t. This also responses to figure 6 above, where low-cost conventional fuel and nuclear power are approximately same at lifetime of 25-years. At the figure, green synthesis fuels were estimated by international energy agency (IEA) to be 4-6x expensive than conventional fuels, total life cycle costs reaching up to USD 2 billion. [5]

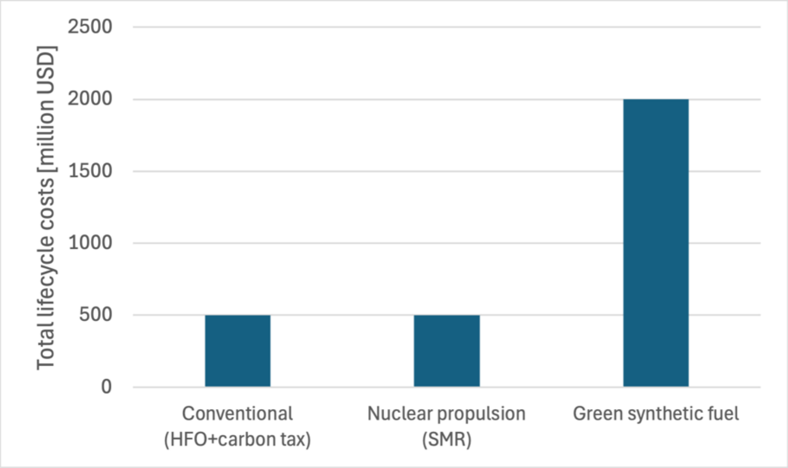

Figure 7. Comparison of total 25-year lifecycle cost (CapEx + OpEx) of conventional fuel, nuclear based and green synthetic fuel. HFO - heavy fuel oil [5]

When comparing weight and volume of conventional and nuclear-powered vessels it is important to notice that nuclear power will replace conventional fuel weight and space. Houtkoop et. al. [8] presented Figure 8 below shows the weight comparison of conventional ship fuel and nuclear reactor estimation as function of power. [8]

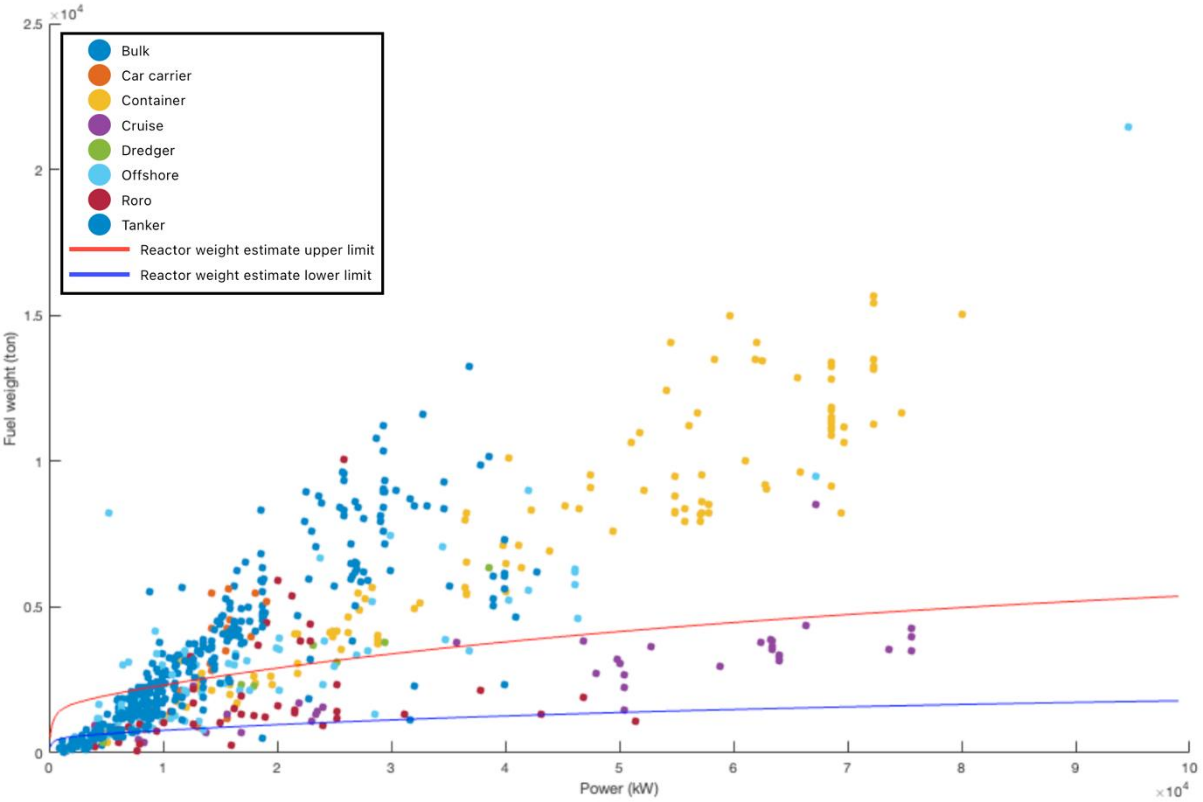

Figure 8. Weight comparison of estimated reactor weight and conventional fuel weight of currently used vessels. Dots – conventional fuel weights at different used ships, lines – estimated high and low reactor weight. [8]

5 Nuclear power

All reactors on maritime usage differ from land-based equivalents. Mobility, exposure to harsh sea conditions and operational profile are main characteristics when compared to land-based reactors. The operational purpose effects lot to the maritime installation. Nuclear reactors can work as o power source for propulsion at nuclear-powered-ship (NPS) or as power generation at floating nuclear power plant (FNPP). [4]

Standardized small sized and with passive safety system equipped reactors may offer advantage for merchant shipping. Also, minimal crew requirement is beneficial for merchant usage. [4] There are three developments that could affect positively for commercial shipping. These are Small modular reactors, Generation 4 technology and the possibility of using thorium instead of uranium. [8]

5.1 Basic information

Nuclear reactor produces energy with controlled fission chain reaction that produces heat on the reactor. Heat is transferred to hot coolant and media material, which is driven through turbines that produces electricity. Nuclear reactor operation principle shares similarities with other powerplants that use coal or natural gas. [6]

Fission process is controlled by regulating density of free neutrons, which is commonly done with active measures raising or lowering neutron absorbing control rods [27]. Passive measures of the fission process regulation are related to physic of the reaction, which are often referred to feedback coefficient [8]. Reactivity can also be affected with blanket or reflector at outer side of the reactor core, absorbing or reflecting neutrons and so-one increasing possibility of neutrons to engage to fission reaction or be absorbed by a fertile material [27].

5.1.1 Nuclear criticality

When nuclear reactor can sustain by itself series of fission reactions without external assist is called critical state. At this state the rate of produced neutrons equals to amount of they are lost completely out from the system or with absorption. Criticality is crucial for nuclear reactor operation, safe handling of fissile material and nuclear engineering. [6]

Beside fission, also absorption and simple collision interaction can happen to neutron. At absorption, neutron is removed from chain reaction by absorption to nucleus. Collisions on the other hand can be either elastic or inelastic; were neutron gives its energy to nucleus without causing it to split. Critical state is achieved when every fission event releases enough neutrons to cause on average one more fission event. At the critical state the multiplication factor (k) equals to 1. If $k<1$, it indicates a subcritical state, where reactor will slow down and eventually stop. If $k>1$, it indicates supercritical state, which can lead to increased power output and be potentially a dangerous condition. The safe and stable operation of reactor requires maintaining a critical state. It is done by adjusting control rods made from material that absorbs neutrons and with moderator and coolant materials. [6]

5.1.2 Maritime nuclear fuel cycle

Maritime nuclear fuel cycle includes front end, operation and back end. Front end includes activities before reactor, such as fuel production (mining, enrichment, fuel fabrication) and logistics. Back end includes fuel post-use management, such as waste disposal and potential processing of the used nuclear fuel. Mining and milling are examples that are identical for both the maritime and the land-based nuclear fuel cycles. For maritime applications fuel production needs more attention for specific reactors, especially fuel qualification and fabrication. Maritime nuclear fuel cycle will in the end vary a lot from land-based fuel cycle, where shipyards and ports working as a key physical and logistical actors. [4]

5.1.2.1 Front end of maritime nuclear fuel cycle

Nuclear fuel is the most fundamental characteristic at nuclear reactor. It contains fissile material providing the needed energy. Nuclear fuel contains fissile material, which can be Uranium U-235, Uranium U-233 or plutonium Pu-239, where U-235 is the only fissile material found in nature. Mined uranium ore contains only 0.7% of U-235 and that’s why nuclear fuel is typically enriched to approximately 3-5% of U235. Low enrichment uranium (LEU) is referred with enrichment level under 20% and high enrichment uranium (HEU) above that [8]. Enrichemnt level 20% is a maximum limit for civilian application as higher enrichment level increases proliferation risks. Thorium Th-232 and Uranium U-238 are called fertile material, which are used on reactor to produce some other fissile material from itself. Th-232 decays to U-233, and U-238 decays to Pu-239 [8]. [4]

5.1.2.2 Operation of maritime nuclear fuel cycle

At nuclear reactor the fission process happens in the fuel. At fission process neutrons, energy and fission products is produced. Neutrons split new uranium atoms sustaining chain reaction enabling reactor to operate at constant power. The released heat can be utilized in a controlled manner. [4]

Fission process can occur with fast or slow (thermal) neutrons. Fast neutrons keep up the chain reaction with neutrons coming straight from the fission and slow neutrons are slowed down with moderator material, which regulate the fission reaction by slowing down neutrons. Moderator materials consist light element, for example water and graphite is used as a moderator material. Moderator material, neutron spectrum, together with coolant material such as water, heavy water, helium, salt or metal determines the type of the reactor. [4]

As in fast reactors neutrons are not slowed down, it allows more compact core design. On the other hand, it makes the reaction more complex and harder to control, which is why only few fast reactors have been put in operation. At fast reactors breeding is more feasible. In breeding reactor more fissile material is produced from fertile material than consumed. [8]. Breeding reactors are more relevant for land-based application than maritime mobile facilities, where fuel handing is more complex. [4]

5.1.2.3 Back end of maritime nuclear fuel cycle

For maritime-nuclear-fuel-cycle back end, the most critical part is the management of spent fuel, which contains major part of the radiation. For marine reactor different operational profiles, the reactor types and burnup rates vary, effecting to spend fuel characteristics. Because of this, spend fuel management requires specialized handling strategies. When spent fuel is extracted from the reactor it needs to be stored extended period to cool down enough for further processing. Best approach is to schedule nuclear operations together with ship regular maintenances. This also requires well-coordinated supply chain and proper infrastructure, effecting to shipyard and port design and equipment. [4]

Fission products such as strontium-90 and cesium-137 are highly radioactive and form key components of spent nuclear fuel. These consists of most part of the radiation produced at the fuel, causing high radiation risk. While operating nuclear reactor produces continuously spent fuel and radioactive waste, which requires active waste management onboard and regular extraction from the ship. [4]

If spent fuel is not processed for reuse it is preferred as open cycle, or as once-through fuel cycle. With fuel reuse processing it is preferred as closed cycle. It is possible to extract uranium from generic fuel types, such as pebbles or homogeneous mixtures and reuse it on bigger land-based reactors. Online refueling opens possibilities of flexibility but also introduces safety and security risks. It has relatively complex design, where fresh nuclear fuel be added to reactor during operation. [4]

5.1.3 Nuclear fuel

Nuclear fuels have high melting point, which is crucial at maintaining structural integrity of the fuel even at high temperatures. The efficiency of transferring thermal energy from fuel to coolant depends on fuel density and thermal conductivity. For example, uranium oxide (UO_2), typical fuel form used in pellets melts at 2,865°C. (UO_2) has on the other hand relatively low thermal conductivity, also effecting fuel rod design to prevent overheating. [6]

TRI-structural isotropic particles (TRISO) fuel is an advanced nuclear fuel type, especially designed for maximum safety, durability and containment under extreme operational conditions. TRISO fuel is composed from balls with diameter of 6 cm [28]. Each TRISO particle is formed with uranium kernel encapsulated with three protective layers. Inner protective layer is porous carbon buffer, middle one is a dense pyrolytic carbon layer, and outer layer is silicon carbide (SiC). By this multi-layer encased structure, fuel is self-contained and each particle acts as its own containment vessel. TRISO fuel remains its mechanical and chemical stability and prevents radioactive leakage even in case of emergency and with temperature exceeding 1600°C [29], [30]. TRISO particle safety features make it almost meltdown-proof at conditions that could be dangerous for traditional nuclear fuels. Even in case of accidental damage or extreme environmental conditions TRISO particles ensures containment of the fuel, making it very resilient. TRISO fuel has also extended life cycle, aligning with maritime application long operational durations. Based on these features TRISO fuel is well suitable for merchant maritime applications. [6]

Thorium is seen as an alternative fuel to currently used enriched uranium. Thorium occurs high abundance on earth when compared to uranium [31]. Thorium fuel cycle improves proliferation resistance and reduces long-lived nuclear waste, with less than 300 years of required storage [32]. [8]

5.1.4 Nuclear reactor capacity

At nuclear power plant the produced electrical power in megawatts (MWe) is typically about one third of the produced thermal power in megawatts (MWt). This loss is result from the energy conversion of heat to electricity with working medium. The efficiency is approximately same when comparing to fossil-fueled power plants, but lower than some modern gas-fired plants. The power plant efficiency is highly depending on this relationship between electrical and thermal output. [6]

Burnup and capacity factor together indicates nuclear reactor efficient usage of fuel and capability to sustaining energy production over time. Burnup indicates the amount of thermal energy that can be extracted from certain amount of fuel, generally given in unit of gigawatt days per metric ton of uranium (GWd/MTU). It is calculated based on total thermal energy output in relation to initial mass of nuclear fuel. High burnup rate is favored, increasing refueling interval and decreasing volume of spent fuel generated. Some advanced reactors can reach to burnup level of 60 GWd/MTU or more. The capacity factor describes operational efficiency and reliability of nuclear power plant and therefor is critical value to evaluate reactor performance. It is defined as a ratio of produced electricity over certain period of time to the amount of electricity it would have produced if it was operated the same time at full capacity. It is influenced by interruptions by maintenance, repairs and assemblies. [6]

5.2 Small modular reactors

Small modular reactors (SMR) are Generation 4 reactors, which electrical output is defined by IAEA to be less than 300 MW [33]. SMR coolant depend on the reactor type, and it can use water, gas, lead or salt as coolant [34]. It offers alternative for larger nuclear reactors, with smaller size and passive safety features improving its safety. With smaller dimensions, possibility of serial produced components and shorter production time makes it more economical technology [35], [36]. Because of these features SMRs are suitable for most ships, also including smaller ones with reactor electrical power starting already from few megawatts. [5]

Security systems at SMRs need to include several design aspects for example fuel type, reactor core structure, how the spent fuel, radioactive waste and transportation is handled. One major problem with reactors is the possibility of dismantling of the reactor and use fissile material for criminal purpose. The nonproliferation is controlled by IAEA [5]

To improve perspective of nuclear energy evolving cost-efficiency and further improved safety, with respect to international framework, can be achieved due development of SMR technologies. Development of different reactor technologies and different approaches of fuel, coolant and safety is ongoing in companies at multiple countries. Preliminary statement of regulators is that efficient implementation of SMR technologies worldwide still needs further changes on way of working. Several smaller reactor designs with high level of standardization could play important role when licensing burden for maritime usage is tried to be reduced. [4]

The goal of SMRs is to increase production rate, volume, applicability and to reduce costs [8]. SMRs modular design could enable mass production of reactor units and drive transportation and installations to more efficient way. SMR specifies the size of the reactor, but the reactor technologies can vary lot. SMR designs can be based on traditional PWR reactor, while some can be designed with more advanced materials and cooling systems targeting even more efficient operation. [6]

5.3 Generation 4 reactors

Generation 4 reactor designs goal is to develop advanced reactors that are safer, more sustainable, produces less waste and are proliferation resistant. Generation 4 nuclear reactor offers potential over reactor operational efficiency, higher energy output, longer fuel lifetime and potentially smaller reactor footprint, which could offer good solution for maritime power systems. The Generation 4 international forum (GIF) is focusing on four areas: Safety, sustainability, economics and proliferation resistance [5]. GIF brings together 13 countries and is leading the development of some advanced reactor concepts, with target to implement them to industrial usage by 2030. Following six reactor technologies are focused on GIF development: [6]

- Very high-temperature reactor (VHTR)
- Gas-cooled fast reactor (GFR)
- Lead-cooled fast reactor (LFR)
- Sodium-cooled fast reactor (SFR)
- Super critical water reactor (SCWR)
- Molten salt reactor (MSR)

Generation 4 reactors high efficiency and passive safety systems offer benefits for ship-based solutions. Due the high efficiency and burnup, reactors are capable to produce more energy than before from same amount of fuel, which will increase refueling intervals [37]. Passive safety systems on Generation 4 reactors works without electrical power and human interaction totally by natural processes such as gravity or convection, minimizing risk of human errors. These reliable safety systems are crucial for vessels especially with long range away from land. For maritime applications small Generation 4 reactors can be considered as most promising choice. [5]

One of Generation 4 reactors main disadvantages it the high initial cost, with most of the reactors being still on development phase requiring permits and trained crew. Based on DNV's Maritime impact 17 analysis, nuclear propulsion could be financially feasible if reactor prices decrease to level of USD 35 – 40 million annually. [5]

5.4 Reactor type classification

Nuclear reactors have various designs with unique approach to achieve safety and efficient conversion of nuclear energy to electricity. In general, all nuclear reactor designs deploy energy from fission reaction at fuel and includes different material choices to affect the fission process and radiation safety. Different reactor designs can be extensively categorized according to energy spectrum of the reactor as thermal or fast, with moderator material used on thermal reactors and with used coolant material. [6]

There are other additional classifications of Generation 4 reactors. They can be categorized based on thermal power or physical size of the reactor. Both are further categorized to small, medium or large thermal power output or physical size. It should be noted that reactors could have similar thermal outputs but different dimensions, depending on reactor technology, coolant material and safety systems.

At following chapters different reactor classifications are presented, with properties related to the reactor type. Reactor types considered are from Generation 4 international forum focused reactor technologies presented on Chapter 5.3.

5.4.1 Reactor classification by reaction type

Classification of reaction type is based on speed of neutrons that sustain the fission chain reaction. This classification divides reactors either thermal or of fast nuclear reactors. [6]

5.4.1.1 Thermal nuclear reactors

At thermal nuclear reactors (TNR) moderator material is used to slow down neutrons to sustain fission chain reaction. Thermal nuclear reactors follow the fundamental principle that U-235 is more susceptible for fission when it is hit by slow (thermal) neutrons rather than fast neutrons. Because of this characteristic TNRs have good operational efficiency. Used moderator materials have their own properties making it effective to slow down neutrons and improve fission reactions with U-235. At TNR wider range of nuclear fuel types can be used, such as natural uranium or slightly enriched uranium, with U-235 concentration around 2-5 %. Burnup levels of TNRs can reach up to 40 – 60 GWd/MTU, compared to 20 – 30 GWd/MTU burnup in some fast reactors. Due this efficiency TNRs refueling intervals can be increased, which makes them suitable for marine application. [6]

5.4.1.2 Fast nuclear reactors

Fast nuclear reactors (FNRs) and fast breeder reactors (FBRs) operate with fast neutrons driving fission process without moderator material. FNR typically requires more enriched nuclear fuel. At breeder reactors more fissile material is produced from fertile material than consumed, also improving the overall efficiency of nuclear power generation. For example, GFR, LFR and SFR are Fast nuclear reactor, but also VHTR/HTGR and MSR can be designed to operate with fast-neutron spectrum. The operational efficiency for FNR is estimated to be 60 % greater than with traditional nuclear reactors, which is partly reason from usage of liquid-metal coolants. [6]

There are also challenges with FNR technology. The need to extract heat efficiently from reactor and its potential for more dynamic behavior are major concerns of FNRs. Usage of metallic nature fuel enables more stable operation, with better control of the fission process. Using metal as coolant enables efficient heat extraction improving thermal efficiency and allows reactor to operate with higher operation temperature, but also results challenges on reactor design. Other coolants such as liquid sodium rises more challenges on safety and design due its high chemical reactivity with need for special handling and containment. [6]

FNRs could play crucial role to solve some of most presence concerns related to nuclear energy. By optimizing usage of available nuclear materials and minimizing waste, It could solve concerns related to proliferation risk, long-lived radioactive waste management and sustainability of nuclear fuel. [6]

5.4.2 Reactor classification by coolant material

Classification based on coolant material focuses on substant used to extract heat from reactor core. Coolant material is a critical characteristic when converting nuclear energy to electricity. Different coolant materials are used on different reactor designs to optimize reactor performance. Coolant material selection can be done to optimize different operational goals, such as passive safety, efficiency or ability to use alternative fuels. [6]

5.4.2.1 Very high-temperature reactor (VHTR)

High temperature gas reactors (HTGR) are graphite moderator reactors with helium coolant, primary developed in 20th century. The outlet temperature is approximately 750°C – 950°C, which is higher than with conventional reactor but lower than very high temperature reactors (VHTR) [38]. Even though VHTR and HTGR are not always classified as a FNR, VHTR and HTGR can be configured to work with fast-neutron spectrum [6]. [5]

VHTR are developed to replace HTGRs [39]. They can operate with temperatures approximately 700°C – 1000°C, which improves thermal efficiency of the reactor up to 50 % in electricity production [40]. Due the high temperature, these reactors are also suitable for applications beyond electricity production, for example hydrogen production and industrial heat processes [6]. VHTRs uses graphite as moderator and helium as coolant. Helium is chemically inert, noncorrosive, nonflammable and it does not become radioactive when exposed to radiation. These coolant characteristics extends material lifetime and improves safety of people on board. On the other hand, gases have generally lower thermal conductivity than liquid coolants, such as water or molten salt, which effect to reactor heat transfer efficiency and requires design actions to maintain sufficient cooling [6]. VHTRs also features passive safety systems without human interaction or external power source [28]. [5]

VHTRs high output temperature offers highly increased conversion efficiency. Different types of VHTRs under development offers different types of fuel arrangement. It can be featured with pebble type fuel, allowing online refueling or with prismatic type fuel, which can be refueled only offline. There are multiple small-scale tests of VHTRs build and operated over past decades making the technology relatively well developed. [8]

For power convention VHTRs can operate with direct cycle or indirect cycle [41]. Direct cycle with gas turbine benefits with simple design improving its reliability, while indirect cycle is more complex and requires some additional components. Direct cycle is also more efficient than indirect cycle because higher temperature of medium at turbine inlet. Using direct cycle on the other hand has some disadvantages to potentially contaminate non-nuclear components with radionuclides carried by the helium. Because of this purification system is installed to remove undesired particles from helium [42]. [5]

5.4.2.2 Gas-cooled fast reactor (GFR)

Gas-cooled fast reactors (GFR) use typically helium as coolant offering excellent heat transfer properties with low operational pressure. GFRs can operate with closed fuel cycle and are characterized with high thermodynamic efficiency. The design allows efficient usage of plutonium or other transuranic waste [43]. GFRs can use nitride nuclear fuels, which features high thermal stability and are suited with gaseous coolants. As GFRs are gas cooled it has high operational temperature of up to 850°C – 950°C. The high temperature allows reactors to operate with supercritical Brayton cycle and thermodynamic efficiency reaching up to 48%. [5]

Structural materials used on GFRs is challenge due high operational temperature and high intensity of neutron radiation. Investigations on usage of advanced materials such as ceramics and metal alloys to prevent corrosion and embrittlement are ongoing. [5]

5.4.2.3 Lead-cooled fast reactor (LFR)

Lead-cooled fast reactor (LFR) uses lead or lead-bismuth eutectic as a coolant, having high boiling point and allowing the reactor to operate at elevated temperature without pressurization. Metallic coolant enables favored thermodynamic properties, thermal conductivity, low operational pressure, chemical inertness and good radiation shielding. On the other hand liquid metal coolant causes corrosion [44]. When comparing LFRs to sodium-cooled reactors (SFR), LFRs provides improved temperature control and coolant circulation [5]. [6]

LFRs can operate with closed fuel cycle making use of nuclear fuel more efficient. Problem with structural material corrosion and embrittlement with liquid lead coolant remains as a problem [45]. [5]

5.4.2.4 Sodium-cooled fast reactor (SFR)

From the used liquid-metal coolant materials Sodium is most used, even though its corrosive properties. At sodium-cooled fast reactors (SFR) used sodium has low melting point, excellent heat-transfer properties and it does not slow down neutrons, which makes it ideal for FNR usage. [6]

Sodium has excellent thermal properties, removing heat from reactor more efficiently. Sodium does not absorb neutrons, and it remains liquid at relatively low pressure, reducing risks related to high pressure reactors. On the other hand, sodium is highly reactive material with water and air, raising significant challenges and requiring additional safety systems [46]. [5]

5.4.2.5 Supercritical water reactor (SCWR)

Super critical water reactor (SCWR) uses water as a coolant and working fluid on the turbine cycle at supercritical pressure and temperature. It offers improved thermal efficiency and reduces system complexity without the need for converting liquid to steam. As there is no phase change on SCWRs, possibility of boiling crisis during normal operation is not possible [5]. SCWRs materials needs to tolerate high temperature and pressure, causing material science and engineering challenges. Currently SCWRs are not commercially available but research and development is ongoing [5]. [6]

The supercritical state where water is held is above 22.06 MPa of pressure and temperature above 374°C [47]. At this state, the difference between gas and liquid vanishes, eliminating the need of steam generation. These characteristics increases thermal efficiency potentially to 45 % or more, which can be compared to PWR and

BWR thermal efficiency 30 – 36 %. High temperature and pressure allow SCWRs to use more compact turbine systems, which enables simpler design. [6]

Operation of SCWRs is based on technologies of LWR and supercritical coal-fired boilers. Depending on core design SCWR can operate with fast or thermal neutron spectrum [48]. With thermal neutron design open uranium fuel cycle is used and with fast neutron spectrum closed fuel cycle can be used with different fuels, such as mixtures of uranium, plutonium and thorium. Enrichment of fuel can vary from 5 % to 20 %. SCWRs can additionally be designed to converter reactors, were non-fissile materials such as U-238 is converted to fissile isotopes such as U-239 for later usage as fuel [49].

5.4.2.6 Molten salt reactor (MSR)

Molten salt reactor (MSR) uses molten salt, fluoride or chloride, such as lithium fluoride as a coolant. At some reactor designs molten salt is also used as a medium where the nuclear fuel is dissolved. MSRs can have high operation temperature with improved thermal efficiency and offer inherent safety features with passive heat removal. MSRs can be used for propulsion at ships, where high demand of power and long-term autonomy is required without refueling [5]. MSRs advantages have known since its prototype operated from 1966 to 1969 as a research reactor [5]. [6]

The design featuring nuclear fuel dissolved in the carries salt enables the reactor to operate high temperatures at range of 650°C – 800°C, significantly increasing thermal efficiency [50]. Because the high operational temperature more efficient thermodynamic cycles can be used, such as supercritical Brayton cycle, to improve power generation [50]. The operational pressure of MSRs is low, near atmospheric pressure, eliminating possibility of explosion [51]. MSRs one disadvantage is the requirements related to used materials, as a result of high temperature and corrosion caused by the salt [5]. [6]

One advantage of MSRs is their inherent safety, due salt used as coolant and or moderator is chemically stable and does not react explosively with air or water. In case of failure the liquid fuel can be cooled down or transported to safety, which minimizes potential for catastrophe for population and environment [52]. MSRs can in case of overheating rely on passive safety feature, such as freeze plug, which is a solid block of salt that melts in case of overheating and lets the molten salt to drain into safe containment where nuclear reaction is stopped. This is relatively simple safety system and eliminates need for more complex active safety systems. [6]

MSRs can use various types of nuclear fuel, such as low-enriched uranium, thorium or plutonium, which makes them capable for breeding fuel. The fuel recycling while operation makes the MSRs long-term nuclear fuel generation relatively low and so on improving reactor footprint. [6]

5.5 Reactor type suitability for merchant applications

Currently only PWRs and LFRs reactor technologies have completely implemented to ship propulsion. PWRs are most used reactors, while LFRs are historically used on military vessels. LFRs coolant and required extensive shielding increases weight, which makes it challenging option at some cases if compactness and weight is prioritized [8]. PWRs are widely used on navies but causes difficulties at usage of merchant ship propulsion integration and operation, due different design priorities. Merchant ships usually target to prioritize cargo capacity and fuel efficiency, which might be challenging to reach with usage of PWRs. Other reactor technologies remain conceptual. [6]

At study done by EMSA [6] SFRs are considered unsuitable for marine reactors due the used liquid sodium coolant high reactivity with water. GFRs operates with high pressurized containment system with inert gas cooling, which increases system complexity. GFRs shows potential to land based models, but specific operational and safety demands on marine environment makes them less suitable for marine applications. [6]

At study done by EMSA [6] LFRs, MSRs, VHTR and HTGR are considered to offers strong potential for vessel propulsion. LFRs and MSRs are suitable especially for long-distance and deep-sea applications due their long refueling intervals and inherent safety features. MSRs inherit many benefits of VHTR/HTGR reactors but can in long term offer promising alternative, with possibility to operate with thorium and have theoretically better load-following capabilities. On the other hand, LFRs and MSRs lower technology readiness and public uncertainty of operation and handling cause challenges when compared to PWRs. VHTRs and HTGRs are also considered as a potential technology, with their high thermal efficiency and stable safety, especially with usage of TRISO fuel. For merchant shipping VHTRs and HTGRs offers low waste generation and strong load-following capabilities aligning well with marine propulsion power requirements. VHTR/HTGR reactors are most likely be used over more conventional PWRs, because improved burnup, ability for higher operational temperature and possibility for continuous refueling. As VHTR/HTGR reactors are Generation 4 reactor they offer also significant safety and improved proliferation resistance. On the other hand, VHTRs and HTGRs requires heavy shielding and causes similar challenges as LFRs and MSRs relating to technology readiness and public acceptance. Even though PWRs hold highest technology readiness all LFRs, MSRs, VHTRs and HTGRs offers high potential for maritime industry. [6]

According to Houtkoop et al [8] study, looking to future (10 – 20) years, VHTR reactors are seen more suitable for marine applications than more developed PWRs. VHTR has improved burnup, higher operational temperature and possibility for online refueling. As it is Generation 4 reactor it also offers development on safety features and non-proliferation. For long term development approximately more than 20 years MSR can be potential option with more potential than other fast reactors. [8]

6 Nuclear power plant at ship

IACS defines nuclear-powered ships as “self-propelled vessels with an onboard nuclear fission reactor providing power generation for propulsion and auxiliary service.” [14]

Nuclear powerplant differs from traditional steam powerplant mainly with the heat production method. At nuclear powerplants there is nuclear reactor and steam generators instead of boiler. [53] Nuclear power plant energy system includes conversion of nuclear fuel to thermal energy and electricity and its distribution. In its entirety from nuclear reaction to electrical grid several losses and efficiencies are involved. Understanding the whole picture is important when evaluating the nuclear power plant efficiency and environmental impacts. [6]

The thermal energy produced on nuclear reactor fission reactor needs to be distributed as hot coolant, which needs to be converted to either mechanical or electrical energy in order to use the energy. A simplified overview of nuclear based marine power and propulsion system is shown on Figure 9 below. [8]

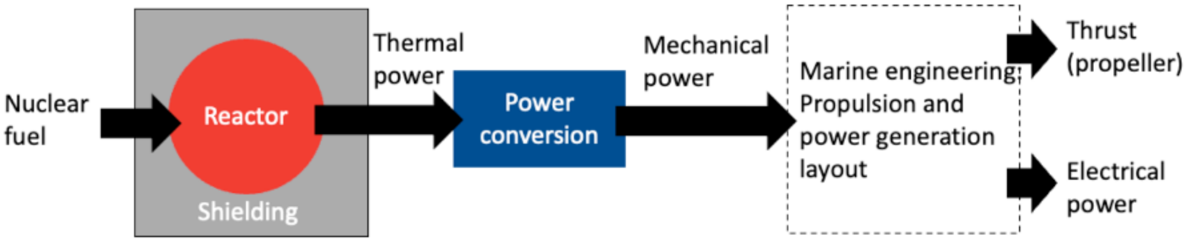

Figure 9. Simplified overview of nuclear based marine power and propulsion system. [8]

Heat produced in nuclear reactor is not totally converted to electricity, where significant amount of thermal energy is lost to environment primarily through cooling system. Cooling is mainly done with natural water sources transferring excess heat away from the plant. Nuclear power plant has typically thermal efficiency approximately 30–40 %, which means that 60-70 % of fission produced thermal energy is not converted to electrical energy. The cooling system might result thermal pollution due heated cooling water is returned to environment potentially effecting to local ecosystem. [6]

6.1 Energy conversion and secondary cycle

Options for energy conversion at marine applications is shown in Figure 10 below. Houtkoop et al. [8] evaluated these options and considered that the converting thermal energy to mechanical power with turbines is more favorable option. Their evaluation to options of thermochemical and steam electrolysis hydrogen generation, was considered impractical for direct usage in maritime applications. Even though hydrogen production methods are technically possible the production of hydrogen and converting it to mechanical or electrical power increases complexity because required additional equipment. [8]

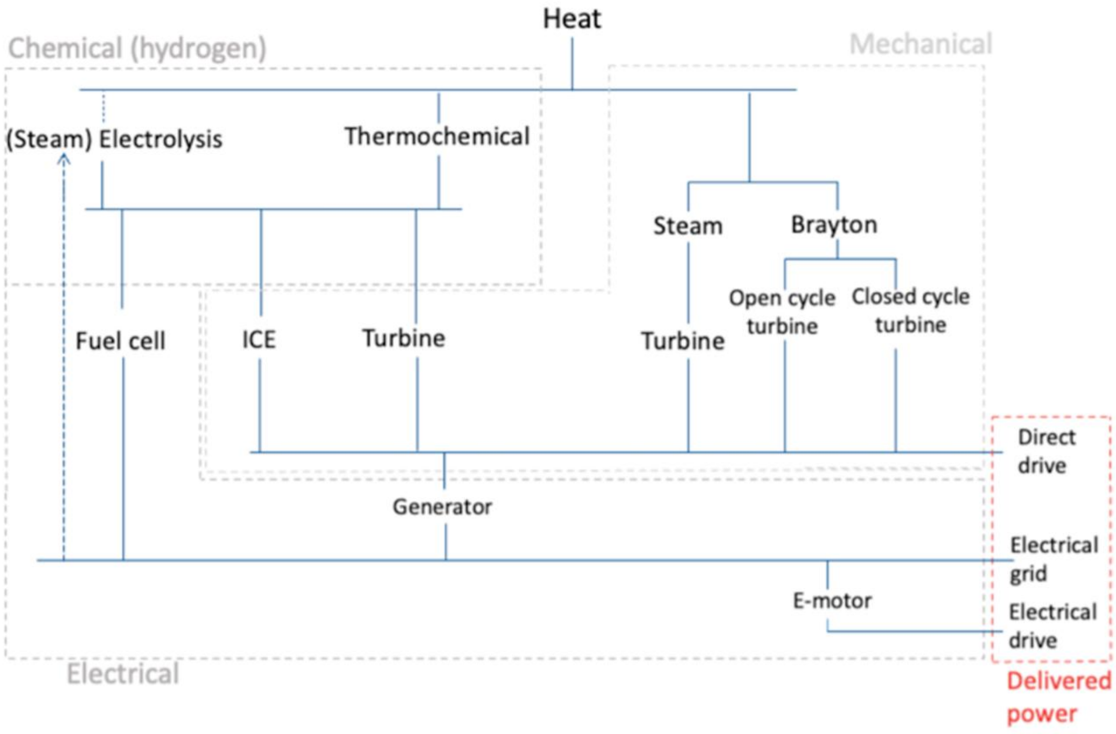

Figure 10. Energy conversion options of marine application. [8]

Houtkoop et al. [8] considered three different options for converting thermal energy to mechanical power. Rankine cycle, closed Brayton cycle and open Brayton cycle, which all requires heat transfer from reactor coolant to their operating media. Rankine cycle using steam as a medium is currently most used energy conversion method. It is well developed, offering good efficiency although at high system complexity. At Rankine cycle the steam condenses back to water after turbines, which allows the cycle to repeat [6]. Closed Brayton cycle uses either helium or supercritical CO_2 as a medium and is still at development phase without commercial units available. It would be compact option, and its efficiency is projected to be good. Open Brayton cycle uses air as a medium, offering reduced system complexity, but has slightly lower efficiency compared to other options. Its design is closely related to currently used aeroderivative turbines. [8]

Turbines need to handle load changes of reactor and demand. For current reactors load following velocity is 5% per min with lower limit of 50% minimum power [54]. To increase load following capability and operation range an option of heat rejection from turbine can be considered. At Houtkoop et al. [8] study, the heat rejection option for open Brayton plant is considered most suitable as it is open system and does not require reuse of the operating medium. [8]

Furthermore, a promising option to improve the energy system efficiency in nuclear powerplants could be usage of combined cycle. At this cycle system the heat from higher temperature cycle, which could be Brayton cycle is used to generate steam for secondary Rankine cycle. With this two-stage process whole plant efficiency can be increased and, in some cases, achieve thermal efficiency over 50%, which would make nuclear power more competitive than advanced gas-fired power plants. [6]

6.1.1 Turbine

When comparing marine steam turbines to more conventional steam turbines it should be noted that in various cases marine steam turbines have much lower energy and exergy efficiency. Smaller size of marine steam turbines and the need to adapt to dynamic operation and load changes decreases efficiency of turbine. [55]

The maximum potential of any steam turbine can theoretically be obtained with the ideal isentropic team expansion process, where all expansion losses are neglected. At steam turbines efficiencies can be achieved to whole turbine and its separate cylinders, which effects the comparison of which cylinder operation is closest to optimal. Also, the ambient temperature changes effect to turbine operation. To optimize and observe many systems, components and processes, the exergy analysis is more used. Exergy defines the amount of work a system can perform at its thermodynamical equilibrium with environment, so it is affected with additional losses related to ambient [56]. [55]

Marine steam turbine with reheating is usually called ultra steam turbine (UST) and usage of it is generally recommended on literature, increasing whole marine power plant efficiency up to 15% [57]. Igor Poljak et al [55] studied two different marine propulsion steam turbines thermodynamic (energy and exergy) analysis based on their operation parameters. Observed marine propulsion steam turbines with operation points are presented on Figure 11. Another turbine had only two cylinders (high-pressure cylinder HPC and low-pressure cylinder LPC) and did not have steam reheating, with mechanical power of 24876.55 kW. The other turbine had steam reheating and was equipped with additional cylinder (intermediate pressure cylinder IPC), with mechanical power of 17426.55kW. It should be noted that produced mechanical power is not directly comparable as study considered two different turbines. [57]

Igor Poljak et al [55] found that the operation of turbine with steam reheating and intermediate-pressure cylinder was closest to optimal. The stem reheating increased efficiency and decreased losses on each turbine cylinder, whole turbine and will increase whole power plant efficiency between 10% - 12%. The turbine with reheating had energy efficiency of 81,46 % and exergy efficiency of 86,48 %. The turbine without reheating had energy efficiency of 76,47 % and exergy efficiency of 80,96 %. They also noticed that exergy parameters of turbine without steam reheating and its cylinders was affected more with ambient temperature changes. For both whole turbines highest mechanical power was produced at LPC and lowest at IPC. From all the cylinders, the IPC of turbine with reheating scored lowest energy and exergy losses, highest energy and exergy efficiency, which makes it cylinder operating closest to optimal. IPC exergy loss and efficiency was also least affected by the ambient temperature change. For both considered turbines, energy analysis detected that HPC is most problematic, while exergy analysis resulted that LPC is most problematic. HPC low scoring with energy analysis is result of highest steam temperature and pressure and LPC worst exergy performance is result of its operation with wet steam.

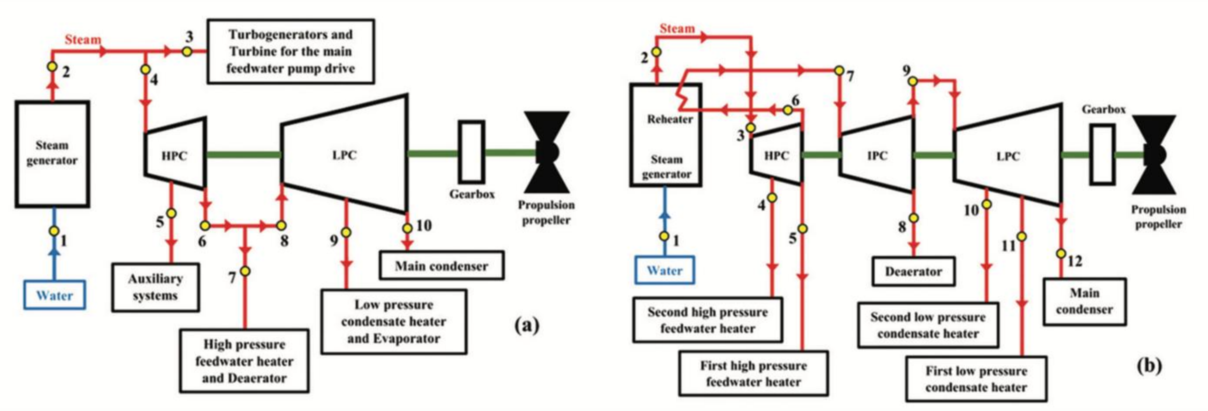

Figure 11. Observed marine propulsion steam turbines with operation points. a. turbine without reheating, b. turbine with reheating and IPC. [55]

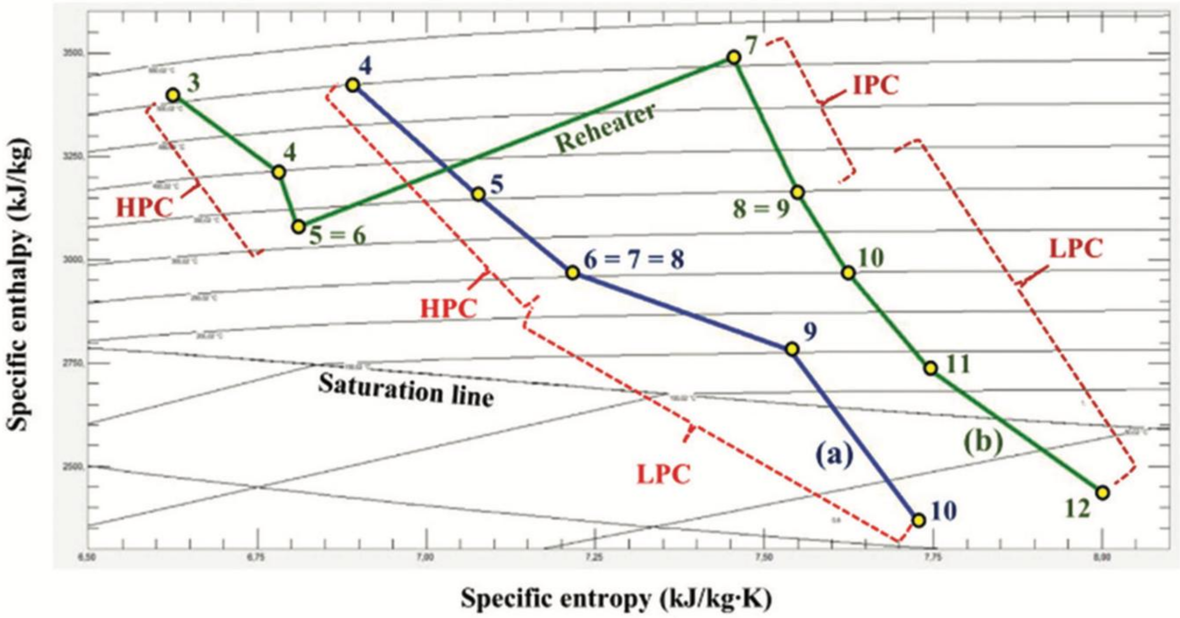

Figure 12. Steam real polytropic expansion process for both steam turbines. blue - without reheating, green – with reheating. [55]

Igor Poljak et al [55] performed thermodynamic analysis of stem real (polytropic) expansion is presented at Figure 12 above. It can be observed that reheating keeps the steam expansion process at superheated area as long as possible, which also enables higher steam quality at the end of expansion of LPC. Better steam quality means that there is less water droplets on steam, which have erosive effect to turbine blades. By reducing content of water droplets, maintenance and replacement periods can be extended with steam turbines using wet steam. [55]

6.2 Propulsion type

Historically military vessels using nuclear-power in U.S., British and Russian navies have used preliminary mechanical steam-turbine propulsion, while French and Chinese navies have used turbines to generate electricity to propulsion. Turbo-electric propulsion system has been used on Russian nuclear-powered ice breakers and at some U.S. submarines. [6]

System efficiency and system complexity are one of the main characters related to marine propulsion systems. Houtkoop et al. [8] considered four different nuclear powered marine propulsion system layouts, which are presented on Figure 13 below with their respective system efficiencies.

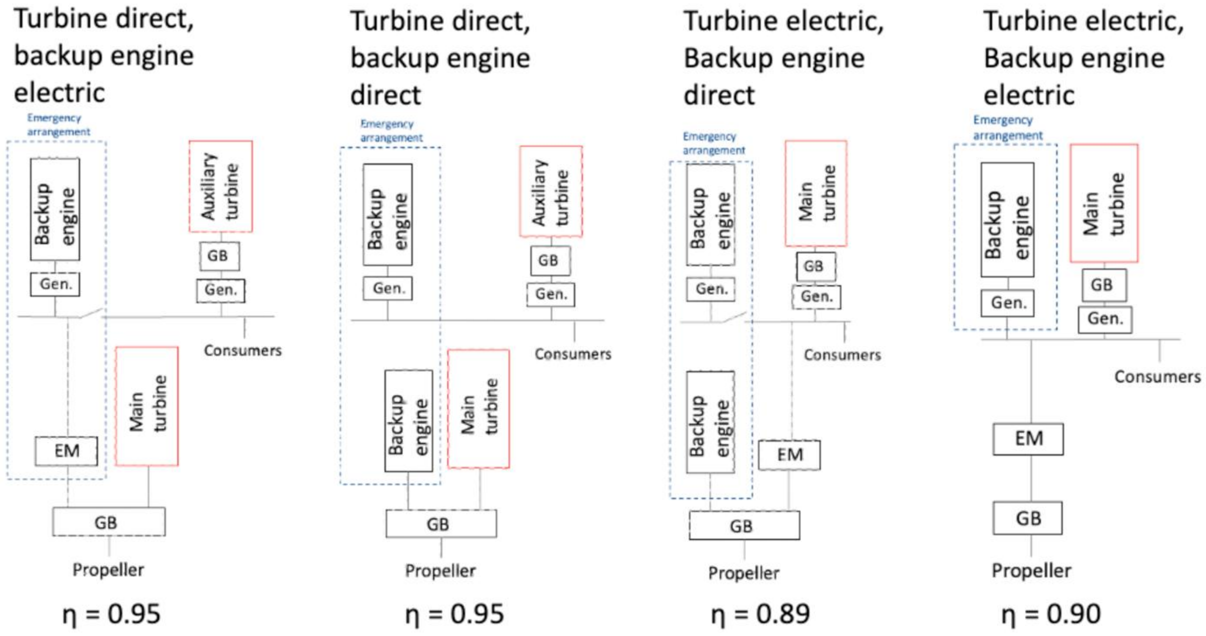

Figure 13. Different implementation layouts of nuclear propulsion system. Red - component is connection to reactor, blue – Emergency arrangement, η – system efficiency. [8]

From the figure above it can be seen that some options are better from efficiency perspective. When further considering system complexity and possibility of using additional battery system to improve load following and to smooth power peaks, only option with electromotor remains. Houtkoop et al. [8] considers the completely electric layout most suitable as it offers best flexibility and requires least machinery. This layout can additionally be doubled to improve redundancy, preventing any single-point failure effect to whole ship operation. [8]

At EMSA study of potential use of nuclear power for shipping [6] it is considered that the direct electric drive would be suitable for SMRs with modular design and for other SMRs more conventional mechanical steam-drive system could be feasible. Depending on the chosen reactor technology and vessel load-following requirements turbo-electric drive would provide better flexibility and improve load-following capabilities while also maintaining fuel-use efficiency.

7 Validation of nuclear reactor

At this chapter most suitable nuclear reactor is selected to concept ship IBELO.

7.1 Methodology

The validation of reactors is based on analytical hierarchy process (AHP), developed by Thomas Lorie Saaty in 1960s. AHP is used to derive ratio scales with paired comparison in multilevel hierarchic structure. The comparison can be done according to actual measurements or with fundamental scale reflecting the relative strength of preferences. AHP widest application is recognized at multicriteria decision making. [58]

At AHP relative measurement, pairwise comparison is done between alternatives according to common attribute and judgement matrix A is formed. Pairwise comparison is done between two elements i and j. Each element n of w_i, i = 1, ..., n, is given with ratio scale value, derived by comparing it pairwise to other element n of w_j, j = 1, ..., n. The fundamental scale presented in Table 5 is used to determine ratio scales between w_i and w_j. [58] Example of judgement matrix A and element comparison is presented below, where 1 represents that element is compared to itself.

$$A = \begin{bmatrix} 1 & w_{12} & w_{13} \\ w_{21} & 1 & w_{23} \\ w_{31} & w_{32} & 1 \end{bmatrix}$$

At the performed AHP an approximate determination method is used. This is done by normalizing each element in judgement matrix, from where an average of each row is determined, presenting the priority of the criteria over others. At Saaty et.al. [58] it is noted that most accurate result is achieved with an eigenvector derivative procedure. At the performed AHP method an approximation is considered to be accurate enough for this concept ship project. As there are many alternatives the direct AHP method is challenging. Because of this AHP was performed after initial screening of exclusion criteria. With this method the scope of AHP was enabled to get at manageable size. Reactor specific characteristics and data used this AHP is gathered from IAEA SMR catalogue [59].

After the initial screening, criteria and sub criteria are prioritized pairwise over each other, resulting the priority of the criteria and sub criteria. After that, a pairwise comparisons are also performed between rating scale, corresponding specific feature response to considered sub-criteria, resulting priority of specific feature.

7.2 Initial screening

At initial screening used exclusion criteria are determined to exclude reactors with features that are not considered suitable for concept ship. When reactor fulfills all exclusion criteria it advances to validation with AHP. Considered exclusion criteria for initial screening are based on Emblemsvåg et.al. [3] determined exclusion criteria, which are based on applicability to marine propulsion and GIF guidelines. Additionally, operational requirement for concept ship specific power output is already set as exclusion criteria.

7.2.1 Exclusion criteria

Following exclusion criteria were determined for initial screening. All excluded reactors from IAEA SMR catalogue [59] and the main criteria for exclusion are presented on Appendix 1.

7.2.1.1 Using water as a coolant

Water-based SMRs, except some SCRW does not meet Generation 4 reactor requirements. Water based reactors might face strong public resistance due their safety performance and historical accidents. At Emblemsvåg et.al. [3] it is considered that the public concerns will also be faced at water-cooled Generation 4 SMRs. Water based SRMs might also face challenges with meeting the enrichment of less than 20 % of U235, which is the limit for civilian operation. The pressure vessels at some water-based reactors rises issues with safety zones at civilian ships. [3] Water based reactors were excluded because of these factors and focus was placed on Generation 4 reactors with alternative coolant material.

7.2.1.2 Lack of passive safety system

Passive safety system and passive shutdown system are main features of Generation 4 reactors. Passive safety systems do not require human interaction, while preventing the release of radioactivity to environment in the case of an accident. [3] Reactors which do not have established passive safety system features are excluded.

7.2.1.3 Limited proliferation resistance

Any nuclear fuel at land and sea constitutes significant safety risk of proliferation [5]. Reactors should be featured with barriers to reduce possibility of extraction of fissile material and usage for example military purpose [3]. Reactors without actions to prevent proliferation of fission material were excluded. Reactors systems where the extraction is relatively hard were not excluded, includes for example once fueled reactors.

MSRs with dissolved fuel presents challenges, requiring safeguard system. Main points of the safeguard system would focus on fuel cycle, reactor design and used fuel type. Reactors with online refueling might increase the risk due increased access to fuel during operation, with challenges related to monitoring quantities of liquid fuel. There is no formally approved technique considering liquid fuel monitoring and control, which is why MSRs with liquid fuel are excluded. [3]

7.2.1.4 Fuel enrichment and highly toxic Bi-products

Enrichment level for civilian applications set by IAEA is 20% of U235, which excludes all reactors using nuclear fuel enriched above that. Highly radioactive bi-products are for example Po210, generated in lead-bismuth reactors and Cl36, generated in chloride-based MSR. [3]

7.2.1.5 Power output

Selected nuclear reactor thermal and electrical power output should be at sufficient level for concept ship requirements. Required propulsion power for concept ship IBELO is presented in Chapter 1.1 “Nuclear powered concept ship IBELO”. Required delivered power at 3 kn speed and 3 m thick ice was 83,5 MW and 3 kn speed with 4 m thick ice was 153,5 MW. To get the required electrical power from required propulsion power we use efficiency of 0,9 determined at Chapter 6.2 “Propulsion type” by Houtkoop et al. [8] for completely electric propulsion system. Now required electrical power for 3 kn speed with 3 m thick ice and 3 kn speed with 4 m thick ice results 92,8 MWe and 170,6 MWe.

The minimum operational capability is set to 3 m thick ice with 3 kn speed. To increase redundancy the target is to fulfill the power requirement with either two or three reactors. Based on this, exclusion criteria for electrical power output were roughly set between (31 MWe – 150 MWe), where upper limit is considered to be sufficient to possibly improve operational profile with increased speed and ice thickness.

7.2.1.6 Less than 5 years of continuous operation

Ships are typically drydocked at every 5 years [6]. Because of this reactor refueling and maintenance interval should be a multiple of 5 year, minimizing additional operational stops. The 5-year minimum continuous operation is used as an exclusion criterion.

7.2.1.7 Using classic pebble bed technology

Reactors used on ships needs to withstand various marine environment conditions. Emblemsvåg et.al. [3] considers classical pebble bed fuel arrangement challenging due possibility of pebbles to move along ship movements, which possibly cause structural damages to fuel and reactor vessel and effect reactor behavior. According to this, reactors with possibly moving fuel pebbles are excluded.

7.2.1.8 High pressure in the reactor primary system

Reactor vessel pressure needs to be limited so that pressure in case of accident can be tolerated by ship structure. At Emblemsvåg et.al. [3] study the reactor pressure vessel limit was set to 60 bars, which is also used as an exclusion criterion at performed initial screening. At some reactor designs whole system is surrounded with design specific containment vessel designed to withstand pressure in case of emergency. Reactors with this kind of containment vessel are not excluded based on 60 bars pressure limit.

7.2.1.9 Violent reaction of coolant with water

Chemical reactivity of reactor coolant and sea water is an issue with reactors operating in marine environment. Based on this SFRs and MSRs using highly soluble compounds as coolant such as NaCl are excluded.

7.3 Selection criteria

Following 5 selection criteria and 16 sub-criteria presented below were determined to be relevant for rector validation.

1. Safety characteristics

    a. Historical incidents and accidents of technology

    This sub-criterion contributes the goal with respect to reactor technology historical accidents. Overall success of the reactor technology in history and social attitude to past problems of reactor technology are affected to this sub-criterion.

    b. Fuel safety

    Fuel characteristics related to operational safety and its behavior during accident or abnormal operation are affected to this sub-criterion. Used fuel material and its different assembly arrays play critical role at fuel safety and its behavior.

    c. Coolant toxicity

    Coolant toxicity and its harmful effect to people on board and environment are considered at this sub-criterion.

    d. Source term

    In case of accident reactor released radioactive and hazardous substances to environment are considered at this sub-criterion.

2. Reactor system characteristics

a. Secondary system

Secondary system type, its complexity and convection type are considered at this sub-criterion. There are different solutions for secondary system, where some are integrated inside the reactor and some relying natural or forced convection.

b. Dimensions

This sub-criterion considers the size of the reactor system.

c. Weight

This sub-criterion considers the weight of the reactor.

d. Coolant temperature

This sub-criterion considers the reactor outlet steam temperature, effecting the cooling system and turbine system.

e. Design life

Design life for the reactor is considered at this sub-criterion. Reactor design life effects whole ship lifecycle.

3. Fuel characteristics

a. Enrichment

At this sub-criterion used nuclear fuel enrichment of U-235 is considered. Natural uranium and low enriched uranium are considered favorable, as enrichment level is primarily a cost and potential political issue [3].

b. Refueling time

At this sub-criterion reactor refueling time and strategy are considered. Refueling effects highly to the ship operation and safety design as refueling is challenging operation done onboard. Also, system used to manage fresh and spent fuel at online refueling reactors effects the whole system design. [3]

   c. Fuel cycle (open / closed)

   This sub-criterion considers back end of the fuel cycle. If spend fuel is not processed for reuse it is preferred as open cycle and with fuel reuse processing it is preferred as closed cycle [4].

4. Licensing status

   a. Status in licensing process

   At this sub-criterion the reactor status at licensing process is considered, reflecting the readiness of the reactor design.

   b. Operational experience of technology

   At this sub-criterion the historical experience of reactor technology is considered.

5. Marine operational performance

   a. Limited operational factor

   At this sub-criteria reactor design specific limitations are considered, which it might face at ship operation. Ship movements caused by marine environment, and limitations they cause to reactor operation are highly effected to this sub-criterion.

   b. Need for special equipment

   At this sub-criterion reactor system specific special equipment are considered. Equipment development, implementation and its effect to system complexity are affected to this sub-criterion.

7.3.1 Priorities of selection criteria

Saaty et.al. [58] determined fundamental scale of values used to present the intensities of judgements at paired comparison is presented on Table 5 below. [58]

Table 5. The fundamental scale

Intensity of importance	**Definition**
1	Equal importance
2	Weak
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong importance
8	Very, very strong
9	Extreme importance

Selection criteria and sub-criteria are compared pairwise with intensity values from fundamental scale. Pairwise comparison judgement matrix of selection criteria is presented below in Table 6, with resulted priorities. It can be seen from the results that marine operational challenges result highest priority, with approximately half of total. Lowest priority on the other hand resulted for reactor system characteristics.

Table 6. pairwice comparison matrix of selection criteria, and resulted priorities.

	Safety characteristics	Reactor system characteristics	Fuel characteristics	Licensing status	Marine operational performance	Priority
Safety characteristics	1	5	3	5	1/3	0,244
Reactor system characteristics	1/5	1	1/3	1/3	1/8	0,043
Fuel characteristics	1/3	3	1	4	1/6	0,128
Licensing status	1/5	3	1/4	1	1/7	0,071
Marine operational performance	3	8	6	7	1	0,514

The pairwise comparison requires that elements are linear independent. This was assessed with consistency index (CI), presented on equation below, where λ_{max} is maximum eigenvalue of the pairwise matrix, and m is the number of independent rows n the matrix.

$$CI = \frac{\lambda_{max} - m}{m - 1}$$

Possibility of consistency error in pairwise matrix can be assessed with consistence ratio (CR), presented on equation below, where RI is an average random consistency index, which is got from Table 7. The CR value should not be higher than 0,1 [58]. Inconsistency of 0.1 or less denote that adjustment on matrix is small, when compared to actual priority vector values [58]. The CR value for matrix of selection criteria was 0,084.

$$CR = \frac{CI}{RI}$$

Table 7. Average random consistency index RI. [58]

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,52	0,89	1,11	1,25	1,35	1,40	1,45	1,49

Pairwise comparison was done also to all sub-criterion under every criterion. Resulted priorities of sub-criteria are presented on Table 8 below.

Table 8. Pairwise comparison resulted priorities of sub-criteria under each criteria

	Priority
Safety characteristics	
Historical incidents and accidents of technology	0,122
Fuel safety	0,558
Coolant toxicity	0,263
Source term	0,057
Reactor system characteristics	
Secondary system	0,503
Dimensions	0,068
Weight	0,035
Coolant temperature	0,134
Design life	0,260
Fuel characteristics	

Enrichment	0,180
Refueling time	0,748
Fuel cycle	0,071
Licensing status	
Status	0,249
Operational experience of technology	0,751
Maritime operational performance	
Limited operational factors	0,751
Need for specific equipment	0,249

7.4 Rating scale and scoring of reactors

After initial screening of reactors, two reactors remain on validation process. One lead-cooled fast reactor “Sealer 55”, and one molten salt reactor “KP-FHR”. Both reactors operate at near atmospheric pressure and feature passive safety systems. Sealer 55 is a lead-cooled fast reactor from Swedish company Blykalla. It has thermal output of 140 MW and electrical output of 55 MW. It uses uranium nitride pellet fuel at hexagonal assembly array. KP-FHR reactor Is molten salt reactor, with TRISO fuel on pebble bed formation. It has thermal output of 320 MW and electrical output of 140 MW. KP-FHR is online refueled reactor, which uses Fluoride based salt as coolant and moderator. It was not excluded with pebble bed fuel arrangement criteria, because it’s compact container. [57]

Each sub-criteria are assigned with rating scale, corresponding feature response to sub-criteria. Rating scales under each sub-criteria are pairwise compared to each other, resulting priority of specific feature under sub-criteria. Reactor alternatives response to each sub-criteria are evaluated on respect of rating scale. Needed information to assigning specific rating scale value for reactors is gathered from, IAEA SMR catalogue [59] and Emblemsvåg et.al. [3] study. The scoring of reactor alternatives at rating scale is presented at Table 9 below.

Table 9. Scoring of reactors at rating scale under each sub-criteria

Selection criteria	**Sub-criteria**	**Sealer-55**	**KP-FHR**
Safety characteristics	Historical incidents /accidents	Some past issues	No past issues
	Fuel safety	Medium	High
	Coolant toxicity	Medium	High
	Source term	Low	Low
Reactor system characteristics	Secondary system	Integral	Loop with forced convection
	Dimension	Small	Large
	Weight	Very heavy	Medium
	Coolant temperature	Medium	High
	Design life	25 y	20 y
Fuel characteristics	Enrichment	High	High
	Refueling time	No refueling	Online refueling
	Fuel cycle	Close	Open
Licensing status	Status	Work in progress	Approved
	Operational experience	Medium	Low
Marine operational performance	Limited operational factor	Limited	Limited
	Need for specific equipment	Low	High

7.5 Results of reactor validation

To determine global priorities of the reactors, distributive mode is used. At this method reactor specific scoring from rating scale is multiplied with specific sub-criteria and selection criteria, which are then multiplied to get the total priority of reactor [58]. Global priorates of reactor alternatives, with selection criteria distributing is presented on Figure 14 below.

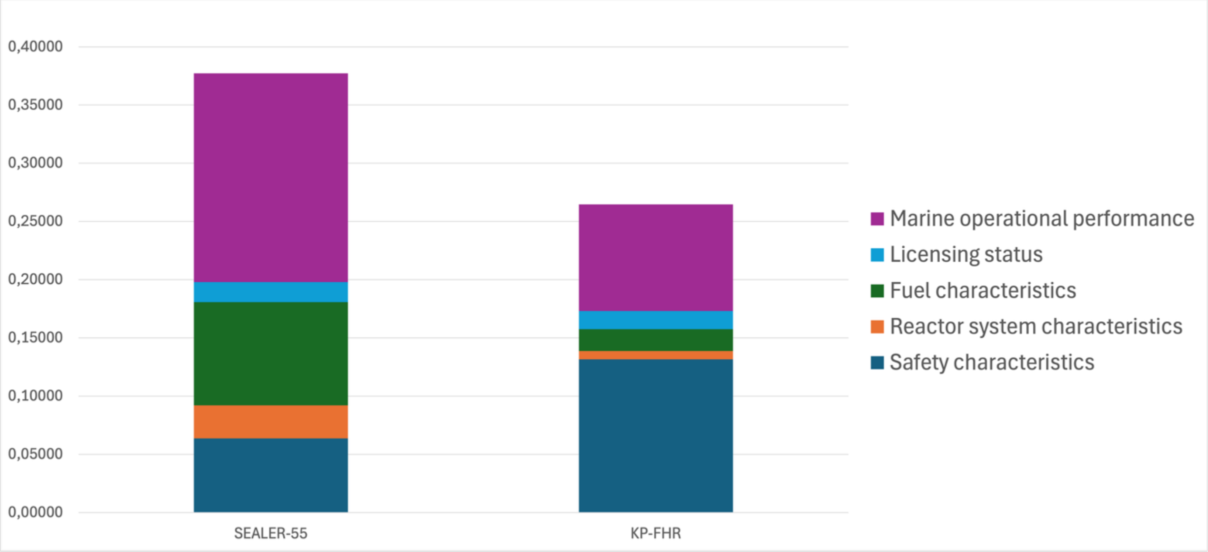

Figure 14. Global priorities of reactor alternatives with selection criteria distribution.

Sealer-55 scored 43 % higher global priority than KP-FHR, with difference of 0,11. Sealer-55 scored significantly higher, with fuel characteristics and marine operational performance criteria. Difference of fuel characteristics is mainly result of refueling time, with Sealer-55 being once fueled reactor and does not require refueling along its reactor lifetime. Marine operational performance is scored higher at Sealer-55 because its reduced system complexity and need for specific equipment. On the other hand, KP-FHR scored much higher at safety characteristics criterion, which mostly resulted from safety of TRISO fuel used on KP-FHR. Licensing status and reactor system characteristics scored for both alternatives relatively same results. These small differences are result of criteria and sub-criteria relatively low weighting. More detailed look of global priority distribution of alternatives is presented in Figure 15 below, which is divided along alternatives scoring at sub-criteria. Based on this validation Sealer-55 is considered most suitable reactor for concept ship IBELO.

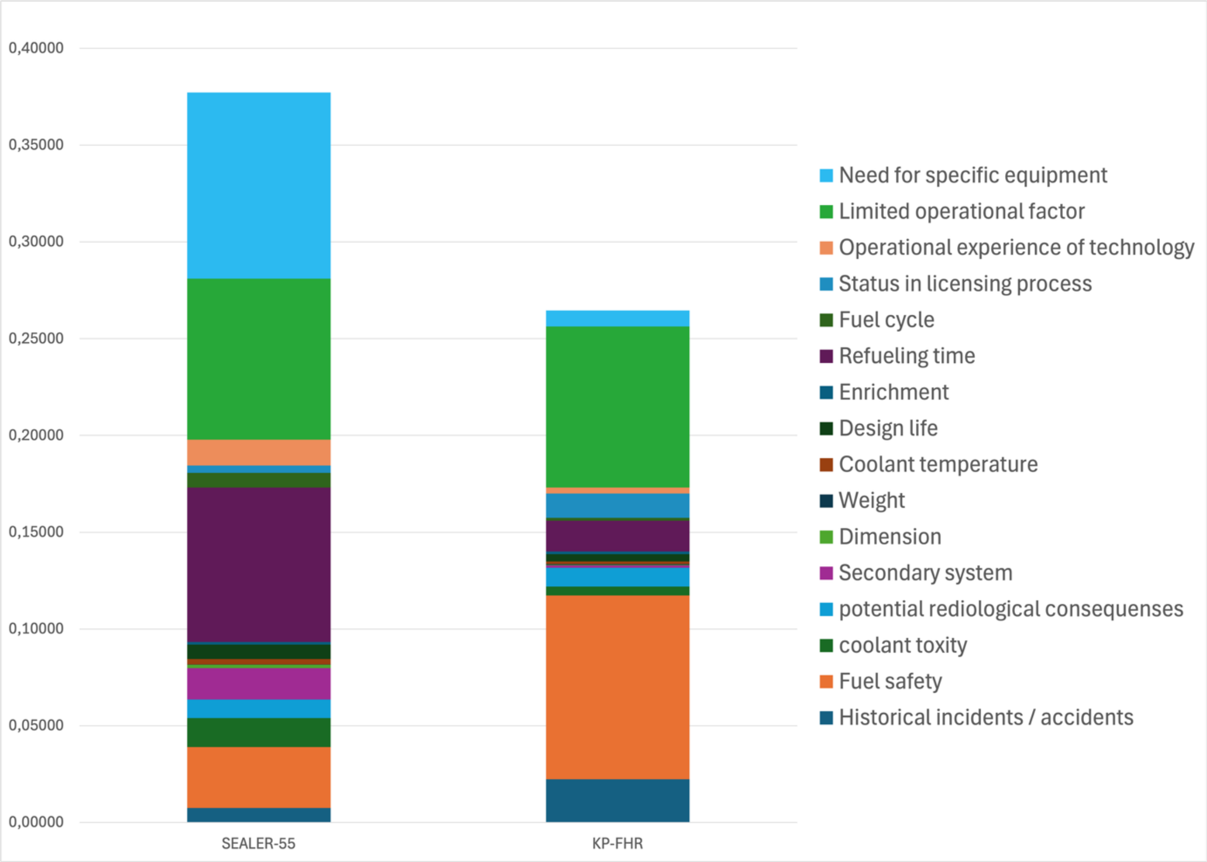

Figure 15. Global priorities of reactor alternatives with sub-criteria distribution.

8 Resulted system features

At this chapter, most suitable nuclear machinery system is put together, based on previously studied features of the system. Some determinations have been done along the study, but the resulting system and features are fully determined at this chapter.

8.1 Determination of beneficial system features

Most suitable propulsion system type considered is electrical propulsion. This propulsion system reduces system complexity, increases flexibility of machinery arrangement, with best adaptation to different operational profiles and load changes. Using full electrical propulsion system, electricity form nuclear power plant energy system is used. Use of heat for alternative consumers can be considered in future development of concept ship IBELO.

To produce electricity from nuclear thermal energy, energy conversion with turbines is considered most favorable. Energy conversion cycles to be most suitable can be considered from different aspects. Most traditional Rankine cycle has good efficiency, but increased system complexity due need for condensers. Closed Baryton cycle offers good efficiency and compact design, but it is not commercially available and not suitable for Sealer-55 as it is not gas-cooled reactor. Open Brayton cycle offers reduced system complexity, but it has slightly lower efficiency compared to other options. As open Brayton cycle is open system and does not require reuse of the operating medium, it would be most suitable for load following with heat rejection option. The combined cycle would increase efficiency, with increased system complexity.

Turbine with reheating and intermediate pressure cylinder is considered more optimal than turbine without reheating and intermediate pressure cylinder. Steam reheating increases efficiency of each turbine cylinder and whole turbine, with its exergy being less affected by ambient temperature change. Reheating keeps the steam expansion process at superheated area as long as possible, enabling higher steam quality at the end of expansion, which decreases erosive effect to turbine blades.

Most suitable nuclear reactor for concept ship IBELO was determined with AHP method. A lead cooled fast reactor Sealer-55 filled all exclusion criteria and scored highest global priority over other alternative. Company Blykalla designing Sealer-55 considers Rankine cycle most favorable to their reactor, which is why Rankine cycle is selected for the result system design.

8.2 System at component level

At this chapter required components for resulting system are considered. The number of required reactors is determined by the total power demand. All other system components are determined to fulfill required system features. Detailed dimensioning of components requires detailed secondary system parameter and operational clarification. Because of this, required components are determined only as features to be added to system.

8.2.1 Number of reactors in respect of power demand

Minimum required operational capability of IBELO was set to 3 m thick ice with 3 kn speed, with propulsion required delivered electrical power of 92,8 MWe. Selected reactor Sealer-55 has established electrical power output of 55MWe. To fulfill required propulsion power with Sealer-55, multiple reactors are required.

Two Sealer-55 reactors respond 110MWe, which is 17,2 MWe more than required propulsion power for minimum required operational capability. Three Sealer-55 reactors, having total 165 MWe of power output, reaches to operational condition of 3,5 m thick ice and 3 kn speed, with 36,2 MWe left for other consumers than propulsion. Total electrical power of three Sealer-55 is 5,6 MWe too low to reach 4 m thick ice and 3 kn speed, which would be reached with four reactors, but having then relatively high power left after propulsion demand. Based on this consideration, three Sealer-55 reactors are determined for the system. Required electrical power for propulsion is calculated with 0,9 efficiency from required delivered power for propulsion presented on Chapter 1.1.

8.2.2 Turbine

As Sealer-55 is reactor without specified secondary system turbine, Rankine cycle turbine is determined for the system. Rankine steam cycle parameters of Sealer-55 are established at IAEA SMR catalogue [59], with steam at superheated state at pressure of 165 bar (16,5 MPa) and temperature 350°C – 530°C. Turbine selection is based on power range and steam parameters of one Sealer-55 reactor, with possibility for reheating and flexible connections.

Siemens SST-300 is one example of suitable turbine. The SST-300 turbine has inlet steam pressure of 140 bar and temperature of 540°C and have power output up to 60MWe. It is single casing turbine containing all expansion phases with several steam extraction and induction points, enabling steam reheating. It features different exhaust orientation possibilities with upward, downward or axial directions. SST-300 modular full package solution consists of turbine, gear box and generator, which are all placed on top of base frame containing integrated oil unit. All parts of modular package can be selected separately to get most suitable solution. [60]

Detailed analysis of turbine and package component selection, with determination of steam expansion process is purposefully left out of the scope of this study, although recognized as necessary. This requires component specific parameters with more advanced knowledge of ship and rector operation.

8.2.3 Auxiliaries

Reactor and secondary circuit require different auxiliary systems. Some of the auxiliaries are specific for reactor type, while secondary system Rankine cycle main auxiliaries are commonly known. There is relatively low information of Sealer-55 required auxiliaries, as it is still at design phase. For example, possible lead supply system, lead auxiliary heating at operational downtime, oxygen control system to prevent lead oxide precipitation and lead purification system are not clearly established by Blykalla. Decay heat removal of Sealer-55 is done with auxiliary cooling system of reactor vessel, which is based on air circulation and convection [59].

In addition of the SST-300 package, including turbine, gear box and generator, Rankine cycle requires different components. The secondary cycle includes, shut-off valves and control valves regulating the inlet steam going to turbine. Condensers condense steam from turbine exhaust back to water, which is then pumped through feedwater heat exchanger, preheating feedwater and reducing exergy loss, with heat extracted from turbine cycle [61]. Before feedwater enters back to steam generator it goes through deaerator, which eliminates dissolved oxygen from feedwater [62]. Feedwater is pumped and pressurized with feedwater pumps back to steam generators [61]. Connection for feedwater tank is added before feedwater pumps suppling cooling water to the secondary cycle. Reheating steam in turbine can be done at reactor steam generators or with additional heat exchanger. The solution for reheating requires more detailed information of Sealer-55 steam generator operation and its possibilities.

8.3 Schematic illustration of resulted system

Following schematic illustration presented in Figure 16, illustrates proposed system to fulfill beneficial features, without specified dimensioning. The system illustration describes one Sealer-55 nuclear reactor related system, with Sealer-55 multiple steam generators presented as one. Number of components, dimensions and parameters, with supportive features between three reactor systems will be needed in future, requiring more clarified reactor and secondary cycle operational parameters.

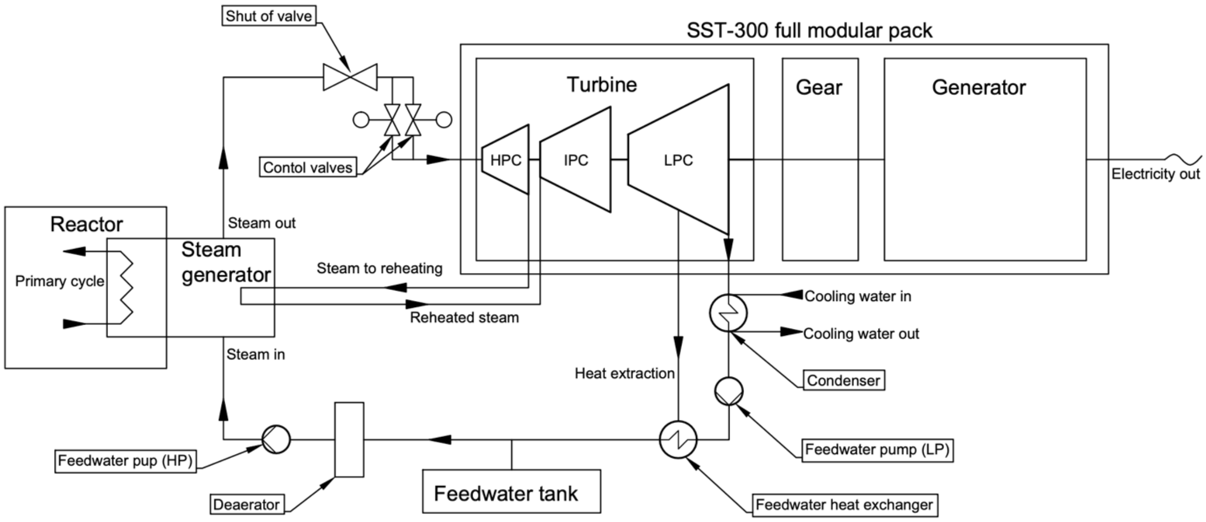

Figure 16. Schematic illustration of one Sealer-55 secondary system, with Sealer-55 multiple steam generators shown as one.

9 Future

When considering future development of this study and its results. More detailed determination of IBELO operational profiles and selected nuclear reactor Sealer-55 operational behavior would be needed. Operational performance and requirements determine the whole system needs and possibilities. Advanced knowledge of system operation behavior would enable more detailed determination of components and system features. For example, secondary system reheating, steam expansion process and auxiliaries would be possible to determine at practical level. Also, additional battery system supporting main energy system respond to power demand is highly affected by main energy system load following capabilities and adaptation to rapid load changes.

Performed analytical hierarchy process reactor validation could be done more accurate in future, with an eigenvector method and if more detailed reactor specific data were available. Additionally, Monte Carlo simulation could be done to analyze validation result dispersion. Analyses of Sealer-55 suitability for marine environment, and specially its lead coolant behavior at moving conditions would be beneficial at future. At literature there is reactor thermal-hydraulic analysis under moving conditions, but special study for Sealer-55 is not performed. The need for this kind of analysis is also recognized by Blykalla but will be further considered when Sealer-55 more detailed licensing and design for marine environment begins.

Possibility of using combined cycle with Brayton and Rankine cycle increases system efficiency. To study integration of combined cycle to nuclear powered ship would be interesting when developing even more advanced nuclear energy system. The combined cycle increased system complexity and its possible effect to reliability should also be noted when it is considered to ship and specially to PC 1 icebreaker.

At this study, the electricity power demand is compared only to the required propulsion power, with electricity left for other consumers considered only to be at sufficient level. Although propulsion is consuming most of produced power, more detailed analysis of other consumers would be needed. This would include for example accommodation, auxiliary and additional equipment power requirement.

10 Discussion

Sealer-55 technology readiness, its ongoing design process and lack of practical regulatory of nuclear installation for merchant vessels makes detailed determination of the system relatively hard, with high level of assumptions. Clarification of regulatory framework different stakeholder levels would be needed, with practical standards and design rules, considering specific reactor technologies and advanced Generation 4 reactors. The problems and differences at regulatory levels can be considered most problematic barrier for Generation 4 reactor development and implementing them to commercial vessels. Uncertainties at regulatory levels increases design time of reactor and requires companies to assume features to get reactor design licensed in future.

Uncertainties of regulatory and standards effects also to performed reactor validation and initial screening of reactors. Number of considered MSRs after initial screening would have been larger, if clear standard of monitoring liquid fuel quantities were established, which lack resulted exclusion of all MSRs using liquid fuel. Also, reactors using TRISO fuel at classic pebble bed formation were excluded, according to assumption that ship movements will face problems with moving particles. Knowledge-based information of TRISO fuel experienced consequences under moving conditions, could have influenced the number of reactors excluded based on this.

Energy conversion cycle was determined to be Rankine cycle, based on Blykalla determination to be suitable. Rankine cycle is well developed, and it has good efficiency, which makes it good choice. On the other hand, open Brayton cycle having best load following capabilities with steam rejection, could also be beneficial cycle at operational area of IBELO. Practical adaptation of open Brayton cycle to ship environment and possibly improved operational performance of ship could affect cycle selection and so-one reactor selection.

11 Conclusion

When comparing nuclear power to conventional power sources at ship, nuclear power would be beneficial, with reduced emissions, fuel space, and possible reduced lifetime costs. Nuclear power long refueling times and high-power output are essentially important features for concept ship IBELO operational area. Nuclear power responds well to IBELO PC 1 ice class, requiring year around operation at all polar waters.

When further considering operational area and profile of IBELO, required propulsion power is affected lot at different areas. It changes heavily between open water and ice breaking operation, with possibility to brake relatively thick ice is increasing required propulsion power even higher. The propulsion system and power supply system needs to adapt these different loads, having possibility to rice produced power significantly when operated at ice. The ice thickness can also vary rapidly, requiring quick respond to propulsion load peaks. Because of the operational profiles, electrical propulsion with additional battery back is determined to be suitable for IBELO. Electrical propulsion system also increases flexibility of nuclear machinery arrangement.

The nuclear reactor was selected with initial screening and analytical hierarchy process (AHP) method. Initial screening consisted of 9 exclusion criteria, which were used to exclude reactor designs that were not considered suitable to commercial ship. The AHP method was structured with 5 selection criteria and 16 sub-criteria considered relevant for reactor validation. At pairwise comparison of selection criteria and sub-criteria, features related to safety, maritime operational, system complexity and refueling time were considered most valuable.

Only two reactor design fulfilling all exclusion criteria. One LFR reactor called Sealer-55 and one MSR called KP-FHR. Reactor alternatives response to each sub-criteria were evaluated on respect of rating scale and scoring of reactors at every sub-criterion was determined. Resulted global priorities, presenting reactor alternatives total scoring was determined with distributive model. Sealer-55 scored 43 % higher global priority than KP-FHR, with difference of 0,11 at global priority, which is why Sealer-55 was selected. Sealer-55 resulted significantly higher at selection criteria “Fuel characteristics” and “Marine operational performance”, without need for refueling and reduced system complexity compared to KP-FHR. On the other hand, KP-FHR scored significantly higher at selection criteria “Safety characteristics”, because it’s using TRISO fuel.

Converting nuclear thermal energy to electricity with turbines was determined to be most suitable energy conversion option. Different turbine cycles have their own benefits and disadvantages. The company Blykalla designing Sealer-55 reactor, prefers Rankine cycle to be used with their Sealer-55 reactor, which is why Rankine cycle is selected for the system. When considering turbine related features, reheating and three different cylinders are determined to be beneficial for secondary cycle operation. Three cylinders and reheating increases efficiency and improves steam quality at turbine exhaust, also making the turbine exergy less effected by ambient temperature change. SST-300 steam turbine and its modular full package made by Siemens is an example turbine, which responds to reactor power range, output steam parameters, with flexible modular design and beneficial features.

The secondary cycle detailed analysis would be needed in future, requiring more specific knowledge of reactor operation and turbine parameters. Additional components for secondary cycle were determined to include at least shut-off valves and control valves, condenser, feedwater heat exchanger, deaerator, feedwater tank and low-and high-pressure pumps. Reheating can be implemented with additional heat exchanger or with usage of reactor steam generator, requiring more knowledge of reactor operation.

The target of this study was to find most suitable options and solutions for nuclear machinery arrangement and put together most suitable system responding to concept ship needs. Target was achieved with selected nuclear reactor, determined machinery arrangement solutions and features responding to required operational performance of IBELO. More detailed practical implementation is needed in future. Lack of reactor specific standards and design rules, with uncertainties related to reactor operation at marine environment are main barriers for nuclear power adaptation to commercial ship.

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Appendices

Appendix 1 Excluded reactors and exclusion criteria, without Water-based reactors

Reactor	Type	Exclusion criteria
EM2	HTGR	Too high power
FMR	HTGR	Too low power
GTHTR300	HTGR	Refueling
GT-MHR	HTGR	Refueling
HTGR-POLA	HTGR	Refueling
HTMR-100	HTGR	Pebble bed
HTR-10	HTGR	Too low power
HTR50s	HTGR	Refueling
HTR-PM	HTGR	Pebble bed
HTTR	HTGR	Too low power
MHR-100	HTGR	Refueling
MHR-T	HTGR	Refueling
PeLUIt-40	HTGR	Pebble bed and too low power
Xe-100	HTGR	Pebble bed
4s	LMFR	Sodium coolant
ARC-100	SFR	Sodium coolant
Blue Capsule	SFR	Sodium coolant
BREST-OD-300	LFR	Too high power
HEXANA	SFR	Sodium coolant
LFR-AS-200	LFR	Too high power
OTERA 300	SFR	Sodium coolant
SVBR-100	LFR	Lead-bismuth coolant
Natrium	SFR	Sodium and refueling
CA Waste Burner	MSR	Liquid fuel
CMSR	MSR	Liquid fuel
Flex Reactor	MSR	Liquid fuel
FUJI	MSR	Liquid fuel
IMSR 400	MSR	Liquid fuel
LFTR	MSR	Liquid fuel
Stable Salt Reactor Wasteburner	MSR	Liquid fuel
Stellarium	MSR	Liquid fuel
ThorCon	MSR	Liquid fuel

Thorizon	MSR	Liquid fuel
XAMR	MSR	Liquid fuel and refueling
AMR	HTGR	Too low power
Aurora	FR	Too low power
ELENA	PWR	Too low power
Energy Well	MSR	Too low power
eVinci	Heat pipe	Too low power
HOLOS-QUAD	HTGR	Too low power
HOLOS-MONO	HTGR	Too low power
Jimmy	HTGR	Too low power
Marvel	LM thermal	Too low power
MMR	HTGR	Too low power
MoveluX	Heat pipe	Too low power
PylonDI	HTGR	Too low power
SHELF	PWR	Too low power
Unitherium	PWR	Too low power