Final Report of the

Nuclear Propulsion for Merchant Ships I (NuProShip I) project

Date: 2025-01-15

This report is the final report of the NuProShip I project submitted to the Research Council of Norway as a partial requirement to the funding under the project ID 336539.

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Preface

Research is work in progress. This research project is certainly like that. The highly ambitious objective of providing merchant ships with a zero-emission technology that can outcompete heavy fuel oil head on, without subsidies, is extremely demanding. The project itself is the result of research done in the years prior to 2021 that shows that nuclear propulsion must become a significant part of zero-emission shipping otherwise there will be no energy transition in shipping.

That being said, the report speaks for itself in the sheer volume of work that has been conducted by the highly engaged and motivated team members in the companies in the consortium. Without their huge effort, the Nuclear Propulsion for Merchant Ship (NuProShip) I project would have never done so well as it has.

I think I speak for us all when I say that I truly believe that nuclear propulsion is just a matter of time. Sure, there are many hurdles to overcome, but mostly there are not technical. I find the engineering aspect of nuclear propulsion far from difficult – it requires financing to be developed, tested and proven – but that is it.

The most difficult part is navigating the large landscape of laws, rules and regulations among flag states, port states, class societies, canal states, nuclear regulatory bodies, insurance, the International Maritime Organization, export control, the concerns of the general public and possibly more. This is where the future of nuclear propulsion will be settled.

I am confident that we shall manage to find a good solution among all the challenges listed above. We shall certainly do our best, and then our children can judge our efforts.

Jan Emblemsvåg, PhD

Project manager, NuProShip I / II

Ålesund, NORWAY, 2025-01-15

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Summary

This report contains the results of two years of research (2023 and 2024) performed under the context of Nuclear Propulsion for Merchant Ships (NuProShip) I, funded by the Research Council of Norway. The successor project, NuProShip II, is well underway as of January 2025.

Starting from the nuclear reactor core and working ourselves outwards to the reactor systems, waste handling, ship systems, ship design, crew and more, we have performed a number or research tasks as presented in this report. Since we started at the nuclear reactor core, based on the idea that we need the right nuclear technology before anything else, the report is dominated by the large amount of work done to select the best possible reactor technologies.

We have selected reactors among all the known reactor concepts by yearend 2022, some 80+ of them, as detailed in Chapter 2. First, we applied a set of 11 exclusion criteria that were very clearcut, after which we had about 8 possible reactor concepts left. These 8 reactor concepts were subsequently subjected to another 26 criteria for further selection. The end result is three reactor concepts; 1) molten-salt reactor using TRISO fuel designed by Kairos Power (USA), 2) a helium gas-cooled reactor using TRISO fuels designed by Ultra Safe Nuclear Corporation (USA), and 3) a lead-cooled reactor designed by Blykalla (Sweden).

By selecting these reactor concepts and studying their intrinsic properties, we realized that one single reactor technology cannot address the entire shipping industry. In NuProShip II, we will continue working on this. Preliminary results, however, indicate that the MSR will work best with large ships that need steam turbines. The helium gas-cooled reactor will work best with ships that need electric propulsion system. The lead-cooled reactor will work best in situations where the load is more stable situations such as baseload operation.

Once these overall findings were clear, the two other work packages – discussed in Chapters 3 and 4 – could start working in earnest. In Chapter 3 we find a lot of insights from a ship design and class society perspective. This is a complex area, and to gain a complete overview of it is difficult, which will go on well into NuProShip II as well. This is evident for the HAZID overview for which many issues are still not solved.

However, we have started to get a very good overview of the class requirements and international regulations. Most of the results presented here must nonetheless be viewed as preliminary. The challenge is to go from the high, conceptual level down to a concrete ship, such as the Cadiz Knutsen owned by Knutsen OAS. This ship has served as a mental reminder of what we are working on, and the ship is also used as a practical working case.

The same can be said about the work presented in Chapter 4. Researching what skills the crew needs, what qualifications they must have and therefore develop an education and training system is also complex work. The fact is that none of the reactor technologies we have identified have ever been used at sea. The closest is the lead-bismuth cooled reactor used unsuccessfully in the Russian navy. One finding that seems to be very clear is that some remote monitoring/operations of ships must be implemented.

Naval ships are today largely self-contained, and for that reason they have a reactor crew that is too large for commercial chips of any sort due to both the availability of crew but ultimately also costs. Therefore, remote monitoring/operations is seen as key enabler. Obviously, all the topics discussed in Chapter 3 are also extended well into NuProShip II.

The report does not contain much information about costs. The reason is that it is basically too early for making any trustworthy estimates. However, this will be adressed in NuProShip II.

Acronyms and abbreviations

AGR	Advanced Gas-cooled Reactor
AHP	Analytic Hierarchy Process
CMSR	Compact Molten Salt Reactor
DSF	Deep Sea Fleet
FCM	Fully Ceramic Micro-Encapsulated
FNPP	Floating nuclear power plant
FOAK	First Of A Kind
GFR	Gas-cooled Fast Reactor
GHG	Greenhouse Gas
HALEU	High Assay Low Enriched Uranium
HFO	Heavy Fuel Oil
HTGR	High Temperature Gas-cooled Reactor
HTTR	High Temperature Test Reactor
IMSR	Integral Molten Salt Reactor
KP-FHR	Kairos Power-Fluoride Salt-Cooled High-Temperature Reactor
LCOE	Levelized Cost Of Energy
LFR	Lead-cooled Fast Reactor
LNG	Liquefied Natural Gas
LOCA	Loss Of Coolant Accident
LWR	Light Water Reactor
MMR	Micro Modular Reactor
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
NEA	National Energy Agency
NOAK	Nth Of A Kind
NPP	Nuclear power plant
NPS	Nuclear powered ships
PWR	Pressurized water reactor
SBNP	Sea-based nuclear projects
SCWR	Supercritical Water-cooled Reactor
SEALER-55	Swedish Advanced Lead-cooled Reactor
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
TRISO	TRi-structural ISOtropic
TRL	Technology Readiness Level
VHTR	Very High Temperature Reactor

1.0 Introduction

Shipping carries over 80% of global trade volume [1] and emits about 3% of the total global greenhouse gas (GHG) emissions, or slightly above the GHG emissions of Germany as a whole country [2]. Without any effective countermeasures, the share is expected to grow to 10–13% [3]. International shipping constitutes 87% of total CO_2 emissions from marine sources, out of which the three vessel classes 1) bulk carriers, 2) oil tankers, and 3) container vessels represent 55%. This amount is also increasing due to demand for higher speeds despite improvements in technology [2].

The new Maritime 21 strategy for Norway has recognized nuclear power as a source for zero-emission shipping [4]. One area is “Oceans” and its direct focus on zero-emission shipping via **Maritime Zero 2050** where this project fits perfectly because its ultimate purpose is to develop technology for zero emissions from seaborn transportation globally.

International shipping is often associated with the “Deep-Sea Fleet”, involving the maritime transport of goods on intercontinental routes, crossing oceans. This is contrasted to “Short-Sea Shipping” which concerns continental distances.

Figure 1 shows a typical LNG carrier (with key technical specifications) of the type the Knutsen Group is considering for converting to nuclear propulsion. Today, these LNG carriers have complete steam power plants (turbines) utilizing HFO boilers.

« Cadiz Knutsen »

Main Dimensions		**Cargo arrangement**	
Vessel type	LNG Carrier	Four (4) cargo tanks, total capacity 138 000 m^3	
Length overall	284.40 m		
Length between perp.	271.00 m	**Propulsion**	
Breadth	42.50 m	Type	Steam driven turbine
Depth to main deck	25.40 m	Power	28 000 kW
Scantling draught	12.30 m	Revolutions	83 rpm
Design draught	11.40 m		
Deadweight (design)	68 200 tns	**Main Boilers**	
Gross Tonnage	93 450 GT	2 x MHI boilers	65 000 kg/h
Service Speed	19.5 knots	Steam condition	61.8 kg/cm^2 x 515 °C

Figure 1 – Typical 138,000 m^3 LNG carrier being considered for conversion to nuclear propulsion.

It should be mentioned that Cadiz Knutsen typically will consume almost 40,000 metric tons HFO per year, which will result in emissions of roughly 120,000 metric tons of CO_2 and 720 metric tons of SO_2 and a host of other minor emissions with potential long-term toxicity such as the 4 kg of Cadmium – a toxic heavy metal. Clearly, there is a need to do something about this situation, otherwise the emissions are expected to double by 2030 [5].

The fuel consumed by shipping, in general, is estimated in various ways and there can be some discrepancies for a number of reasons in the literature. The dataset [6] of fossil fuel consumption has an overall best fit with other literature sources. The data set is from 2012 and must be updated. The data set can be updated by using the annual growth in tonnage from 2011 to 2022, which is 4.9% [1]. However, the growth of tonnage is not necessarily the same as growth in fuel consumption. For example, focusing on the Heavy Fuel Oil (HFO) segment only, the estimated HFO consumption in 2022 would be more than 50 million tonnes (Mtonnes) higher than we find in other sources. Therefore, to stay on the conservative side, 300 Mtonnes HFO [7] are used to scale the data of [6] from 2012 to 2022.

Currently, several concept designs based on utilization of different fuel types are being discussed for replacing HFO as shown in Table 1. Table 1 also shows the expected Unit Procurement Cost, which encompasses cost of storage tanks, engines, fuel cells, electric motors etc. (as applicable). Furthermore, it includes additional costs such as pipelines, gas alarm systems, additional safety systems where required and the Through Life Cost excluding fuel costs. The sum of Unit Procurement Costs, Through Life Costs and fuel costs is the more familiar term Total Cost of Ownership. Note that the numbers in Table 1 are 'old', but with no commercial ships available after 6 years of publication and at best a handful today, it illustrates the difficulties of finding a good solution.

The Deadweight Loss (in Table 1) results from increased weight of the machinery and fuel storage, which therefore results in less cargo carrying capacity and probably a revenue loss. Note that in the nuclear case, we expect a substantial deadweight gain, i.e., a positive increase in the capacity of carrying more cargo.

It should also be mentioned that other concept designs involving fuel alternatives such as ammonia are being evaluated and developed (not included in Table 1), but these alternatives have numbers in the same range as the other concept designs shown in Table 1.

Table 1 – Costs for each concept design. Adapted from [5].

Concept Design	Unit Procurement Cost [MUSD/MW]	Through Life Cost [MUSD/MW]	Deadweight Loss [t/MWh]
Hydrogen + fuel cells + electric motor	5.30	0.17	0.26
LNG + reformer + fuel cells	2.40	0.17	0.09
Methanol + reformer + fuel cells	1.70	0.17	0.07
LNG + 4-stroke pure gas spark ignition	1.65	N/A	0.09
LNG + 2/4-stroke dual fuel gas engine	1.65	N/A	0.09
Methanol + 2/4-stroke dual fuel gas engine	0.95	N/A	0.07

Yet, the most pressing issue is not costs but the fact that green alternative fuels will not exist in relevant quantities for an energy transition at sea. In Figure 2, we see the electricity required to produce the same amount of green ammonia, green methanol and green hydrogen to produce the same amount of work as being performed by fossil fuels at the end of 2022. Furthermore, the amount of electricity is compared to major geographical entities for comparison. Essentially, certainly if losses are included, we would need all the power in the OECD to produce green alternative fuels for shipping. Obviously, this will not take place in foreseeable future and probably well beyond.

Therefore, global shipping really faces just two real options – continue like today or investigate the nuclear propulsion possibilities. This does not imply, however, that green alternative fuels cannot succeed locally for domestic shipping, as demonstrated by [8] for Norway. Although, even for local shipping it is very demanding.

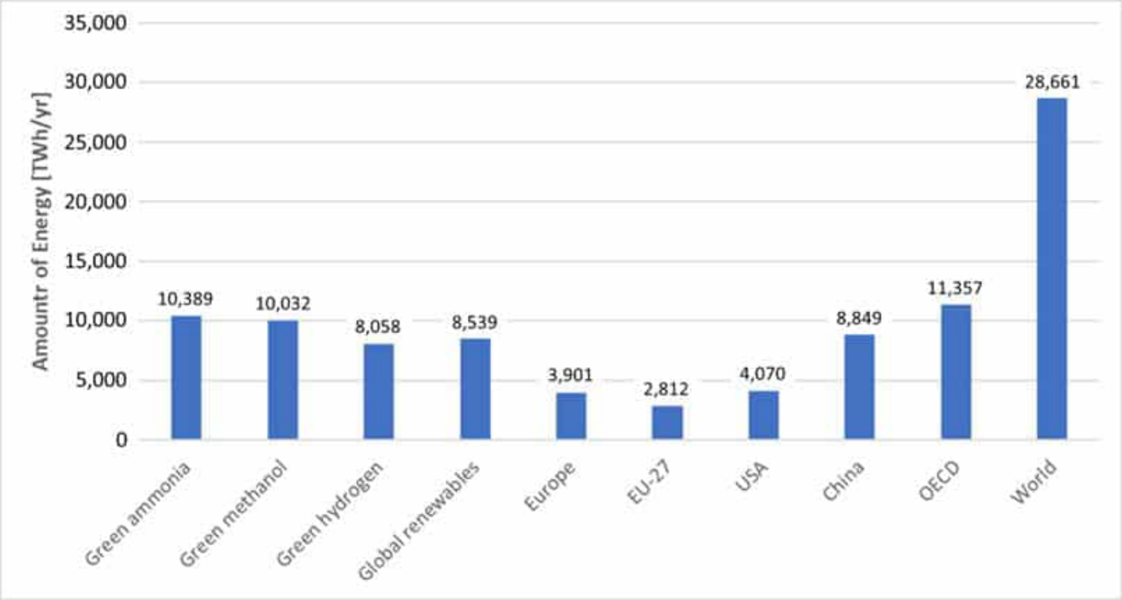

Figure 2 – The electricity requirement of decarbonizing shipping [TWh/yr] compared to large geographical entities. Note that renewable energy in the figure also includes hydro. Source: [9].

The interesting fact, but not surprising, is that nuclear options are not considered by [5], nor by most other studies in the literature. This is because nuclear propulsion is associated with traditional reactors (Generation II and III) only used in military ships and large icebreakers due to their complexity and costs. Also, using Small Modular Reactors (SMR) based on traditional Light Water Reactor (LWR) technology has been studied by [10], but they find many challenges. Therefore, nuclear energy is not often discussed in a marine context in the literature [11] despite the fact that achieving zero emissions will under all circumstances require large investments.

In [12], however, it is demonstrated that for an AfraMax tanker, the life-cycle cost savings are expected to be about 65-70 MUSD. However, this is a simple study based on a fuji reactor design, which is a denatured Molten-Salt Reactor (MSR) – never built. This is, however, a Generation IV technology. This study is in line with present work carried out by e.g., ThorCon US in Indonesia. However, their work is not completed and obtaining results thereof today is infeasible.

Furthermore, there are several MSRs under development and one or more of them will most likely be feasible within the timeframe of the overall research program. Despite these facts, SMRs, regardless of technology, have only been used in a marine context in a few cases (however MSRs have been demonstrated successfully for propulsion of airplanes), and the purpose of NuProShip I is to identify some promising nuclear technologies that can solve the emission problems for the deep-sea fleet.

In a pre-project, we have already established that there is enough space, the acceleration of the ship (due to movements) does not inhibit usage of any reactors, the impact on trim and stability is negligible and several other aspects. In Figure 3, a simple 3D rendering of a MSR with the dimensions of 8 x 8 x 8 meter is shown. The mass is somewhere in the region of 1,900 tonnes depending on reactor design. With the old engines removed and no need for HFO storage, the total deadweight (cargo carrying capacity) of the ship increases by 6,500 tonnes mathematically. In reality, the increase in deadweight tonnes will much less since much of the HFO is stored in tanks not possible to use for cargo.

Figure 3 – Nuclear reactor (blue box) in the Cadiz Knutsen LNG tanker of Figure 1.

Hence, there is a strong case for studying Generation IV SMRs more closely because not only can it be competitive to HFO, but it can provide the marine industry with the technology required for reaching the zero-emission target.

1.1. State of the art and project main objective

The current state of the art of reactors applicable to our project is very succinctly presented in [13] report on Small Modular Reactors (SMR). However, none of that is discussed in the context of marine propulsion, which is the focus here.

The key enabler for the proposed project is the technological leap from Generation III nuclear technology to Generation IV. The four pillars of Generation IV development are sustainability, economics, safety and proliferation resistance, and Generation IV reactors refer to six promising advanced reactor concepts for development from among 130 proposals [14]. These technologies include the: Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR) and Very High Temperature Reactor (VHTR).

However, today, only a handful of Generation IV technologies exists and even fewer on commercial reactors. Importantly, none have ever been developed or tested for marine applications. **The ultimate objective is to identify which Generation IV nuclear technology, if any, that can be developed further for commercial shipping in direct unsubsidized competition with HFO while satisfying all requirements from all stakeholders.**

The chosen technologies must have a certain technology readiness level so that commercialization can start before or around 2030. With this in mind, some Generation IV reactor technologies have already achieved some level of readiness such as 1) the BREST reactor, 2) the helium gas cooled- reactor and 3) a denatured MSR. The reactor types have all been tested at various points in history.

Before we continue, a couple of key terms must be defined. First, a BREST reactor is a Russian design aiming to the standards of a generation IV reactor[1], operating in the fast neutron spectrum and molten lead or lead-bismuth eutectic coolant. It has been used on Russian submarines. Second, helium gas-cooled reactors have been around since the 60s but never succeeded to compete effectively against the LWR for large-scale power

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[1] https://www.world-nuclear-news.org/NN-Design-completed-for-prototype-fast-reactor-0209147.html

production on land. Third, MSRs have many different designs operating at both thermal and fast spectrum in which the primary nuclear reactor coolant and/or the fuel is a molten salt mixture.

Note that NuScale Power has developed an SMR that is a natural circulation LWR with the reactor core and helical coil steam generators located in a common reactor vessel in a cylindrical steel containment. The reactor vessel containment module is submerged in water in the reactor building safety related pool, which is also the ultimate heat sink for the reactor. The NuScale Power SMR is the first ever SMR to receive a design approval from the US Nuclear Regulatory Commission (US NRC), but it is not deemed suitable for this project because it does not meet all design requirements as shown later in Chapter 2.

The ultimate objective cannot be approached in one single project. A series of projects forming a research program called NuProShip must be executed. The research program will follow the recommended development cycle for nuclear technology as proposed by the IAEA and relevant regulatory bodies (national and international). In particular, the IAEA Safety Standards and Licensing Procedures for Nuclear Installations will be important. It is assumed that getting a full or partial license by the US NRC will be required to ensure flexible operation (i.e., access to ports worldwide) of the ships with nuclear propulsion following completion of the commissioning phase. Additionally, the guidelines and recommendations given by the US National Nuclear Safety Administration (NNSA), the International Maritime Organization (IMO), flag state, port state and class societies should be met to ensure operational flexibility.

The research- and development program will cover these main steps:

1. **Concept Assessment**: Assessment of concepts and needs, which continues the work initiated by [12].
2. **Feasibility Study and Design Options**: The project develops design options and assesses feasibility dependent upon characteristics, regulatory requirements, timelines, and resource constraints.
3. **Design Definition and Cost Study**: Further refinement of options by updating criteria, developing design and qualification plans, identifying production needs, and creating preliminary life-cycle plans. Phase culminates with the release of an Integrated Project Plan.
4. **Development Engineering**: Experiments, tests, and analyses conducted to develop and validate selected design.
5. **Production Engineering**: Developmental design refined into producible design and preparations of the production facility for production. Final and updated cost estimates.
6. **Scaling and Commercialization**: Obtaining funding to finance scaling and the final commercialization process. This step typically warrants a company, joint-venture or similar.

This particular project concerns steps 1 and 2, which in sum constitute an initial phase – the first phase in the research program, which is why we denote it NuProShip I.

The objective of NuProShip I is to perform a concept and feasibility study of marine propulsion for merchant shipping by identifying the reactor designs that will fulfill all criteria considering technical, regulatory, competitiveness towards HFO, impact on ship design and other issues.

A complete list of future work must also be developed in NuProShip I. The future work identified in NuProShip I will be addressed in NuProShip II (the Design and Development Phase, step 3 above).

The final three steps will be addressed in separate demonstration projects born out of the Center for Research-Based Innovation (SFI) SAINT, and also possible several other NuProShip projects in years with specific research objectives necessary to address before the demonstration projects can be launched.

Starting in 2022, the timeframe is 10 – 12 years largely depending on the licensing process and funding. There is also considerable uncertainty concerning how the IMO will handle a commercial nuclear ship in terms of rules on the high seas as well as local jurisdictions where these carriers will operate. To increase the likelihood of a successful licensing process, the project will position itself towards the US NRC because most countries in the world have requirements that are either identical or very similar. Following stringent qualification and commissioning tests (fulfilling all relevant requirements from authorities and regulatory bodies) of the prototype system, nuclear propulsion systems will be installed into newbuilt ships and into ships currently running on HFO. Similarly, close cooperation with IMO and class society is important, and both DNV and Sjøfartsdirektoratet (Norwegian Maritime Authority) are members of the project consortium.

1.2. Brief outlines of research questions

There are a number of research questions that must be addressed. These are related to the Work Package (WP) discussed in the subsequent chapters. To address the research objective of this initial phase project, we must define feasibility. Feasibility has three main aspects, each addressed in its own WP. The WPs interrelate as shown in Figure 4.

Note that WP 4 has been moved in its entirety to NuProShip II due to data availability issues.

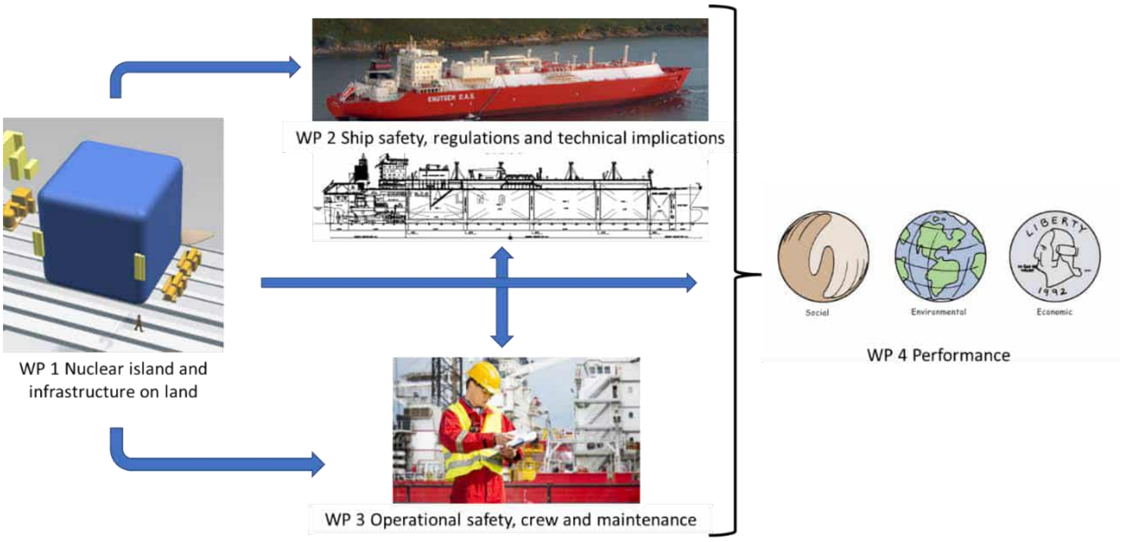


Figure 4 – WP interrelation scheme and deliverables.

It is important to note that the three first WPs are guaranteed to create valuable output for future research independently of each other because there are many generic issues related to nuclear reactors that must be addressed in all three WPs.

1.2.1 WP 1 – Nuclear island and infrastructure requirements on land

This WP focuses on all relevant issues related to nuclear physics, reactor physics and nuclear engineering as well as nuclear safety and security, radiation protection, infrastructure on land, decommissioning and management of spent fuel and radioactive waste.

The WP will address issues such as:

1. How will the reactor perform under different operational ship modes?
2. How will proliferation issues be handled?
3. How will the reactor be refueled (if necessary)?
4. How can the nuclear island survive collisions and sinking?

5. How to maintain the reactor including primary heat exchanger loop?
6. For reactors requiring refueling, how will refueling take place?
7. Are there any harbor implications that must be analyzed and solutions found?
8. How can piracy, terrorism and similar treats be managed?
9. What are the key uncertainties and risks to address in future work?

Note that the reactor physics will be primarily provided by the reactor suppliers but verified by this team. This work package is addressed in detail in Chapter 2.

1.2.2 WP 2 – Ship safety, regulations and technical implications

Nuclear propulsion enables several interesting research issues to be addressed such as:

1. With an inexhaustible source of energy, hull lines can be changed to increase speed and hence the revenue potential for the fleet (Top-down approach). How can this be achieved?
2. Where should a reactor be placed in a ship? The research question is ship-type specific.
3. How can ships sink without compromising the nuclear island?
4. How can rules and regulatory framework be applied? Are any amendments required?
5. How will different reactor designs impact the safety and reliability of the ship?
6. What are the risks and how can they be managed?
7. How can piracy, terrorism and similar treats be managed?
8. What are the key uncertainties and risks to address in future work?

This work package is addressed in detail in Chapter 3.

1.2.3 WP 3 – Operational safety, crew and maintenance

A nuclear ship will put certain requirements on the crew that must be identified and analyzed covering research issues such as:

1. What are the requirements for the crew? Competence, training, etc.
2. How will different reactor designs perform when it comes to emergency situations, and how can they most effectively be dealt with?
3. How can piracy, terrorism and similar threats be managed?
4. How can the vessel be remotely operated to improve safety?
5. What are the key uncertainties and risks to address in future work?

This work package is addressed in detail in Chapter 4.

1.3 Theoretical approach and methodology

All these research questions will be addressed for various ship designs, operational modes and reactor designs, resulting in a large possible solution space, that will be tested through hypotheses (not included here due to space limitations). When it comes to the theoretical approach, or research approach, it will use three primary approaches;

1. **Literature reviews** – structured and integrative to ensure we have full grasp of the state of the art in WPs 1, 2 and 3. Concerning WP 3, there is very little to be found so it is likely we must start from almost nothing unless we can find publicly available information concerning management of military vessels having nuclear propulsion. This project will **rely on publicly available information** to avoid the stringent export control regime concerning nuclear technology.

2. **Analysis and simulations** – various issues will be analyzed or simulated to provide additional understanding to the literature.
3. The general applicability of solutions will subsequently be analyzed and discussed.

The surviving solutions will be verified on some concrete cases for real-life verification. For example, Knutsen OAS is interested in studying how 4 of their large LNG carriers, see Figure 1, may be converted to nuclear propulsion. Preparing these ships for nuclear propulsion basically will involve replacing the HFO boiler systems with suitable nuclear reactors. In addition, all related existing systems will have to be updated accordingly and there are likely additional systems that need to be installed as a result of installing the nuclear reactors. This discussion has already started in earnest with the aim of defining a full-scale demonstration project in commercial operation.

1.4 Novelty and impacts

Generation IV is a radical shift from earlier generations of nuclear technology [14] which various navies around the world have used for decades. The novelty level of the project is therefore 'new to the world' as it concerns both technology and application of technology that has never been combined before. As such, the project is ambitious, original and novel in every interpretation of the terms. If the project can be challenged for something, then it must be that it is too novel and too ambitious. However, this is exactly why the overall research program is structured in phases and this first phase (NuProShip I) is essentially a major fact-finding mission.

More specifically, the project will operate on a new-to-the-world level of novelty when it comes to:

1. Generation IV, specifically the chosen, applied at sea has never been done before – not even in naval context. This will lift the knowledge, not only on nuclear engineering but also in ship design, rules and regulations and class approval of nuclear ships.
2. The detailed implications for merchant shipping. It should be noted that there are a couple of nuclear merchant ships in world history, but they all succumbed to costs or regulatory complexity or lack of stakeholder involvement.
3. The operational impact of this technology on crew, safety and operations at large.

The scientific impact is high since the technology is 'new to the world', and with the deep-sea fleet constituting a large part of marine emissions, the societal impact can be very large as the project aims at providing technology that can potentially eliminate 2% of global climate emissions. This impact will directly relate to Sustainability Development Goals (SDG) no. 7 (affordable and clean energy) and no. 13 (climate action).

When it comes to the industrial impact, there are several. First, we have started the process of helping nuclear reactor designers to test their designs, which will enable innovations in nuclear technology in general. This meets not only SDG nos. 7 and 13, but also no. 11 (Sustainable cities and communities). We do not foresee this to become an industry in Norway in foreseeable future, but this is nonetheless important context because it is perhaps the starting point of a new industry within the maritime industry – also for Norway. This addresses SDG no 4. (quality education) and no. 9 (industry, innovation and infrastructure).

This will give our current marine industry in Norway potentially a major positioning advantage in a future, zero-emission marine industry (SDG 7 and 11). Providing Norwegian shipowners and marine industry with a technological edge in the new, marine context of zero emissions is the primary purpose of this project from an industrial point of view. More specifically the project can foster industries 1) delivering heat exchangers, 2) system integrators such as shipyards and equipment system integration, 3) support systems in the ship such as rest energy management, 4) harbor technologies such as electricity to land (as opposed to from land today), and 5) education and training of crew. Currently, the deep-sea market for Norway predominantly consists of ship-owners and minor system suppliers, but this project could ultimately reopen the deep-sea fleet as a market for major deliveries from the Norwegian maritime industry.

For Norway, the project will also kick-start education, research and general competence building where we create value from the nuclear innovations taking place internationally. However, this will become much more prominent in future projects. This also addresses SGD no. 4.

The stakeholders of the project are many covering not only the maritime industry but also banks, insurance, academia, politics and even the general population, which will have an opinion about a project of this nature. The project team has reached out in academic outlets, academic conferences, newspaper articles, magazine articles, podcasts, radio interviews and TV appearances concerning nuclear technology, and more is scheduled in months going forward. We also arranged a conference on nuclear propulsion for merchant shipping.

1.5 Project consortium

The project consortium consists of the following organizations:

- Knutsen OAS (Norway) – they own the 4 LNG tankers that is used as case objects. Contact person is Project & Innovation Manager at Knutsen Group, Even Bjørnevik.
- NyHill Shipping & Trading (Norway) – bulk shipping management company that will provide general bulk case objects. Contact person is Chairman at Nyhill Shipping & Trading AS, Stig Hilland.
- NTNU (Norway) – the university that will execute some of the research and coordinate the project. Contact person is Professor Jan Emblemsvåg.
- IDOM (Spain) – internationally recognized technical consulting company who is also part-owner of Moltex (MSR design and construction company) in UK. IDOM will be key subcontractor to NTNU. Contact person is Operations Director for Nuclear department in IDOM, Óscar Larrosa Peruga.
- Vard Group AS (Norway) – they are working on newbuilds that may fit nuclear propulsion. Vice President R&D, Håvard Vollset Lien.
- KTH (Sweden) – contribute with a BREST reactor design that will be evaluated. They will also contribute with significant knowledge on corrosion concerning the other reactors. Contact person is Professor Pär Olsson.
- Escola Superior Náutica Infante D. Henrique (ENIDH) (Portugal) – contribute with insights on operations of Deep-sea fleet ships. Contact person is Professor Luis Filipe Baptista.
- Det Norske Veritas (Norway) – contribute with the class society expertise in the project. Contact person is Director Business Development, Maritime, Jan Kvålsvold.
- Sjøfartsdirektoratet (Norwegian Maritime Authority) – contribute with regulatory insights. Contact person is Head of Department Vessels and Seafarers, Lars Alvestad.

The project was overall managed by Professor Jan Emblemsvåg, at NTNU in Ålesund, Norway.

It should be noted that several other shipping companies joined the effort, and they are now included in the NuProShip II consortium. The same is true also for insurance companies and trade associations.

2.0 Nuclear Island and infrastructure on land

The first step in the selection process is to develop a set of criteria for the evaluation of each of the reactor designs. The challenge lies in the diversity of the criteria, leading to a classic multi-objective selection process involving both quantitative and qualitative objectives or criteria. Therefore, the selection process will be subjective with such a variety of criteria.

One of the best qualitative methods for providing decision-support in multi-objective situations, is the Analytic Hierarchy Process (AHP) developed in the late 1960s by [15]. The AHP has been used in a wide array of situations, including resource allocation, scheduling, project evaluation, military strategy, forecasting, conflict resolution, political strategy, safety, financial risks, and strategic planning [16]. AHP has also been used in supplier selection [17], business performance measurement [18], quantitative construction risk management and selection of maintenance strategy and organization [19].

However, given the high number of alternatives, the direct application of the AHP can be challenging. This issue was resolved by performing an initial screening using basic exclusion criteria [19] with the purpose of bringing the complexity down to a manageable size. The resulting shortlist of reactor concepts is subsequently presented in Section 2.3 followed by a discussion of the future work in Section 2.4.

The overall method is a decision process structured in 3 Stages as shown in Figure 5. The justification for this structure is the simple fact that selecting among several tens of different reactor concepts with varying degree of information availability using a large set of multidimensional qualitative as well as quantitative criteria is a major job.

In Stage 1, a preliminary selection of the reactor designs is performed using decision constraints as depicted in Figure 5. These constraints are essentially exclusion criteria defined as whereby reactor concepts having this specific feature or characteristic are by default excluded from the overall decision process. The quality of the decision process hinges therefore greatly on this first selection.

In Stage 2, the selection criteria allow the categorization of the most suitable designs for marinization using the AHP method. These selection criteria and sub-criteria, as well as the exclusion criteria derived from Stage 1, are gathered and deeply explained in [20]. On the other hand, the posterior weighting analysis and the results derived from the reactors scoring have been gathered in [21].

Finally, Stage 3, considered out of the scope for the initial NuProShip I project, is the future step where, with the selected reactor concepts and their vendors, concrete solutions can be found for specific cases. This final stage will be conducted in the following years, in the framework of the NuProShip II project, discussed in Section 5.

The over 80 reactor designs to evaluate are detailed in the IAEA (International Atomic Energy Agency) SMR Handbook [13] and the NEA (Nuclear Energy Agency) SMR Dashboard [18].

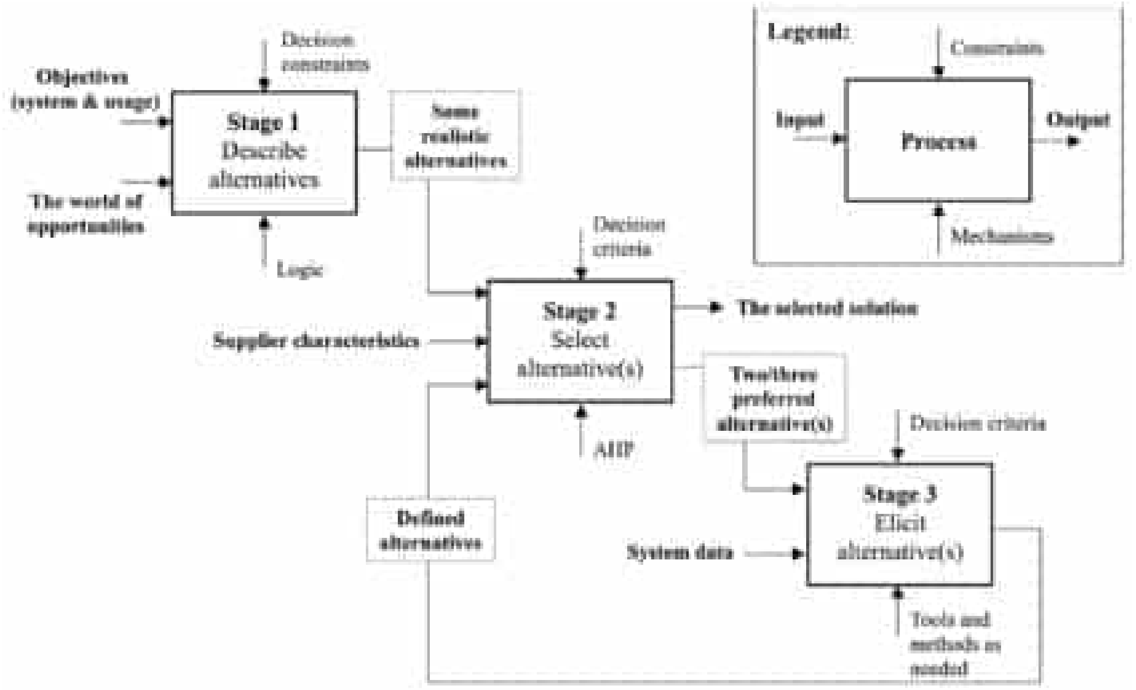


Figure 5 – The overall selection process. Source: [19].

2.1 Stage 1 – Exclusion

This stage consists of the screening of over 80 reactor designs to a reduced number of feasible alternatives. To do so, a set of exclusion criteria is defined in Section 2.1.1, which are essentially hard constrains defined as criterion whereby reactor concepts having this specific feature or characteristic are by default excluded from the overall decision process. As a result, the feasible reactor designs that pass these exclusion criteria are obtained. However, instead of focusing on specific designs, the different reactor technologies that are possible for ship propulsion are introduced in Section 2.1.2.

2.1.1 Exclusion criteria

To screen the 80 reactor designs a set of exclusion criteria has been defined. The set is based on the guidelines of the Gen IV Forum as well as the applicability for marine propulsion. The exclusion criteria are:

1. Using water as coolant: Some of the reactors use water as a coolant, but all water based SMRs (Small Modular Reactor) are excluded from the analysis. The reason for this is that water-based reactors may face strong public opposition, regardless of their safety performance. This is based on the observation that many people cannot differentiate between Generation III reactors and Generation III+ reactors, which have advanced safety features and impeccable records, and Generation II reactors, which were involved in major accidents such as Chernobyl and Fukushima (both accidents were greatly miscommunicated by media [22]). It is expected that this negative belief will also affect water-based Generation IV SMRs. Water-based reactors will also struggle to meet the 5-year continuous operation requirement, discussed later, with the enrichment-level civilian operators will be allowed to use. Therefore, the analysis focuses on Generation IV SMRs that use alternative coolants, such as helium, molten salt, or liquid metal, which offer higher efficiency, lower waste, and enhanced safety.
2. Reliance on active safety systems: One of the main characteristics of Generation IV reactors is their dependence on passive safety systems or passive shutdown systems, which require no human action and aim to prevent any release of radioactivity to the environment by air or water. Reactor concepts that lack this feature or do not specifically establish their safety systems are discarded.

3. Limited proliferation resistance: Reactor concepts that do not enhance barriers that reduce to a minimum the extraction and use for military purposes of fissile material were excluded from further consideration. This is obviously important for ships crossing in and out of jurisdictions on frequent basis. However, it must be noted that fast reactor designs that are fueled only once in their lifetime are not excluded by this criterion, since the fissile material can't be easily extracted from the reactor. Annex I contains additional discussions pertinent to certain types of MSR.
4. Fuel enrichment and highly toxic bi-products: Reactor concepts must require fuel enrichment below 20% of uranium-235 and no significant highly radioactive bi-products. The limit in uranium enrichment is set by international agencies, such as the IAEA, and enhances safety, security and non-proliferation goals. Examples of highly radioactive bi-products are Polonium-210 that is generated in lead-bismuth reactors or Chlorine-36 produced in chlorine-based molten salt reactors. Annex II contains additional insights.
5. Too large power output: The thermal- and electric-output should be in line with the needs for marine propulsion. For the largest oil/LNG tankers and container ships, the need for power could be more than 50 MWe while for the smallest ships the requirements may go down to less than 5 MWe. Reactors of higher power output should be able to scale down with minor design changes (for example reducing the volume of fissile material in the reactor vessel), otherwise they are excluded.
6. Technology is not mature enough: Among the over 80 SMR concepts analyzed, only a handful are at a noteworthy Technology Readiness Level (TRL) and most of them are in an early stage of development and not in a licensing preparedness process. On the other hand, new concepts are continuously being introduced and some of these concepts could be developed and be at a demonstration stage (prototype or licensing) before several of those listed. This selection is limited to those that are at a high Technology Readiness Level for being commissioned.
7. Less than 5 years of continuous operation: There are several prerequisites that must be met to introduce nuclear reactors on a ship, and one of these are the 5-years intervals where ships are brought to a dry dock for inspection and maintenance according to classification society rules. This means a minimum of 5-years continuous operation before maintenance and ideally an interval for refueling over 5 years. However, some reactors have continuous or short period refueling which means that they are refueled onboard, such as some molten salt reactors.
8. Using classic pebble bed technology: In a challenging marine environment, there are certain limitations on structures that cannot withstand sudden movements or disturbances of ocean waves. That could be the case for High Temperature Gas-cooled Reactors (HTGR) based on pebble bed technology, being the main reason why these are excluded from the list.
9. High pressure in the reactor primary system: Similarly, it is also important to limit the pressure allowed in the reactor vessel, so that it is guaranteed that the pressure limit in accidental conditions is below the limit of what the ship structures can sustain. Reactor concepts that cannot guarantee this, are excluded.
10. Violent reaction of coolant with water: In a marine environment, the chemical reactivity of coolants and salts is an issue. This excludes molten salt reactors based on highly soluble compounds such as NaCl due to the violent reaction of high temperature molten salt interacting with water. Based on the same criteria, Sodium-cooled Fast Reactor (SFR) technology is excluded.
11. Violation of export control: Export control issues (and trade embargos) with some countries must also be considered. These embargoes condition the import of either reactor designs or constructive materials such as graphite from restricted countries.

2.1.2. Feasible reactor technologies

Based on the discussion of exclusion criteria, only three categories of reactors were considered for marine applications in this study and will be briefly described in this chapter. Only seven reactor concepts of these technologies survived the exclusion process.

2.1.2.1 Molten Salt Reactor (MSR)

In a molten salt reactor, the primary coolant and/or the fuel is a mixture of molten salt with a fissionable material. An MSR could also be a combination of Tri-structural Isotropic (TRISO) particle fuel in pebble form coupled with molten fluoride salt as coolant. There are several reactor concepts of Molten Salt Reactors (MSRs) [13], and it would be beyond the scope of this report to describe the different concepts in detail. Altogether 13 reactor concepts were reviewed, and only a few of these reactor concepts survived the evaluation by exclusion criteria.

One of the main advantages of MSRs for marine applications is that they can operate at or close to atmospheric pressure and can be refueled while in operation. However, this can also face problems related to proliferation and crossing of different jurisdictions. Another advantage is the retention of fissile material in the salt, or intrinsic retention in TRISO fuel, and the complete unit decommissioning. Depending on the reactor concept, refueling could take place onboard continuously (online refueling or during certain periods (months/years)), or in other cases during the 5-year maintenance intervals of ships. Note that the refueling operations in the MSRs considered involve only the addition of tiny amounts of fresh makeup fuel salt to maintain power and no extraction of spent fuel salt is performed, which would pose serious challenges from the proliferation point of view. MSRs are expected to need extensive qualification of materials to address possible corrosion issues.

2.1.2.2 High Temperature Gas-Cooled Reactors (HTGR)

High-Temperature Gas-cooled Reactors use uranium fuel and helium coolant to produce very high temperatures. The fuel in the reactor core can be either in the form of prismatic blocks or a pebble-bed. In the first, TRISO particles are embedded in a solid prismatic block of structural material (typically graphite) that are arranged in an array inside the reactor vessel. In the last, TRISO particles are embedded on spherical fuel elements (pebbles) and the reactor vessel is filled with thousands of these pebbles, which are continuously cycled through the reactor. This last design is rejected due to the 8th exclusion criterion (Pebble bed technology) mentioned previously in Section 0.

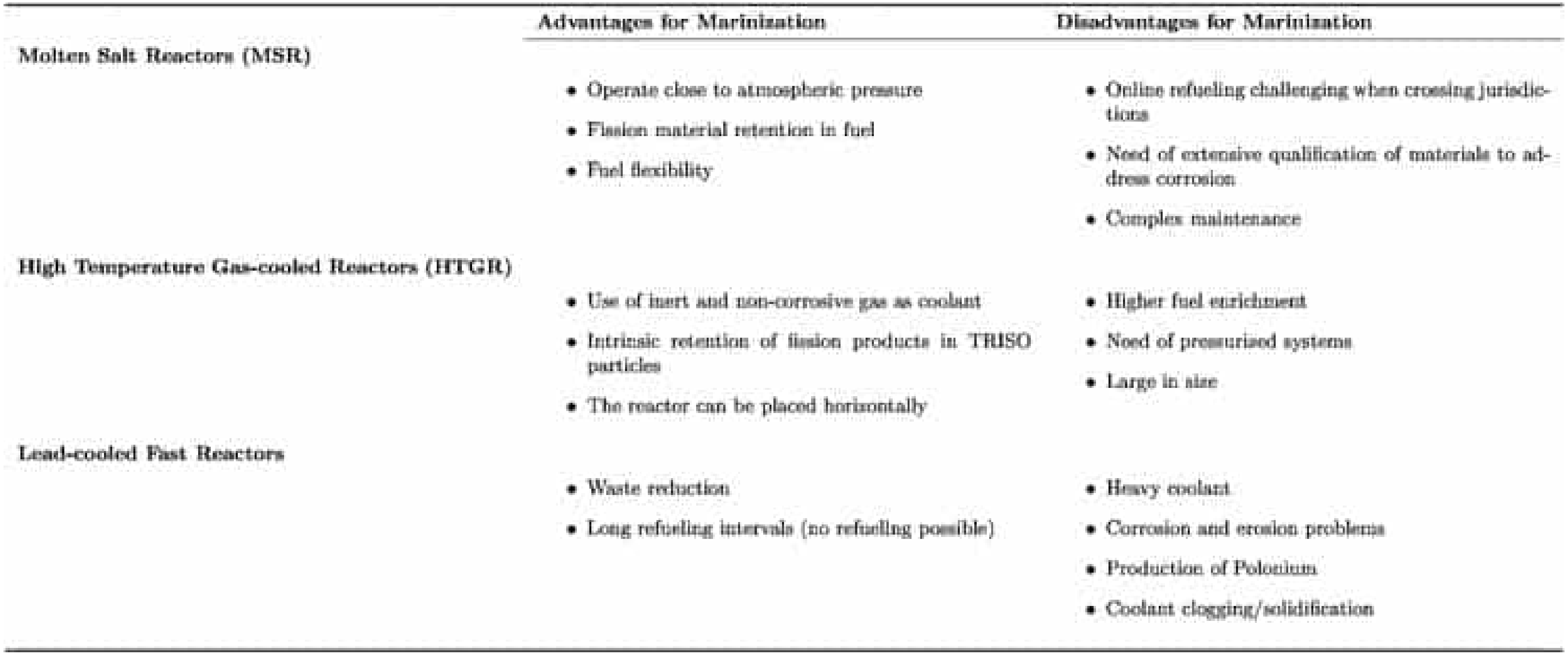
The main advantages of HTGR are the use of an inert and non-corrosive gas (helium) as the coolant, the intrinsic retention of fission products in TRISO particles and its high proliferation resistance despite high fuel enrichment (between 9.99% and 19.75%). However, the coolant requires the use of a pressurized vessel. Another advantage for marine applications is that the reactor has no moving parts and can be placed horizontally, thus limiting the space occupied.

2.1.2.3 Lead-Cooled Fast Reactors (LFR)

Lead-cooled reactors use liquid lead or lead-bismuth eutectic as the primary coolant. This type of reactors has several advantages such as high operating efficiency at atmospheric pressure, inherent safety, no need of refueling, and closed unit decommissioning. The main drawback is the production of Po-210, which, in case of coolant leakage, constitutes a radiological hazard, requiring methods based on alkaline extraction to safeguard both personnel and the environment. Lead is considered a more attractive coolant option than lead-bismuth, mainly due to its higher availability, lower price, and lower amount of induced polonium activity (by a factor of 10^4 compared with lead-bismuth [23]), which is why lead-bismuth reactors are strongly penalized during the selection process.

The pure liquid-lead cooled reactors have potential problems of clogging during operation and will need external heating while reducing/increasing the power. However, the use of lead as a coolant has advantages as it is a radiation shielding and makes it possible to achieve passive safety systems. Liquid-lead reactors are also known to have experienced corrosion issues in the past which new reactor designs promise to solve.

Table 2 – Advantages and disadvantages of feasible reactor technologies.



	Advantages for Marinization	Disadvantages for Marinization
Molten Salt Reactors (MSR)	• Operate close to atmospheric pressure • Fission material retention in fuel • Fuel flexibility	• Online refueling challenging when crossing jurisdictions • Need of extensive qualification of materials to address corrosion • Complex maintenance
High Temperature Gas-cooled Reactors (HTGR)	• Use of inert and non-corrosive gas as coolant • Intrinsic retention of fission products in TRISO particles • The reactor can be placed horizontally	• Higher fuel enrichment • Need of pressurized systems • Large in size
Lead-cooled Fast Reactors	• Waste reduction • Long refueling intervals (no refueling possible)	• Heavy coolant • Corrosion and erosion problems • Production of Polonium • Coolant clogging/solidification

2.2 Stage 2 – Selection

As noted above, the selection process follows the AHP approach section by section.

2.2.1 Identifying the selection criteria

Following the discussion of 11 exclusion criteria, a total of 8 selection criteria and 22 sub-criteria were identified through a series of workshops and discussions of the NuProShip I project throughout 2023. These criteria and sub-criteria stand for those aspects that get more relevance for the final selection goal. This task has been performed by the participants in the NuProShip I project, which includes staff with extensive experience in a wide variety of relevant fields, including nuclear engineering, ship design and ship building. In Figure 6, the set of evaluation criteria and sub-criteria are hierarchically displayed.

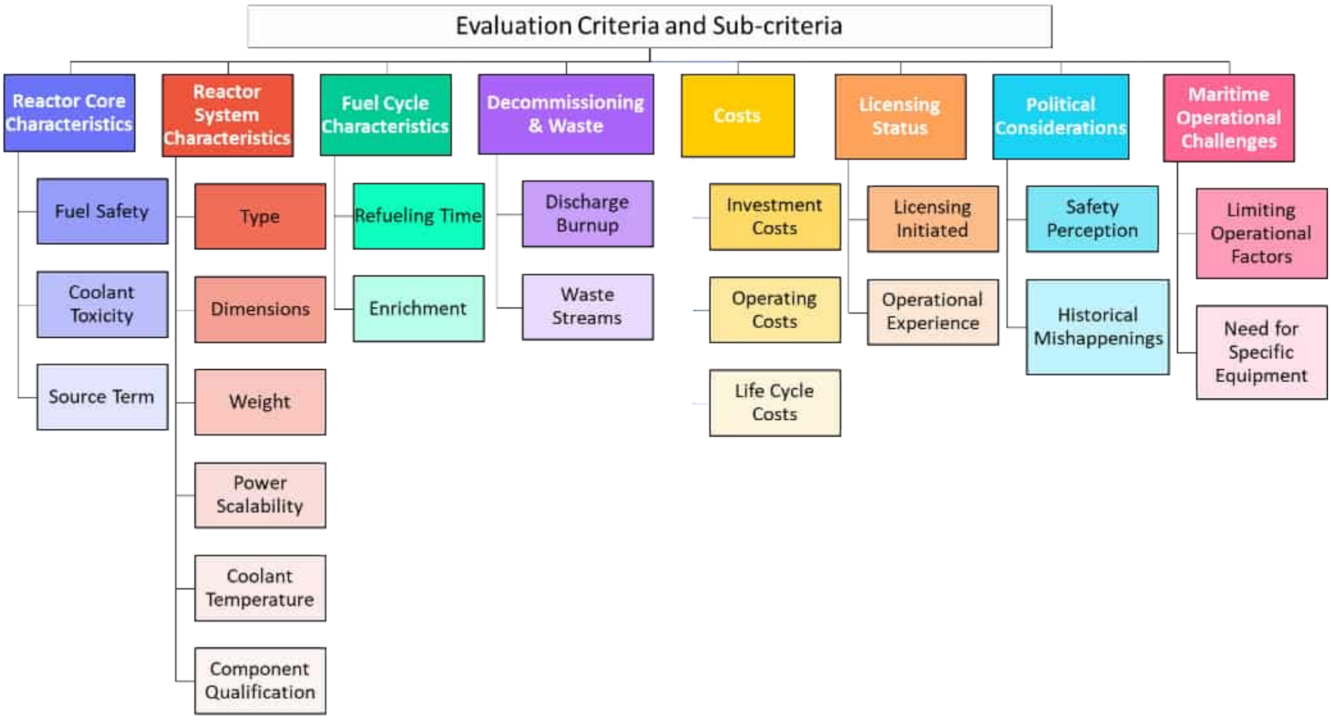


Figure 6 – The criteria for selecting nuclear reactor concepts for propulsion of merchant ships. Source: [21].

These criteria and sub-criteria are explained hereafter, starting from the left to the right:

1. Reactor Core Characteristics: The core of the reactor will decide its behavior, and it is therefore an important criterion to consider. It is refined into 3 sub-criteria:
   a) Fuel Safety: Behavior of the fuel in an accident and its environmental impact is a key factor. Different reactor concepts make use of nuclear fuel in different forms with a different degree of safety. For example, TRISO fuel is considered the most robust nuclear fuel ever engineered [24] given its capability to retain fission products and to withstand extreme temperatures. In contrast, conventional oxide pellets organized in fuel assemblies have shown potential safety issues, such as swelling, cracking or mechanical interaction with cladding, that could lead to fission product release when operating at abnormal temperatures [25].
   b) Coolant Toxicity: This sub-criterion is related to the harmful effect of the coolant. While the safety shall be excellent, there can always be a small possibility of coolant leakage or spillage during

    maintenance operations, and therefore, minimizing the toxicity of the coolant is important for workers and the environment.
    c) Source Term: The types and amounts of radioactive or hazardous substances that could be released to the environment following an accident – reflecting the potential radiological consequences – are also important safety parameters. Different reactor concepts may have different source terms, depending on the fuel type, coolant type, operating conditions, etc.

2. Reactor System Characteristics: This criterion is important as it is key for the interaction with the ship, and it is refined into 6 sub-criteria:
    a) Type: Whether the secondary system consists of one or more loops (with natural or forced convection) or the design is integral, with the secondary system held inside the reactor vessel, will have consequences for the overall system complexity and performance.
    b) Dimensions: This criterion measures the size of the propulsion unit, which relates to the fact that space is scarce on ships.
    c) Weight: Weight of the propulsion unit is another physical aspect that must be considered, not because of its magnitude per se, but because the location of this weight may affect the stability of the ship.
    d) Power Scalability: Considers the different ways the propulsion unit can increase/decrease its power, whether by adding more reactor units, by increasing/decreasing the enrichment or size, etc. This criterion rewards those reactor designs with higher adaptability to ship power requirements.
    e) Coolant Temperature: Outlet temperature of the reactor coolant is an important sub-criterion since it will affect the heat insulation needs of many subsystems.
    f) Component Qualification: This sub-criterion considers the often-time-consuming qualification processes needed for development of new components and materials.
3. Fuel Cycle Characteristics: There are particularly two aspects of the fuel cycle that are considered important, leading to the following sub-criteria:
    a) Refueling Time: Refueling may constitute one of the most critical operations to be performed. On the one hand, spent nuclear fuel and fresh fuel are manipulated, and on the other hand it usually requires the shutdown of the reactor and the opening of the reactor vessel, with the corresponding need of specialized structures for the shielding of the radiation (i.e., a hot cell). Thus, reactors without refueling are considered advantageous. Nevertheless, since most reactors at some point need to be refueled, this should ideally take place when the ship docks for inspection. This docking takes place every 5 years, being the expected life of the ship 30 years.
    b) Enrichment: This factor considers the increased percentage of U-235 needed for the operation of the reactor. Enrichment is primarily a cost issue as well as, potentially, a political issue. This is why Natural Uranium and Low Enriched Uranium are favored.
4. Decommissioning and Waste: Both decommissioning and waste are important criteria because they can be a challenge in certain political and economic scenarios. This criterion is broken down into two sub-criteria:
    a) Discharge Burnup: This sub-criterion is a measure of how much energy has been extracted from the nuclear fuel. This is why higher levels of discharge burnup are favored.
    b) Waste Streams: This sub-criterion accounts for the estimated types and amounts of radioactive waste generated in operation of each reactor design.
5. Costs: The sub-criteria related to costs are omitted in the first selection because the information is not mature enough to provide reasonable accurate cost estimates. Furthermore, the cost estimates provided by the vendors themselves vary too much to be consistent as some vendors provide costs for the First Of A Kind (FOAK) and others provide them for the Nth Of A Kind (NOAK), some provide estimates

for the of LCOE, a metric often used to compare technologies and policymaking worldwide, etc. The following sub-criteria will therefore be reviewed at a later stage, once more mature information is available, to primarily ensure that double counting is avoided, and correct estimates of individual costs are used:

   a) Investment Costs: The costs of the fabrication, construction, commissioning, and licensing of the propulsion unit compose an important economic sub-criterion because of the strong focus on investment costs in the shipping industry. Note that the propulsion unit includes the reactor as well as any auxiliary systems such as heat exchangers, turbines and load management system needed for its safe operation to propel ships.
   b) Operating Costs: It refers to the costs of the operation of the propulsion unit, which considers among others cost of the fuel, maintenance.
   c) Life Cycle Costs: Costs of the decommissioning of the propulsion unit as well as waste handling will ultimately impact the total economics of the reactor concept.

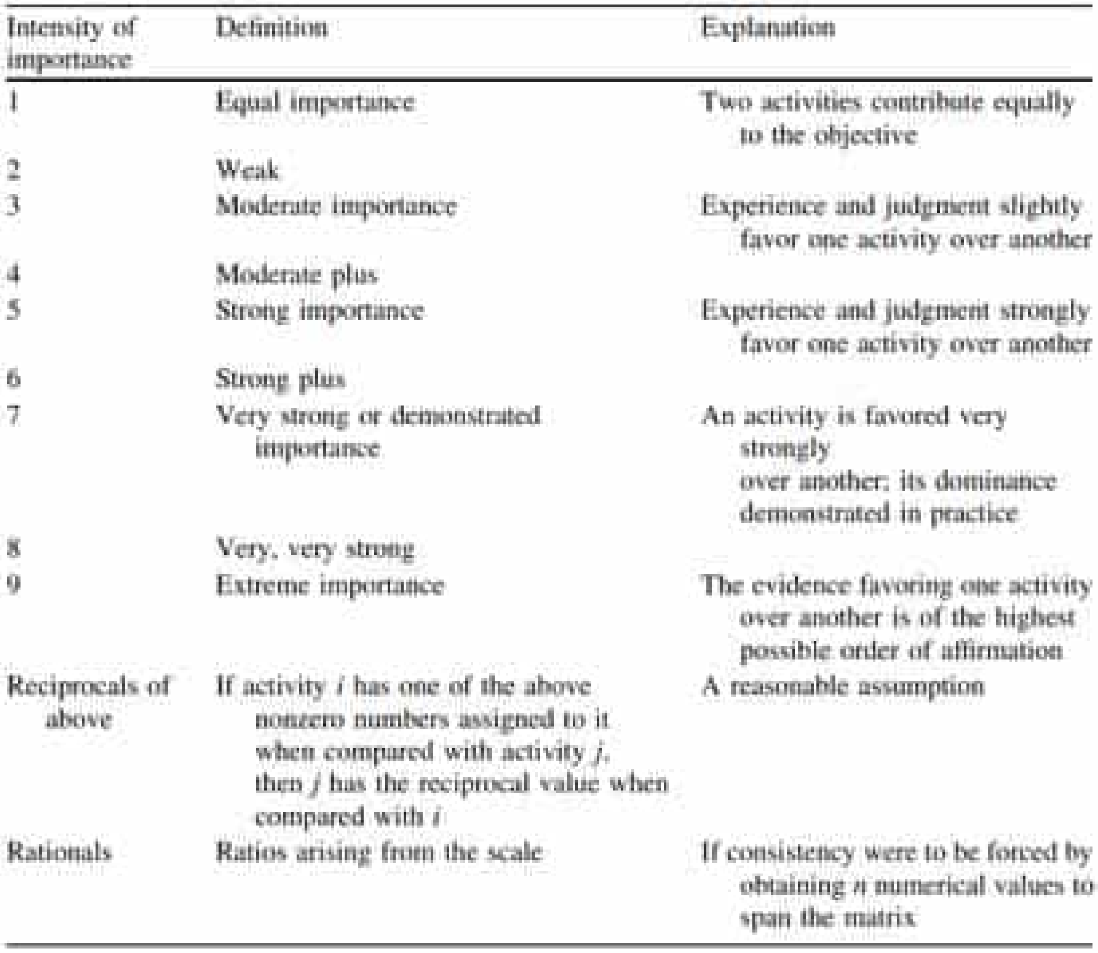
6. Licensing Status: The purpose of this criterion is to avoid selecting reactor concepts that face many difficulties in terms of approval or are far into the future. This criterion has been divided into 2 sub-criteria:
   a) Licensing Initiated: This sub-criterion refers to the status of the reactor considering its phase in the licensing process.
   b) Operational Experience: Describes whether the technology of the nuclear reactor is completely new, or some previous experience already exists.
7. Political Considerations: Nuclear power is highly influenced by politics. To this, the fact that ships cross several jurisdictions on their voyages must be added, increasing this influence and the political issues that reactor concepts will meet. This criterion has been divided into 2 sub-criteria:
   a) Safety Perception: This sub-criterion refers to the public and political awareness and understanding of potential hazards and risks of the specific reactor concept, which is a main factor for the public acceptance of nuclear reactors for shipping.
   b) Historical incidents and accidents: This sub-criterion accounts for events that occurred in the past, related to the technology with negative or unintended consequences, which could jeopardize the deployment of that technology in a reactor concept for shipping.
8. Maritime Operational Challenges: Ships undergo various operational modes through their life cycle, so choosing a reactor that can satisfy these modes is crucial. This criterion has been divided into 2 sub-criteria:
   a) Limiting Operational Factors: This sub-criterion refers to the aspects of each reactor design that can limit its application towards nuclear propulsion. Examples of these challenges are, the effect of the sea movement on reactors relying on natural circulation, the potential clogging problems on Lead-Cooled Reactors due to load variations, etc.
   b) Need for Specific Equipment: This sub-criterion essentially focuses on the need for development or implementation of specific equipment for the optimal performance of the reactor in maritime environment.

2.2.2 Weighting the selection sub-criteria

Since the criteria sub-criteria do not all hold the same level of importance in the selection process, their weighting is conducted as follows. First, the weight of each sub-criterion within the same criterion is obtained by pairwise comparison of the sub-criteria, assigning intensity values in these comparisons. These intensity values can be seen in Table 3.

Next, the weight of each criterion is obtained by pairwise comparison of the criteria, as detailed in Section 2.2.3. This sequence of assignment is based on the rationale that it is easier to evaluate the general criteria after reviewing the various sub-criteria that comprise them.

Table 3 – Intensities for pairwise comparisons. Source: [26].



Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

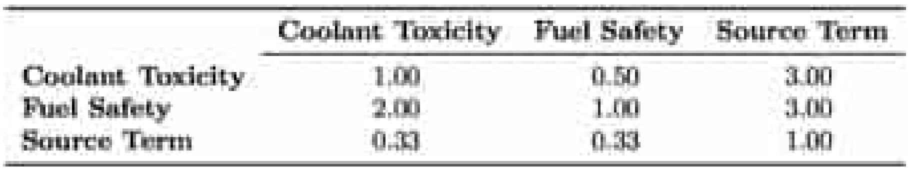
2.2.2.1 Reactor Core Characteristics (RCC)

The core of the reactor will determine its behavior, and it is therefore an important criterion to consider. This criterion is composed of 3 sub-criteria: *Fuel Safety, Coolant Toxicity* and *Source Term*. The intensity of each of the sub-criteria has been decided by pairwise comparison with the SuperDecisions software (on the scale from 1 to 9 seen in Table 3). Thus, with three sub-criteria, three pairwise comparisons were performed:

1. *Fuel Safety* is **equally to moderately** more important than *Coolant Toxicity*: While *Coolant Toxicity* is also a concern, the consequences of fuel-related accidents, considered in *Fuel Safety,* are potentially more severe, involving release of radioactivity and core damage.
2. *Fuel Safety* is **moderately** more important than *Source Term*: while *Source Term*, which refers to the types and amounts of radioactive or hazardous material released to the environment following an accident, is certainly of importance, *Fuel Safety* is a more fundamental aspect of SMR designs ensuring the prevention of such releases from occurring during normal operation and prior to any accident.
3. *Coolant Toxicity* is **moderately** more important than *Source Term*: while *Source Term* is related to the types and amounts of radioactive or hazardous material released to the environment following an accident, *Coolant Toxicity* is a day-to-day operational concern that has immediate safety implications for the crew, ship, and environment. Hence, it is given moderate precedence over *Source Term* in the selection criteria.

With these comparisons, the pairwise comparison matrix can be built, as shown in Table 4, and the local weights for each sub-criteria are obtained, as shown in Figure 7. The most important sub-criterion, in the *Reactor Core Characteristics* criterion, is *Fuel Safety* accounting for 52.75% of the score, followed by *Coolant Toxicity*, that accounts for one third of the score. The consistency ratio for this pairwise matrix is 0.052.

Table 4 – Pairwise comparison matrix for the *Reactor Core Characteristics* sub-criteria.



	Coolant Toxicity	Fuel Safety	Source Term
Coolant Toxicity	1.00	0.50	3.00
Fuel Safety	2.00	1.00	3.00
Source Term	0.33	0.33	1.00

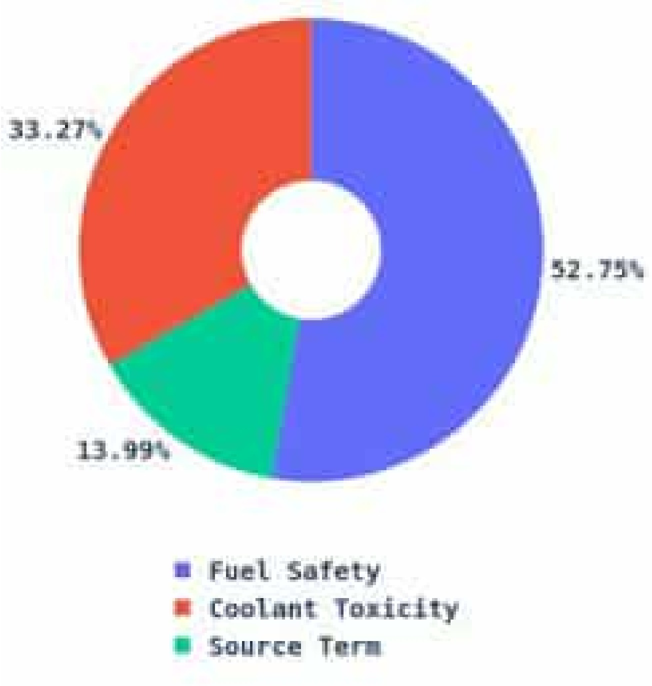


Figure 7 – Relative weights for the *Reactor Core Characteristics* sub-criteria.

2.2.2.2 Reactor System Characteristics (RSC)

Description and evaluation of all characteristics related to the reactor system itself which is key for the interaction with the ship. This criterion is composed of 6 sub-criteria: *Type, Dimensions, Weight, Power Scalability, Coolant Temperature* and *Component Qualification.*

The intensity of each of the sub-criteria has been obtained by pairwise comparison with the SuperDecisions software (on a scale from 1 to 9 seen in Table 3). As for six sub-criteria the number of comparisons is 15, just the rationale for the first 5 are shown in this report for illustration purposes, corresponding to the *Power Scalability* sub-criterion. The rationale for the rest of comparisons can be obtained by request only.

1. *Power Scalability* is **moderately to strongly** more important than *Component Qualification*: For the maritime application of nuclear energy, the capacity of each reactor design for varying its power output turns essential to adapt to a wide variety of nuclear ships. This feature is covered by the power scalability sub-criteria, which acknowledges that the most suitable reactor design is the one that may also cover different ship segments. On the other hand, the component qualification is a requirement by the regulators and can primarily cause deployment delays.

2. *Power Scalability* is **moderately to strongly** more important than *Coolant Temperature*: The power scalability can improve the performance, flexibility and economy of the ship's operation, while coolant temperature mainly affects the operational conditions and efficiency of the reactor.
3. *Power Scalability* is **strongly** more important than *Dimensions:* The ability to adjust the power output can improve the performance, flexibility and economy of the ship's operation while the dimensions are almost irrelevant for a large size cargo ship. Thus, the power scalability is strongly more important than the dimensions.
4. *Power Scalability* is **moderately** more important than *Type*: The power scalability can improve the performance, flexibility and economy of the ship's operation. Therefore, the power scalability of the reactor is moderately more important than if the reactor is integral.
5. *Power Scalability* is **strongly** more important than *Weight:* Weight of the reactor in the case of large cargo ships takes a backseat, while the capacity to vary the power output of the reactor when installed in different ship types is remarkable.

With these comparisons, the pairwise comparison matrix can be built, as shown in Table 5, and the local weights for each sub-criteria are obtained, as shown in Figure 8.

Table 5 – Pairwise comparison matrix for the *Reactor System Characteristics* sub-criteria.

	Component Qualification	Coolant Temperature	Dimensions	Power Scalability	Type	Weight
Component Qualification	1.00	2.00	2.00	0.25	0.33	2.00
Coolant Temperature	0.50	1.00	3.00	0.25	0.50	0.33
Dimensions	0.50	0.33	1.00	0.20	0.20	0.25
Power Scalability	4.00	4.00	5.00	1.00	3.00	5.00
Type	3.00	2.00	5.00	0.33	1.00	4.00
Weight	0.50	3.00	4.00	0.20	0.25	1.00

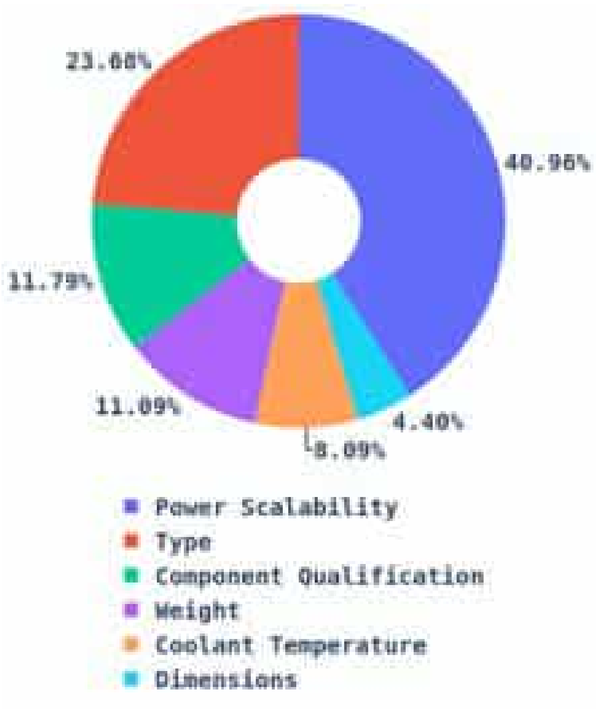


Figure 8 – Relative weights for the Reactor System Characteristics sub-criteria.

The most important sub-criterion, in the *Reactor System Characteristics* criterion, is *Power Scalability* accounting for 40.96% of the score, followed by *Type*, that accounts for 23.68% of the score. The consistency ratio for this pairwise matrix is 0.088.

2.2.2.3 Fuel Cycle Characteristics (FCC)

FCC is a description and evaluation of all characteristics related to the fuel cycle itself. This criterion is composed of 2 sub-criteria: *Refueling Time* and *Enrichment*. With two sub-criteria, only one pairwise comparison is performed:

1. *Refueling Time* is **moderately** more important than *Enrichment*: Being refueling a critical operation and considering that all the reactor designs follow the maximum achievable level of *Enrichment* for civil applications, *Enrichment* is not as restrictive as *Refueling Time*.

With these comparisons, the pairwise comparison matrix can be built as shown in Table 6, and the local weights for each sub-criteria are obtained, as shown in Figure 9. The most important sub-criterion, in the *Fuel Cycle Characteristics* criterion, is *Refueling Time* accounting for 75% of the score, followed by *Enrichment*, that accounts for 25% of the score. The consistency ratio for this pairwise matrix is 0, as there are only 2 sub-criteria.

Table 6 – Pairwise comparison matrix for the *Fuel Cycle Characteristics* sub-criteria.

	Enrichment	Refueling Time
Enrichment	1.00	0.33
Refueling Time	3.00	1.00

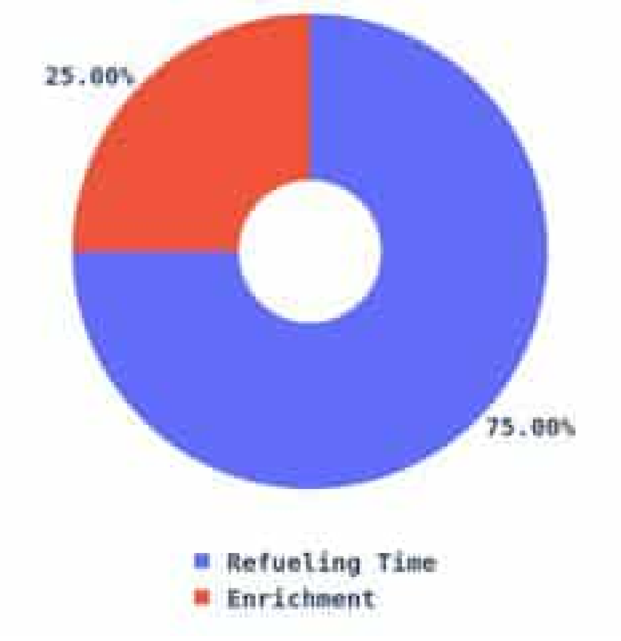


Figure 9 – Relative weights for the *Fuel Cycle Characteristics* sub-criteria.

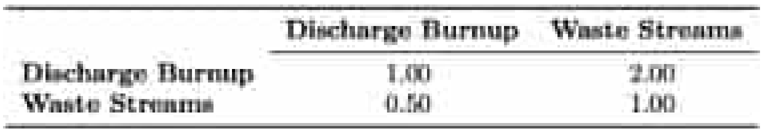
2.2.2.4 Decommissioning & Waste (D&W)

Characteristics related to Decommissioning and Waste. Both Decommissioning and Waste are important criteria because they can be potential showstoppers in certain political and economic scenarios. With two sub-criteria, only one pairwise comparison is performed:

1. *Discharge BU* is **slightly** more important than *Waste Streams*: The *Discharge Burn-up* determines the amount of energy extracted from the fuel and the economic viability of the nuclear reactor, which has a great importance, while the *Waste Streams* composition affects the storage and disposal options, for which it is considered that enough experience has been acquired from the conventional reactor fleet.

With these comparisons, the pairwise comparison matrix can be built as shown in Table 7, and the local weights for each sub-criteria are obtained, as shown in Figure 10. The most important sub-criterion, in the *Decommissioning & Waste* criterion, is *Discharge BU* accounting for 67% of the score, followed by *Enrichment*, that accounts for 33% of the score. The consistency ratio for this pairwise matrix is 0, as there are only 2 sub-criteria.

Table 7 – Pairwise comparison matric for the *Decommissioning & Waste* sub-criteria.



	Discharge Burnup	Waste Streams
Discharge Burnup	1.00	2.00
Waste Streams	0.50	1.00

Note that managing radioactive waste is discussed in greater details in Annex III.

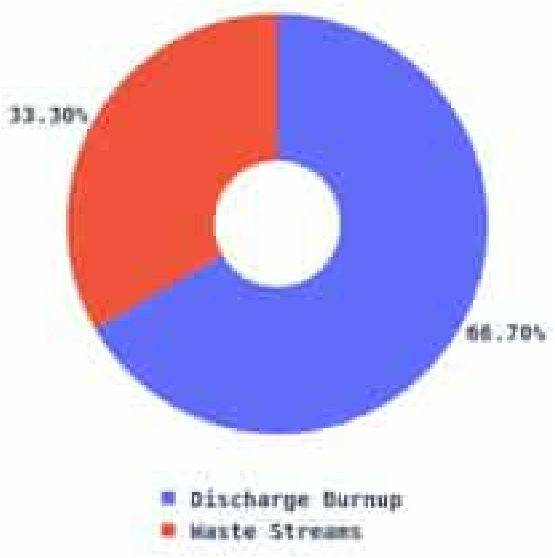


Figure 10 – Relative weights for the *Decommissioning & Waste* sun-criteria.

2.2.2.5 Licensing Status (LS)

The purpose of this criterion is to avoid selecting reactor technologies that can face difficulties during the approval process or whose deployment extends too far into the future. This criterion is composed of 2 sub-criteria: *Licensing Initiated* and *Operational Experience*. Again, only one pairwise comparison is performed:

1. *Operational Experience* is **moderately** more important than *Licensing Initiated*: The existence of previous operational experience is more important, as if there already is an experience on operating the reactor technology, the process of licensing will be shorter, being therefore less important the license status.

With these comparisons, the pairwise comparison matrix can be built as shown in Table 8 and the local weights for each sub-criteria are obtained, as shown in Figure 11. The most important sub-criterion, in the *Licensing Status* criterion, is *Operational Experience* accounting for 75% of the score, followed by *Licensing Initiated*, that accounts for 25% of the score. The consistency ratio for this pairwise matrix is 0, as there are only 2 sub-criteria.

Table 8 – Pairwise comparison matrix for the *Licensing Status* sub-criteria.

	Licensing Initiated	Operational Experience
Licensing Initiated	1.00	0.33
Operational Experience	3.00	1.00

Figure 11 – Relative weights for the *Licensing Status* sub-criteria.

2.2.2.6 Political Considerations (PC)

Political Considerations gathers the society induced political decisions that reactor technologies will meet. This criterion is composed of 2 sub-criteria: *Safety Perception* and *Historical Mishappenings*. Again, only the following pairwise comparison is performed:

1. *Safety Perception* is **moderately** more important than *Historical Mishappenings*: Regardless of past accidents, intrinsic safety and features of new reactor designs can influence positively in public opinion.

With these comparisons, the pairwise comparison matrix can be built as shown in Table 9, and the local weights for each sub-criteria are obtained, as shown in Figure 12. The most important sub-criterion, in the *Political Considerations* criterion, is *Safety Perception* accounting for 75% of the score, followed by *Historical Mishappenings*, that accounts for 25% of the score. The consistency ratio for this pairwise matrix is 0, as there are only 2 sub-criteria.

Table 9 – Pairwise comparison matrix for the *Political Considerations* sub-criteria.

	Historical Mishappenings	Safety Perception
Historical Mishappenings	1.00	0.33
Safety Perception	3.00	1.00

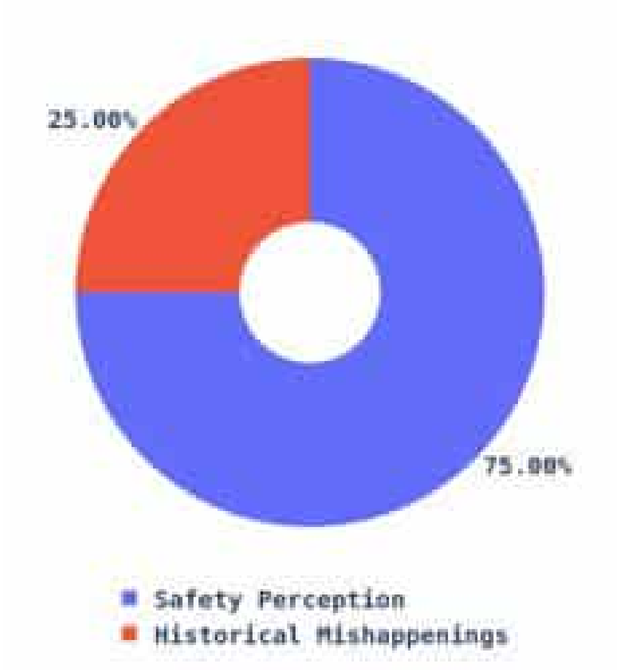


Figure 12 – Relative weights for the *Political Considerations* sub-criteria.

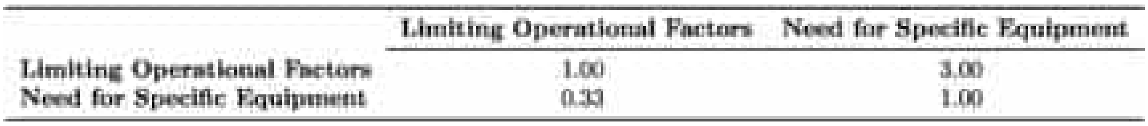
2.2.2.7 Maritime Operational Challenges (MOC)

Maritime Operational Challenges gathers all issues related to marinization that each reactor design must confront. This criterion is composed of 2 sub-criteria: *Limiting Operational Factors* and *Need for Specific Equipment*. Again, only the following pairwise comparison is performed:

1. *Limiting Operational Factors* is **moderately** more important than *Need for Specific Equipment*: *Limiting Operational Factors* can be showstoppers that affect feasibility of the project while the *Need for Specific Equipment* is already considered and can mainly affect Costs.

With these comparisons, the pairwise comparison matrix can be built as shown in Table 10 and the local weights for each sub-criteria are obtained, as shown in Figure 13. The most important sub-criterion, in the *Maritime Operational Challenges* criterion, is *Limiting Operational Factors* accounting for 75% of the score, followed by *Need for Specific Equipment*, that accounts for 25% of the score. The consistency ratio for this pairwise matrix is 0, as there are only 2 sub-criteria.

Table 10 – Pairwise comparison matrix for the *Maritime Operational Challenges* sub-criteria.



	Limiting Operational Factors	Need for Specific Equipment
Limiting Operational Factors	1.00	3.00
Need for Specific Equipment	0.33	1.00

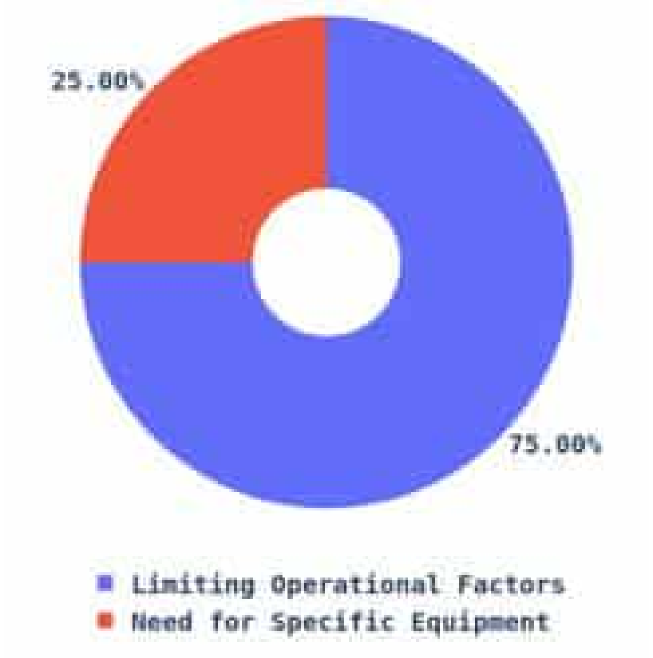


Figure 13 – Relative weights for the *Maritime Operational Challenges* sub-criteria.

2.2.2.8 Costs

As in any project, the cost is one of the main feasibility aspects. Even though the project represents a positive path for society, if it is not economically feasible, the project is doomed to failure.

Most of the Generation IV SMR designs are in a preliminary phase which leads to a great uncertainty in several aspects, being costs one of the most influenced. After the reciprocal communications with the different vendors, the conclusion that has been extracted is that the values for the different costs are given in diverse ways depending on the company and sometimes these values are for the FOAK reactor, and not for NOAKs, with the associated cost reduction due to economies of scale (must remember that industrial production of these kind of reactors is one of their key features). This, added to the mentioned fact that costs undoubtedly have a huge weight when comparing the different criteria of the reactor designs, leads to large uncertainties in the final results.

This way, final rankings extracted from an AHP that considers costs can be undermined, as an error in cost estimation could completely change the final punctuation of the designs. Therefore, as a way of assembling a more solid method, costs have been extracted from the analysis, leading to simply evaluating the various aspects of the reactor designs, and then considering their different ratings and differences, ending with the selection of the most suitable candidate. The cost criteria will be reviewed at a later stage once more mature information is available to primarily ensure correct estimates of individual costs. To do so, this criterion will be divided into 3 sub-criteria: Investment Costs, Operating Costs and Life Cycle Costs.

2.2.3 Weighting of selection criteria

As for seven criteria the number of comparisons is 21, the rationale for the first 6 are shown in this report. The rationale for the rest of comparisons can be obtained upon request.

1. *Maritime Operational Challenges* is **moderately to strongly** more important than *Decommissioning & Waste*: Regardless Decommissioning & Waste, which considers the main issues faced in the last stages of the reactor life, in Maritime Operational Challenges, most negative aspects during the operation of each reactor design for maritime implementation are considered and therefore, must have a greater importance.

2. *Maritime Operational Challenges* is **moderately to strongly** more important than *Fuel Cycle Characteristics*: Regardless Fuel Cycle Characteristics, which deepens in relevant aspects such as Refueling Time or Enrichment, in Maritime Operational Challenges, most negative aspects of each reactor design for maritime implementation are considered and therefore, must have a greater importance, as they can trigger the unfeasibility of a design.
3. *Maritime Operational Challenges* is **moderately to strongly** more important than *Licensing Status*: Maritime Operational Challenges directly affect the status of Licensing, as a greater number of hurdles could lead to delays in the deployment of the technology.
4. *Maritime Operational Challenges* is **equally to moderately** more important than *Political Considerations*: Maritime Operational Challenges directly affect public opinion, and therefore Political Considerations are also affected by this.
5. *Maritime Operational Challenges* is **equally to moderately** more important than *Reactor Core Characteristics*: Although in Reactor Core Characteristics, safety related sub-criteria are considered, in Maritime Operational Challenges, most negative aspects of each reactor design for the marinization case are taken into account and therefore, must have a slightly greater importance.
6. *Maritime Operational Challenges* is **strongly** more important than *Reactor System Characteristics*: In Maritime Operational Challenges, most negative aspects of each reactor design are considered for maritime implementation. On the other hand, Reactor System Characteristics considers sub-criteria such as Type or Power Scalability that despite being relevant, are one step behind of Maritime Operational Challenges.

With these comparisons, the pairwise comparison matrix can be built as shown in Table 11, and the local weights for each sub-criterion are obtained, as shown in Figure 14. The consistency ratio for this pairwise matrix is 0.066.

Table 11 – Pairwise comparison matrix for the selection criteria.

	Decommissioning And Waste	Fuel Cycle Characteristics	Licensing Status	Maritime Operational Challenges	Political Considerations	Reactor Core Characteristics	Reactor System Characteristics
Decommissioning and Waste	1.00	0.33	0.33	0.25	0.33	0.33	3.00
Fuel Cycle Characteristics	3.00	1.00	0.50	0.25	0.50	0.50	3.00
Licensing Status	3.00	2.00	1.00	0.25	0.33	0.25	2.00
Maritime Operational Challenges	4.00	4.00	4.00	1.00	2.00	2.00	5.00
Political Considerations	3.00	2.00	3.00	0.50	1.00	0.50	3.00
Reactor Core Characteristics	3.00	2.00	4.00	0.50	2.00	1.00	3.00
Reactor System Characteristics	0.33	0.33	0.50	0.20	0.33	0.33	1.00

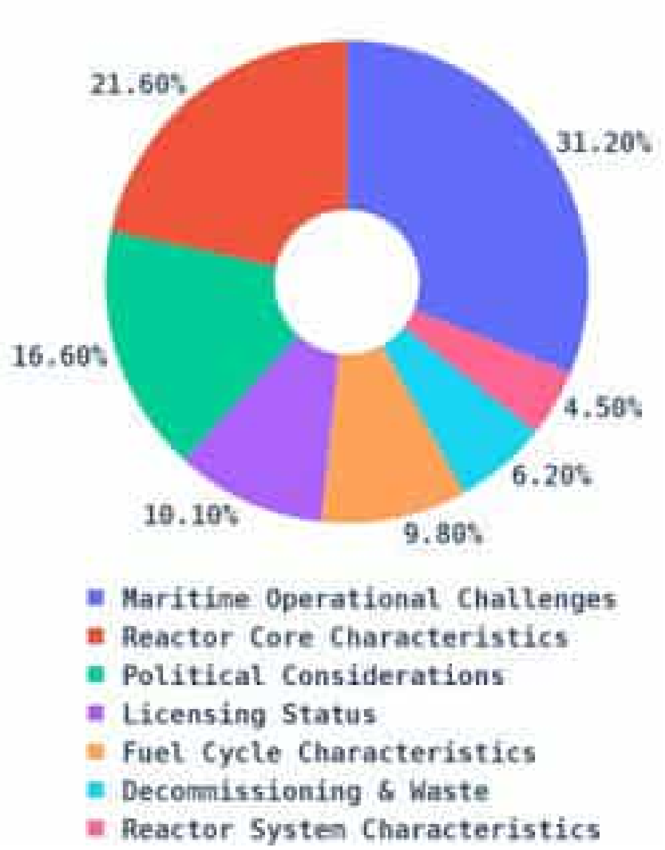


Figure 14 – Relative weights for the selection criteria.

2.2.4 Global weights of selection criteria and sub-criteria

Once the pairwise comparison process is performed, the global weights for each sub-criteria can be obtained by multiplication of the sub-criteria local weight by the weight of the parent criteria. Figure 15 shows the global weight for the criteria (inner ring) and the sub-criteria (outer ring).

As it can be seen, *Maritime Operational Challenges* is the top-level criterion with the highest weight, being almost one third of the total. Under this criterion, there are two sub-criteria of which *Limiting Operational Factors* is the most important and accounts for almost one fourth of the overall weight. This is as expected since this sub-criterion is related to aspects that can limit or make difficult the application of nuclear propulsion – such as the effect of sea movement on reactors relying on natural circulation for cooling and/or circulation of fuel pellets.

Reactor Core Characteristics is the criterion with the second highest weight, mainly since it accounts for various aspects related to safety. However, the sub-criterion with the second highest weight is *Safety Perception,* under the *Political Considerations* criterion, which has the third highest weight of the criteria. Arguably, even if a design is proven to be technologically safe, it can still fail if the public does not understand or perceive it as safe. Thus, *Safety Perception* accounts for one eighth of the overall weight.

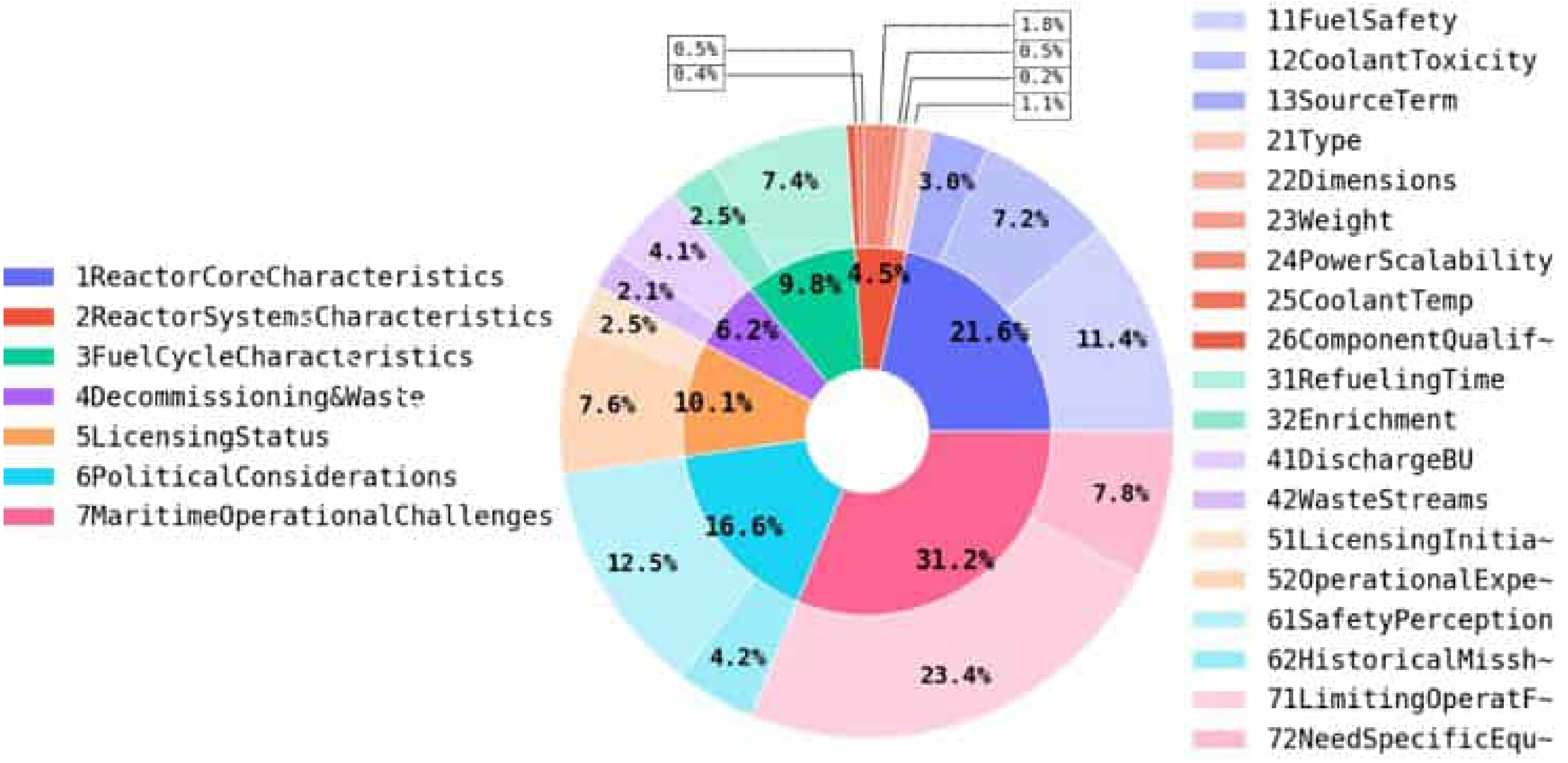


Figure 15 – Global weights for the criteria (inner ring) and the sub-criteria (outer ring).

The third sub-criterion with the highest weight, slightly above 10%, is *Fuel Safety*. It considers the behavior of the fuel in case of an accident and its subsequent environmental impact. Next, four sub-criteria with weights of 7-8% can be found: 1) *Need for Specific Equipment* that takes into account the need for the development or implementation of specific equipment for the optimal performance of the nuclear reactor in a maritime environment; 2) *Operational Experience,* under the main criterion *Licensing Status* (the fourth most important criterion) that considers whether operational experience with the technology exists which would ease the licensing process; 3) *Refueling Time,* under the main criterion *Fuel Cycle Characteristics,* that considers the cycle length which can affect the ship operations, and 4) *Coolant Toxicity* that accounts for the harmful effect of the coolant. The rest of the overall weight, which accounts for a 24%, is distributed between 13 sub-criteria, all of which are of less importance, varying between less than 1% to 4%. At this stage and as previously said, costs in the analysis have not been included due to insufficient data to enable relevant assessments.

2.2.5 Rating scales of selection sub-criteria

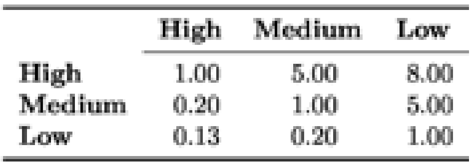
In the conventional AHP method, as proposed by Saaty, the next step would be to perform pairwise comparisons of the alternatives for each sub-criterion. However, in this case, considering that some sub-criteria account for quantitative characteristic (*Dimensions, Weight,* etc.) that are rather easy to compare, and others account for qualitative characteristics (*Fuel Safety, Power Scalability*) that are unmeasurable and rather difficult to compare, and also taking into account the uncertainty associated with the information obtained, a qualitative approach is employed for all sub-criteria. A qualitative rating scale is defined for each sub-criterion.

2.2.5.1 Reactor Core Characteristics

Fuel Safety, or the behavior of the fuel in an accident and its environmental impact, is a key factor since different reactor concepts make use of nuclear fuel in different forms with a different degree of safety.

Rating scale for this sub-criterion is: *High*, *Medium* and *Low*. TRISO particles are considered the safest fuel type, due to their high resistance to high temperatures, as well as the capability to retain fission products. Molten salts, even though they have good fission product retention capability, have more elements which lead to a higher activity. Besides, depending on the composition of the salts, these can have reactive elements such as F or Na which can cause explosions in contact with water or air. Lowest rating corresponds to pellets, which have shown potential safety issues, such as swelling, cracking, mechanical interaction with cladding, that could lead to fission product release, when operating at abnormal temperatures. The intensity of each of the ratings in the scale (Table 12) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 16.

Table 12 – Pairwise comparison of *Fuel Safety* ratings.



	High	Medium	Low
High	1.00	5.00	8.00
Medium	0.20	1.00	5.00
Low	0.13	0.20	1.00

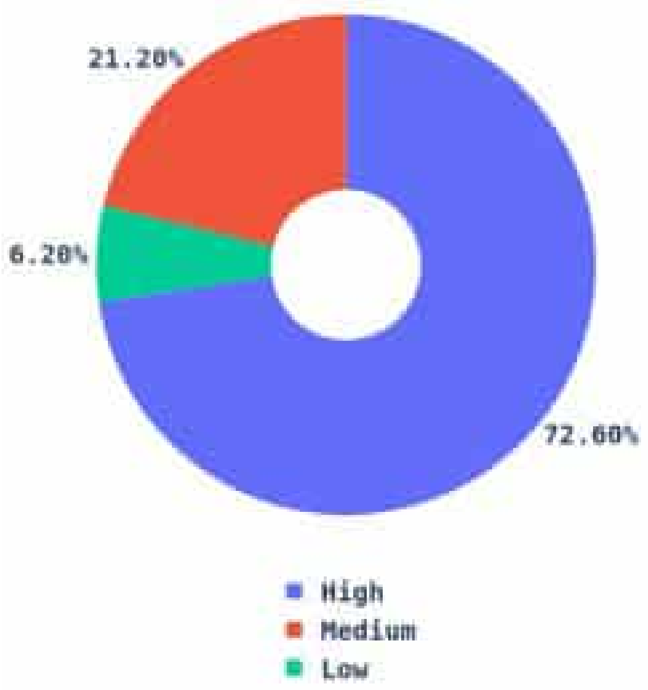


Figure 16 – *Fuel Safety* rating scale.

Coolant Toxicity is the harmful effect of the coolant, in case of spills and leakage, that can harm workers and the environment. In this case, just toxicological characteristics are taken into account to ensure crew safety and wellbeing during a LOCA type incident or spillage during maintenance operations.

In this case, the rating scale is divided in *High*, *Medium* and *Low*. Since helium is a non-toxic inert gas, it has the lowest toxicity. On the other hand, in the case of molten salts and lead, based on the severity and rapidity of the effects, as well as the availability of treatment options (lead poisoning can be treated by removing the source of exposure and using chelation therapy or other medical interventions, while there is no specific antidote for molten salt poisoning, and the treatment is mainly supportive and symptomatic), lead is considered in the medium toxicity rating, and molten salts in the high toxicity. The intensity of each of the ratings in the scale (Table 13) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 17.

Table 13 – Pairwise comparison of *Coolant Toxicity* ratings.

	High	Medium	Low
High	1.00	0.25	0.13
Medium	4.00	1.00	0.20
Low	8.00	5.00	1.00

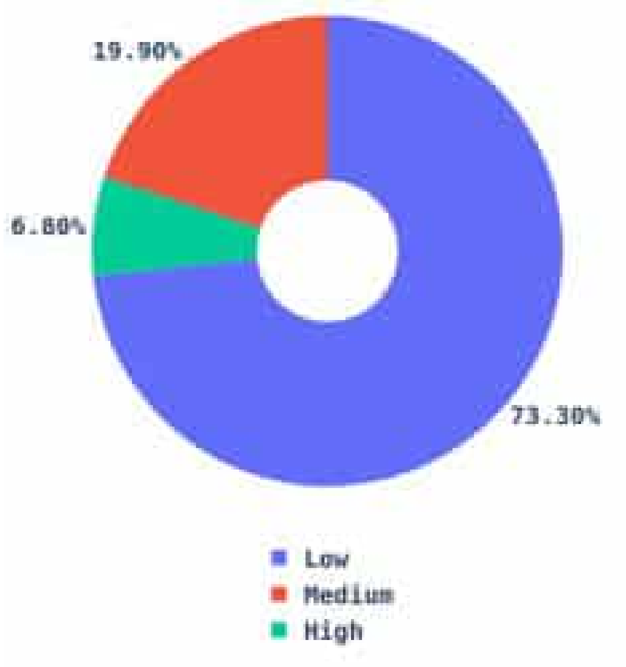


Figure 17 – *Coolant Toxicity* ratings scale.

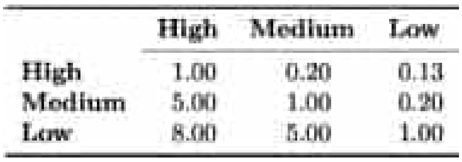
Source Term, the types and amounts of radioactive or hazardous substances that could be released to the environment following an accident, reflecting the potential radiological consequences, are considered in this sub-criterion. Different reactor designs may have different source terms, depending on the fuel type, coolant type, operating conditions, etc.

Ratings selected for this sub-criterion are *High*, *Medium* and *Low*. Given the current state of development of the different designs a qualitative classification is performed rather than quantitative.

In this sense, MSR designs with flowing fuel salt (IMSR-400 and CMSR) are considered the worst, since fission products would be present, see Annex I. Similarly, designs using Lead-bismuth as coolant are also considered among the worst given the high Po-210 production, see Annex II. On the other hand, MSRs with the fuel isolated from the molten salt, either in tubes or in TRISO particles, are considered slightly better (in the *Medium* rating) as well as designs using pure Lead as coolant. Finally, Helium cooled designs are considered the best since Helium is transparent to neutrons.

The intensity of each of the ratings in the scale (Table 14) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 18.

Table 14 – Pairwise comparison of *Source Terms* ratings.



	High	Medium	Low
High	1.00	0.20	0.13
Medium	5.00	1.00	0.20
Low	8.00	5.00	1.00

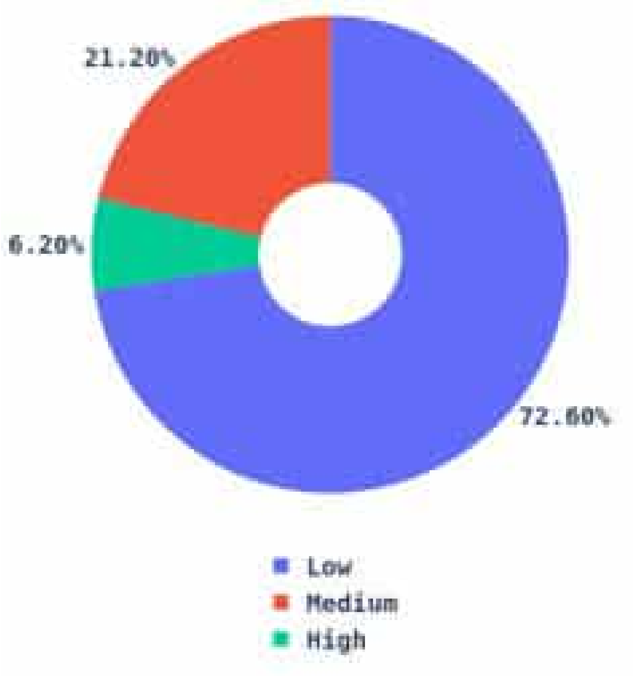


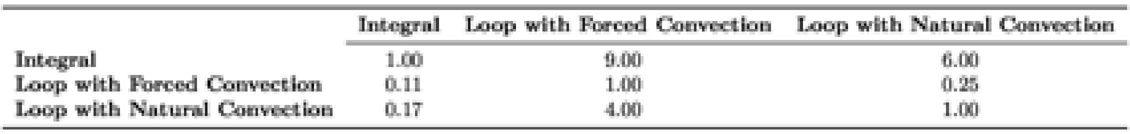
Figure 18 – *Source Terms* rating scale.

2.2.5.2 Reactor System Characteristics

Type describes whether the secondary system consists of one or more loops (with *natural* or *forced convection*), or the design is *integral*, with the secondary system held inside the reactor vessel.

Integral reactor types are favored since the complexity and need of equipment and therefore the chance of failure is reduced. *Forced* and *natural convection loop* ratings have a similar intensity, being higher for the first one due to natural convection disadvantages in maritime context. The intensity of each of the ratings in the scale (Table 15) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 19.

Table 15 – Pairwise comparison of *Type* ratings.



	Integral	Loop with Forced Convection	Loop with Natural Convection
Integral	1.00	9.00	6.00
Loop with Forced Convection	0.11	1.00	0.25
Loop with Natural Convection	0.17	4.00	1.00

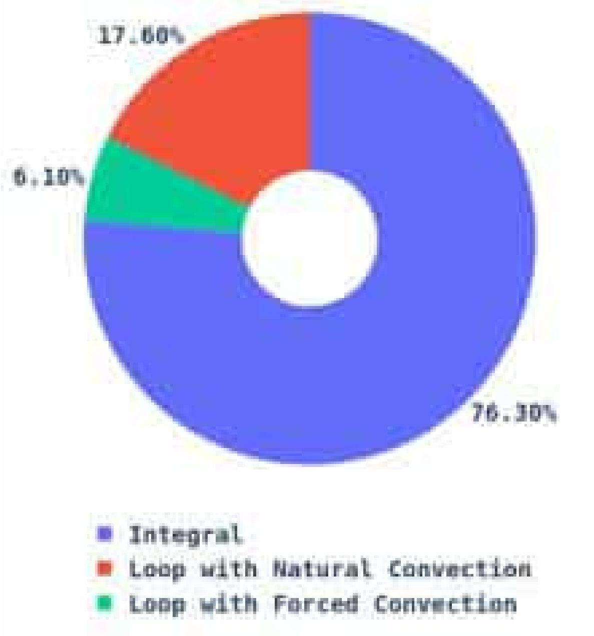


Figure 19 – *Type* ratings scale.

Dimensions, considers the size of the propulsion unit, which is important because space is limited on ships.

It has been determined that when talking about a system which is to be implemented inside a vessel, the smaller the better, so ratings included are *Small (< 100* m^3*)*, *Medium (100*-300 m^3*)*, and *Large (*> 300 m^3*)*. In this case, considering the whole ship, the size of the reactor system will not be of major influence, if it is between an acceptable range. The intensity of each of the ratings in the scale (Table 16) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 20.

Table 16 – Pairwise comparison of *Dimensions* ratings.

	Large (> 300 m3)	Medium (< 100-300 m3)	Small (< 100 m3)
Large (> 300 m3)	1.00	0.50	0.33
Medium (< 100-300 m3)	2.00	1.00	0.50
Small (< 100 m3)	3.00	2.00	1.00

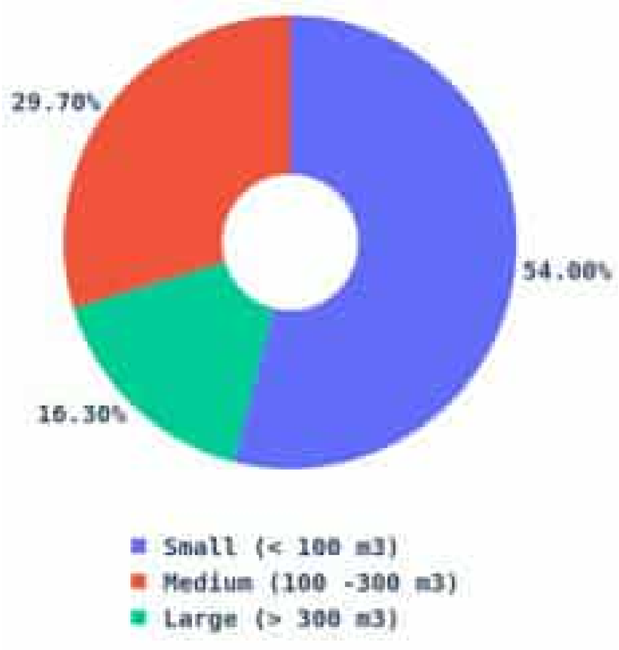


Figure 20 – *Dimensions* rating scale.

Weight considers the weight of the propulsion unit. If more than one unit would be needed this sub-criterion will be influenced by the total weight.

As in the previous section, as this nuclear system must be included in a ship, it has been determined that the lower the weight (t = tonne), the higher the score, dividing the rating scale in *Light (< 250 t)*, *Medium (250-500 t)*, *Heavy (500-1000 t)* and *Very Heavy (> 1000 t)*. But again, in this case, considering the whole ship, the weight of the reactor system will not be of major influence, if it is between an acceptable range. The intensity of each of the ratings in the scale (Table 17) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 21.

Table 17 – Pairwise comparison of *Weight* ratings.

	Light (< 250 t)	Medium (250-500 t)	Heavy (500-1000 t)	Very Heavy (> 1000 t)
Light (< 250 t)	1.00	3.00	5.00	7.00
Medium (250-500 t)	0.33	1.00	2.00	3.00
Heavy (500-1000 t)	0.20	0.50	1.00	2.00
Very Heavy (> 1000 t)	0.14	0.33	0.50	1.00

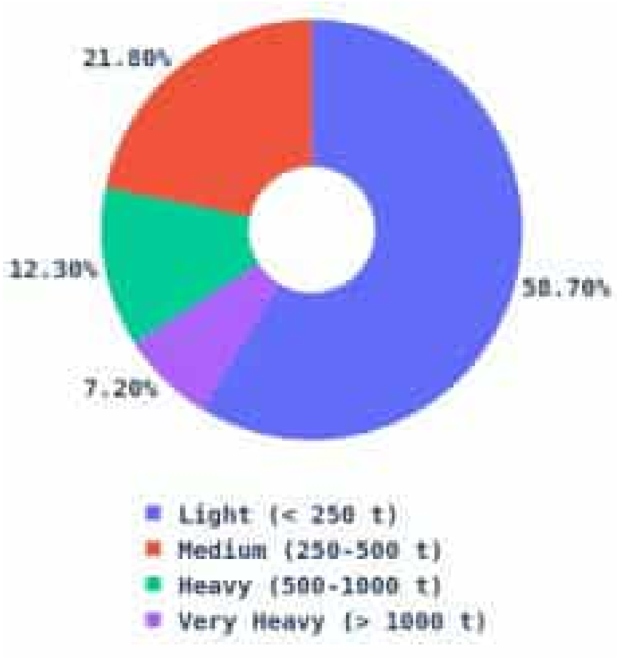
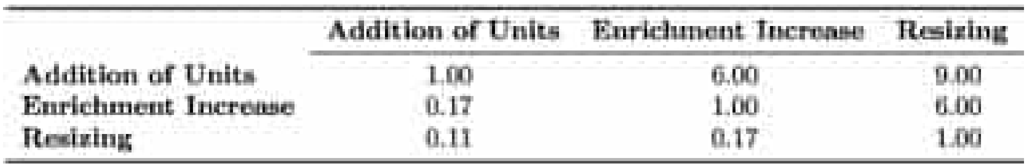


Figure 21 – *Weight* ratings scale.

Power Scalability considers the diverse ways the propulsion unit can increase/decrease its power, whether by adding more reactor units, by increasing/decreasing the enrichment or size, etc. This sub-criterion concerns the fact that ships come in all shapes and sizes with different requirements.

Therefore, ratings in this category are classified as the different ways a reactor can increase its power, which are *Addition of Units*, *Enrichment Increase* and *Reactor Resizing*. *Addition of Units* appears as the most simple and valuable way of increasing power requirements, having the highest intensity. On the other hand, *Enrichment Increase* is easier than *Reactor Resizing*, mainly due to excessive costs related to redesign, but it is not possible in all designs. Consequently, *Enrichment Increase* has a higher intensity. The intensity of each of the ratings in the scale (Table 18) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 22.

Table 18 – Pairwise comparison of *Power Scalability* ratings.



	Addition of Units	Enrichment Increase	Resizing
Addition of Units	1.00	6.00	9.00
Enrichment Increase	0.17	1.00	6.00
Resizing	0.11	0.17	1.00

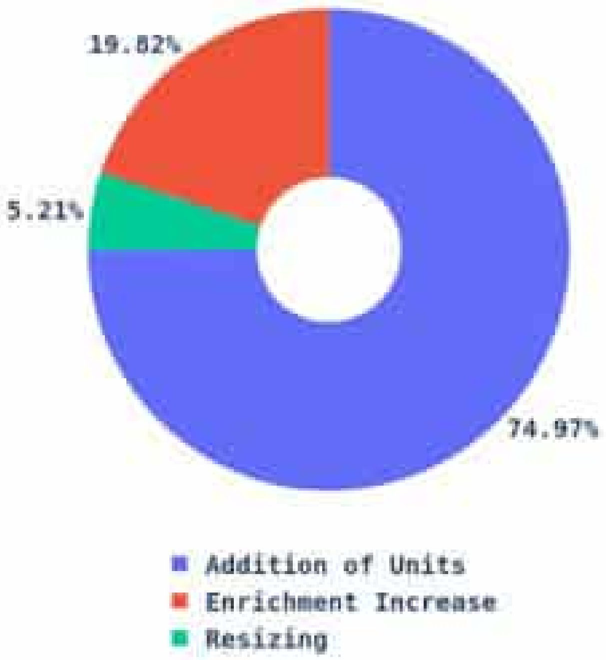


Figure 22 – *Power Scalability* rating scale.

Coolant Temperature refers to the outlet temperature of the reactor coolant. Ratings for coolant temperature are divided in *High*, for temperatures above 850 K, *Medium*, for temperatures between 700 and 850 K and *Low*, for temperatures below 700 K.

In this case, the highest intensity belongs to *Medium* rating, as from a point of efficiency the higher the temperature the greater the efficiency, but also extremely high temperatures involve a more complicated process. The intensity of each of the ratings in the scale (Table 19) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 23.

Table 19 – Pairwise comparison of *Coolant Temperature* ratings.

	High (>850 K)	Medium (700-850 K)	Low (<700 K)
High (>850 K)	1.00	0.50	1.00
Medium (700-850 K)	2.00	1.00	2.00
Low (< 700 K)	1.00	0.50	1.00

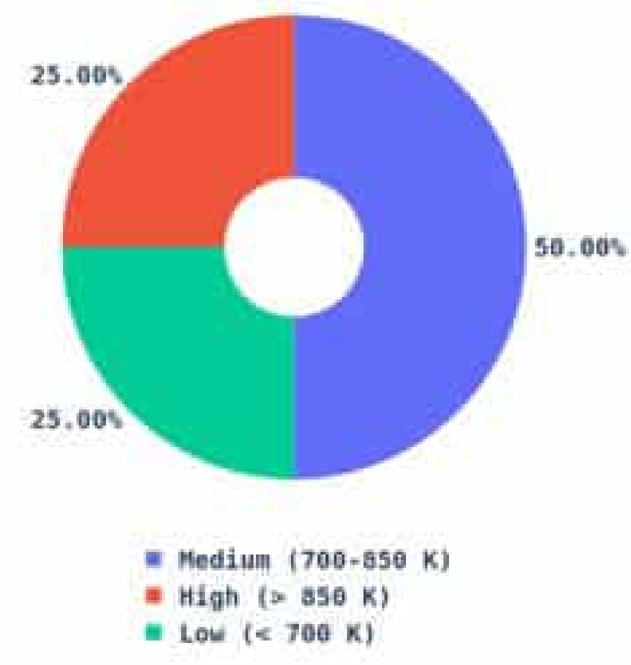
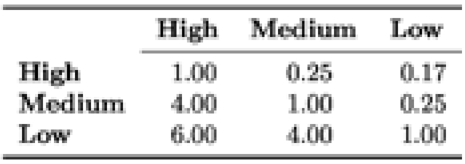


Figure 23 – *Coolant Temperature* rating scale.

Component Qualification refers to the need for qualification of new components for the correct operation of the nuclear reactor, like pumps, which can lead to deployment delays.

Taking into account the multifactorial dependence of the sub-criterion and therefore, the difficulty in comparing objectively the various designs, a *Low*, *Medium* and *High* rating scale has been selected. For the assignation of the rating the main systems and components to be qualified and their complexity in each design is considered. The intensity of each of the ratings in the scale (Table 20) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 24.

Table 20 – Pairwise comparison of *Component Qualification* ratings.



	High	Medium	Low
High	1.00	0.25	0.17
Medium	4.00	1.00	0.25
Low	6.00	4.00	1.00

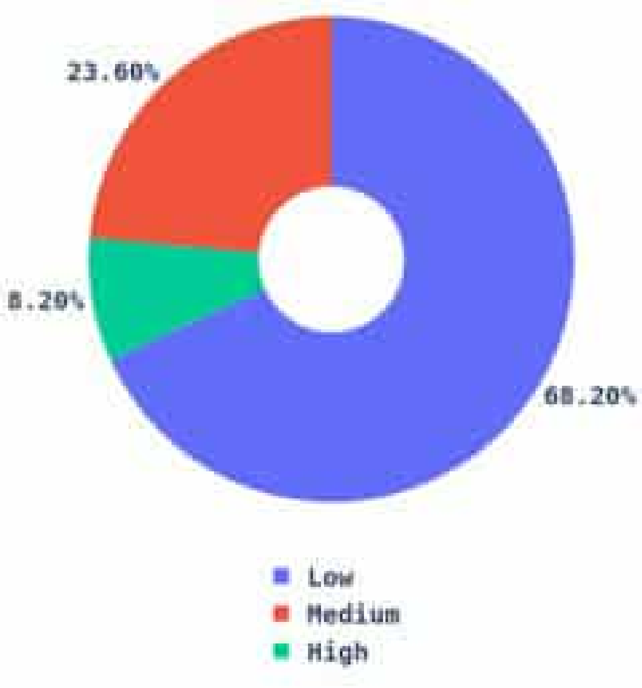


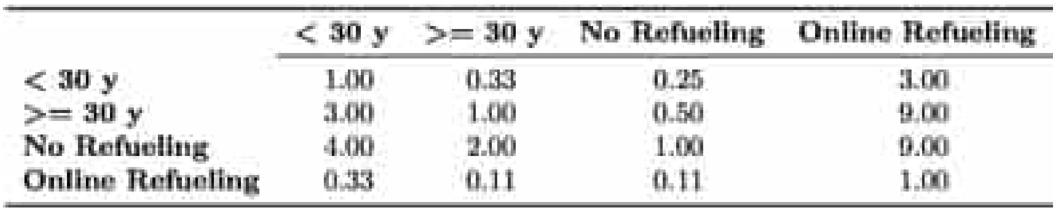
Figure 24 – *Component Qualification* rating scale.

2.2.5.3 Fuel Cycle Characteristics (FCC)

Refueling Time accounts whether refueling operations will be needed during the lifetime of the ship and their frequency.

For the ratings, four options are described: *No Refueling* needed, *equal or more than 30 years*, *less than 30 years* or *Online Refueling*. The reason the 30 years mark is important is because this is approximately the average lifetime of a merchant ship. Obviously, lower frequencies in refueling lead to higher rating values. *Online Refueling* represents the worst choice derived from proliferation and handling issues. The intensity of each of the ratings in the scale (Table 21) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 25.

Table 21 – Pairwise comparison of *Refueling Time* ratings.



	< 30 y	>= 30 y	No Refueling	Online Refueling
< 30 y	1.00	0.33	0.25	3.00
>= 30 y	3.00	1.00	0.50	9.00
No Refueling	4.00	2.00	1.00	9.00
Online Refueling	0.33	0.11	0.11	1.00

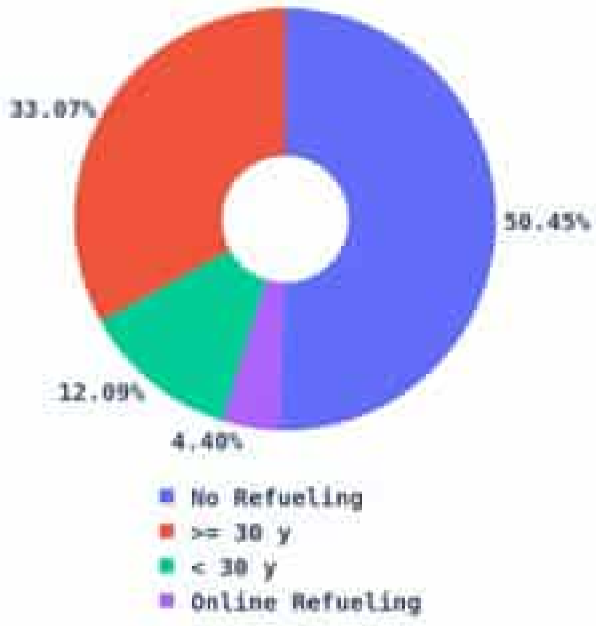


Figure 25 – *Refueling Time* rating scale.

Enrichment of uranium is the process by which nuclear fuel is produced by increasing the percentage of U-235. The enrichment process requires the uranium to be in a gaseous state, due to the different chemical and physical properties of the different isotopes.

From a political perspective, the enrichment of uranium is an internationally sensitive issue since availability of enrichment technology in a country is considered a requirement for a country in pursue to develop nuclear weapons and the country must be subject to international safeguards and inspections by the IAEA.

Moreover, enrichment implies a higher cost and worse public perception. This is why ratings are the highest for natural and low enriched uranium, and lowest for HALEU (High Assay Low Enriched Uranium).

It must be said that as a civil ship, enrichment must always be below 20%. The intensity of each of the ratings in the scale (Table 22) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 26.

Table 22 – Pairwise comparison of *Enrichment* ratings.

	High (10 - 20 %)	Medium (5 - 10 %)	Low (0.7 - 5 %)	Natural (0.7 %)
High (10 - 20 %)	1.00	0.33	0.20	0.14
Medium (5 - 10 %)	3.00	1.00	0.33	0.25
Low (0.7 - 5 %)	5.00	3.00	1.00	0.33
Natural (0.7 %)	7.00	4.00	3.00	1.00

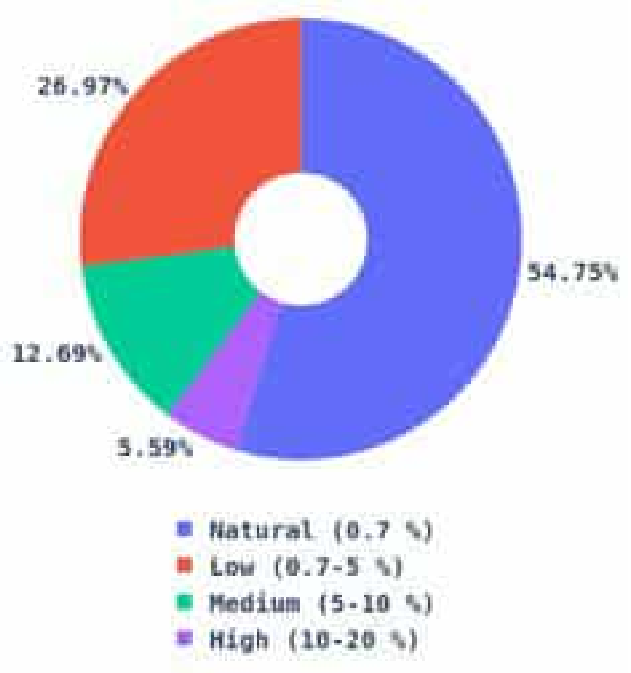


Figure 26 – *Enrichment* rating scale.

2.2.5.4 Decommissioning & Waste (D&W)

Discharge Burnup is a measure that quantifies how much energy has been extracted from the reactor fuel, in other words, how much fuel has been used.

Rating scale in this case has been divided in three ratings, which are, *Low (< 40 MWd/kg)*; *Medium (40 - 60 MWd/kg)* and *High (> 60 MWd/kg)*. As High *Discharge Burnup* is the best situation, this rating has the highest intensity. The intensity of each of the ratings in the scale (Table 23) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 27.

Table 23 – Pairwise comparison of *Discharge Burnup* ratings.

	High (> 60 MWd/kg)	Medium (40-60 MWd/kg)	Low (< 40 MWd/kg)
High (> 60 MWd/kg)	1.00	2.00	4.00
Medium (40-60 MWd/kg)	0.50	1.00	2.00
Low (< 40 MWd/kg)	0.25	0.50	1.00

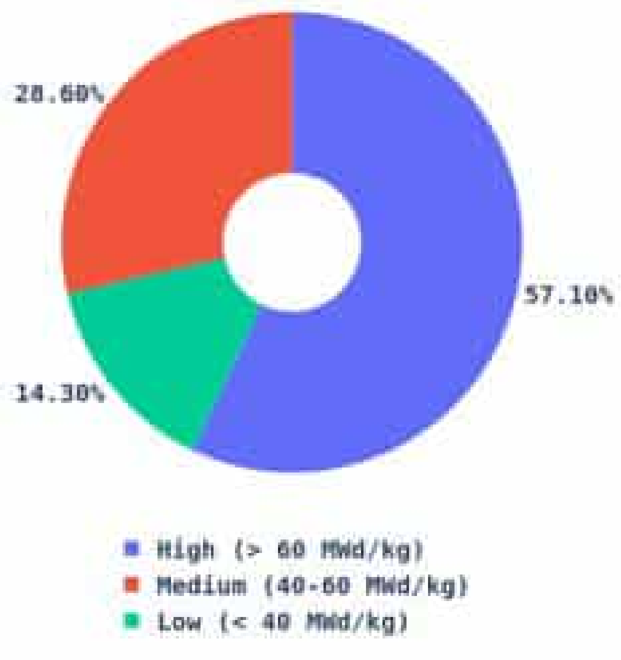
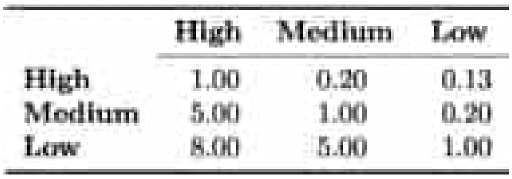


Figure 27 – *Discharge Burnup* rating scale.

Waste Streams constitutes the estimated types and amounts of radioactive waste generated in operation. This sub-criterion considers the type of radioactive waste generated during operation and the difficulties related to its management and safe disposal.

Inside *Waste Streams*, the moment of generation of the waste stream and the nature of the waste are considered. In this sense, designs without refueling are considered the best since they may allow cradle-to-grave approach (*Low*). On the other hand, designs that need refueling are considered the worst (*High*), since spent nuclear fuel will need to be handled, except if the fuel is in TRISO form, which is considered in the mid-range (*Medium*). The intensity of each of the ratings in the scale (Table 24) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 28.

Table 24 – Pairwise comparison of *Waste Streams* ratings.



	High	Medium	Low
High	1.00	0.20	0.13
Medium	5.00	1.00	0.20
Low	8.00	5.00	1.00

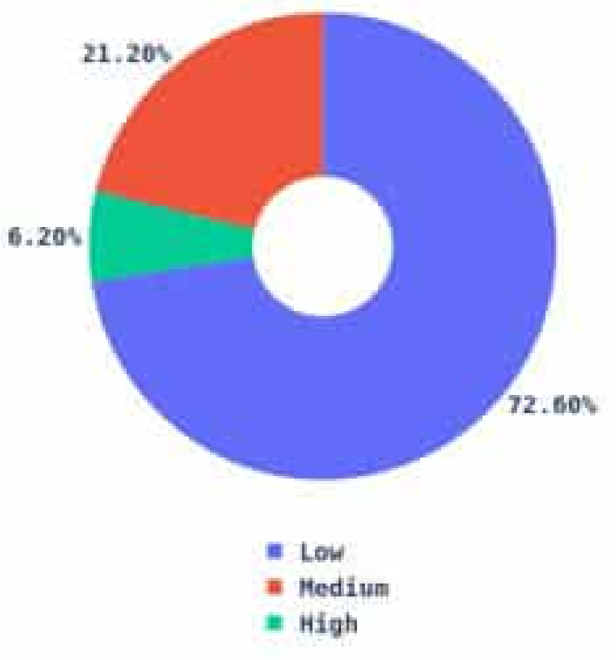


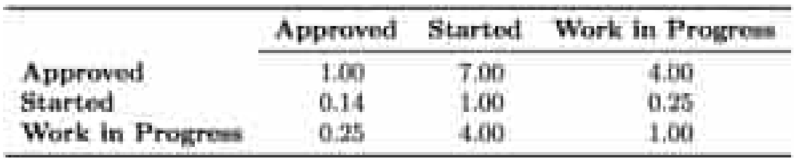
Figure 28 – *Waste Streams* rating scale.

2.2.5.5 Licensing Status (LS)

Licensing Initiated is important. Since most of the designs are still in an early development state and all of them are land-based reactors, only if the licensing process has been started at any country is considered in Licensing Initiated sub-criterion.

Therefore, the ratings chosen for this sub-criterion are *Started*, *Work in Progress* and *Approved*. Obviously, the last rating is the one with the highest intensity. *Work in Progress* implies required document handling and review between the vendor and the regulator for the licensing process and *Started* just considers a first contact with the regulator without going into more bureaucratic aspects. The intensity of each of the ratings in the scale (Table 25) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 29.

Table 25 – Pairwise comparison of *Licensing Initiated* ratings.



	Approved	Started	Work in Progress
Approved	1.00	7.00	4.00
Started	0.14	1.00	0.25
Work in Progress	0.25	4.00	1.00

It must be noted that this sub-criterion is subject to change in the future to consider the specific stage of the licensing process. Furthermore, WP2 discusses the licensing for marine operation.

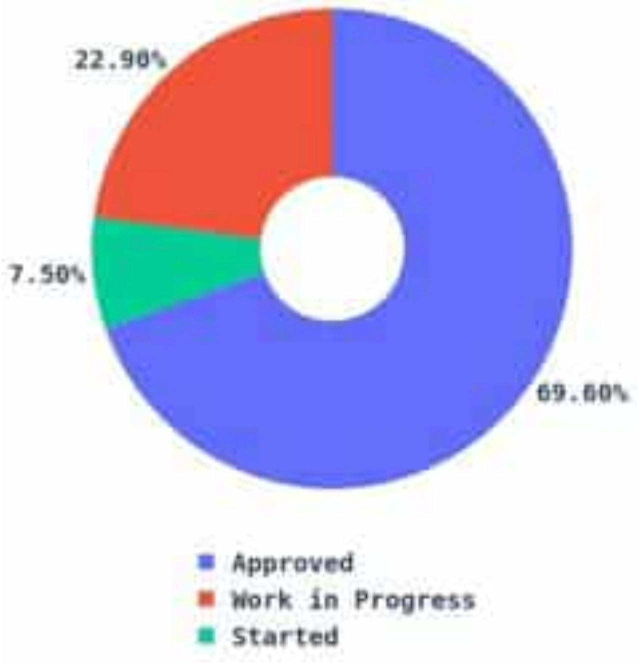


Figure 29 – *Licensing Initiated* rating scale.

Operational Experience describes whether the technology of the nuclear reactor is completely new or already exists some operational experience. For most of the technologies, indeed, there have been at least one or two research reactors that have proven in some way the feasibility of the technology, even though their development has been low over the years.

The technology with the highest number of operating hours is High Temperature Gas-cooled Reactors (HTGR), and therefore the rating *High* is assigned to this kind of reactors (experience in Peach Bottom, HTTR, Fort ST Vrain and British AGRs). Lead cooled reactors have a *Medium* rating as they have a slightly inferior operational experience, just present in submarines, and the *Low* rating belongs to Molten Salt Reactors, as Molten Salt Reactor Experiment (MSRE) is the main relevant source of experience for this kind of reactors. The intensity of each of the ratings in the scale (Table 26) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 30.

Table 26 – Pairwise comparison of *Operational Experience* ratings.

	High	Medium	Low
High	1.00	4.00	9.00
Medium	0.25	1.00	6.00
Low	0.11	0.17	1.00

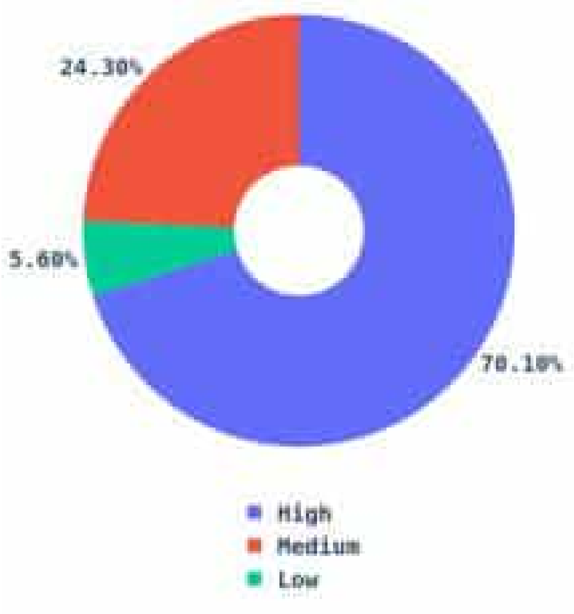


Figure 30 – *Operational Experience* rating scale.

2.2.5.6 Political Considerations (PC)

Safety Perception considers public and political awareness and understanding of potential hazards and risks of each specific technology, which is a main factor for the public acceptance of nuclear reactors for shipping. Primarily, it is considered that the perceived safety of "battery" type designs (from cradle to grave) will be higher than for designs that present a need to open the reactor during its lifetime for maintenance or refueling operations.

Taking this into account, just two ratings are defined, which are *High* and *Low*, corresponding to this mentioned feature. The intensity of each of the ratings in the scale (Table 27) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 31.

Table 27 – Pairwise comparison of *Safety Perception* ratings.

	High	Low
High	1.00	7.00
Low	0.14	1.00

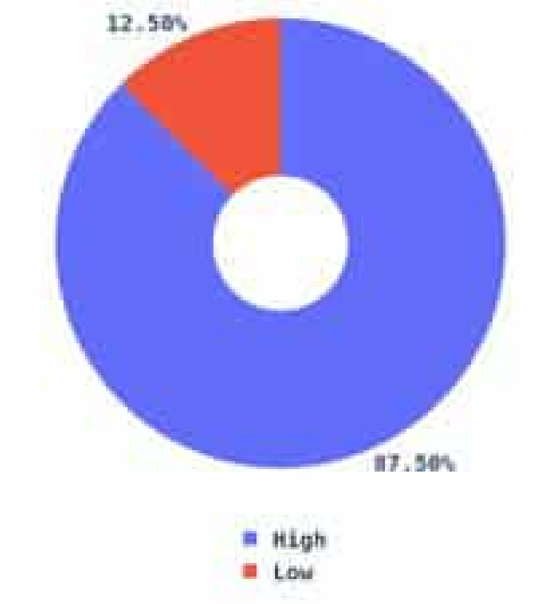


Figure 31 – *Safety Perception* rating scale.

Historical Mishappenings considers events occurred in the past, related to the technology with negative or unintended consequences, could jeopardize the deployment of that technology for shipping.

On the rating scale, two intensities are considered *Limited Past Reactor Issues* and *No Past Issues*, having the second one the highest intensity. The intensity of each of the ratings in the scale (Table 28) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 32.

Table 28 – Pairwise comparison of *Historical Mishappenings* ratings.

	Limited Past Reactor Issues	No Past Issues
Limited Past Reactor Issues	1.00	0.20
No Past Issues	5.00	1.00

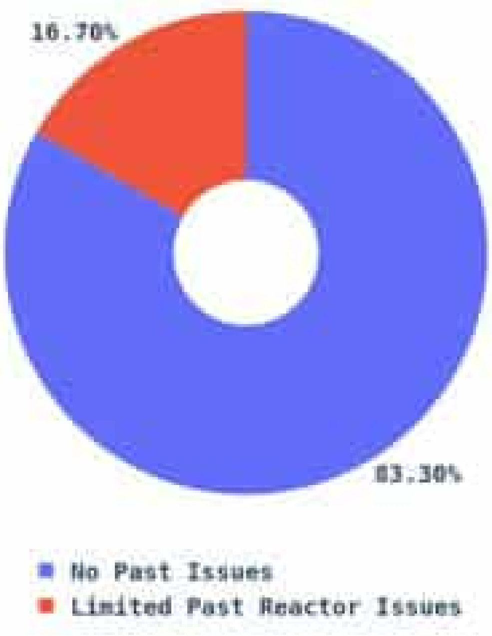


Figure 32 – *Historical Mishappenings* rating scale.

2.2.5.7 Maritime Operational Challenges (MOC)

Limiting Operational Factors refers to operational factors and/or challenges that can limit or difficult the applicability of the technology to marine propulsion. Examples of these challenges are, the effect of the sea movement on reactors relying on natural circulation, the potential clogging problems on Lead-Cooled Reactors due to load variations, etc.

Due to the multifactorial dependence of this sub-criterion and therefore, the difficulty in comparing objectively the different designs, a *Few Limitations, Limited* and *Very Limited* rating scale has been selected. For the assignation of the rating each design is evaluated. The intensity of each of the ratings in the scale (Table 29) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 33.

Table 29 – Pairwise comparison of *Limiting Operational Factors* ratings.

	Few Limitations	Limited	Very Limited
Few Limitations	1.00	5.00	9.00
Limited	0.20	1.00	5.00
Very Limited	0.11	0.20	1.00

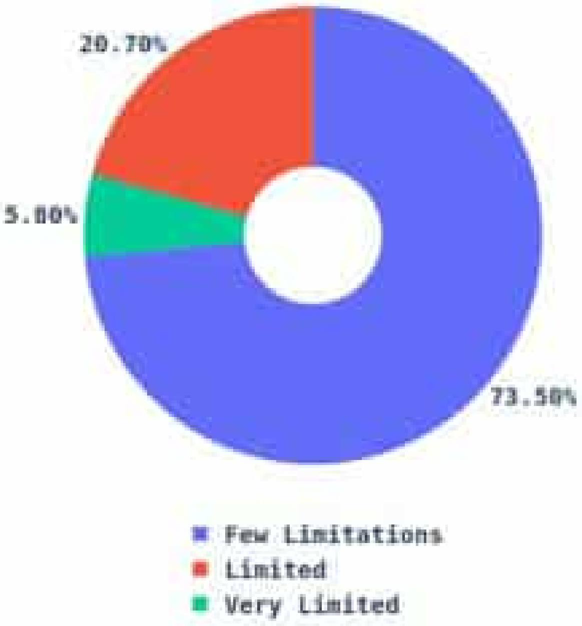


Figure 33 – *Limiting Operational Factors* rating scale.

Need for Specific Equipment essentially focuses on the need for the development or implementation of specific equipment needed for the best performance of the nuclear reactor for the maritime environment. For example, refueling system, coolant corrosion prevention and/or purification systems…

As a result of the diversity of equipment needed for the various designs, a *Low, Medium, High* rating scale has been selected. For the assignation of the rating each design is evaluated. The intensity of each of the ratings in the scale (Table 30) is obtained by pairwise comparison with the SuperDecisions software, displaying the resulting weight values in Figure 34.

Table 30 – Pairwise comparison of *Need for Specific Equipment* ratings.

	High	Medium	Low
High	1.00	0.25	0.11
Medium	4.00	1.00	0.17
Low	9.00	6.00	1.00

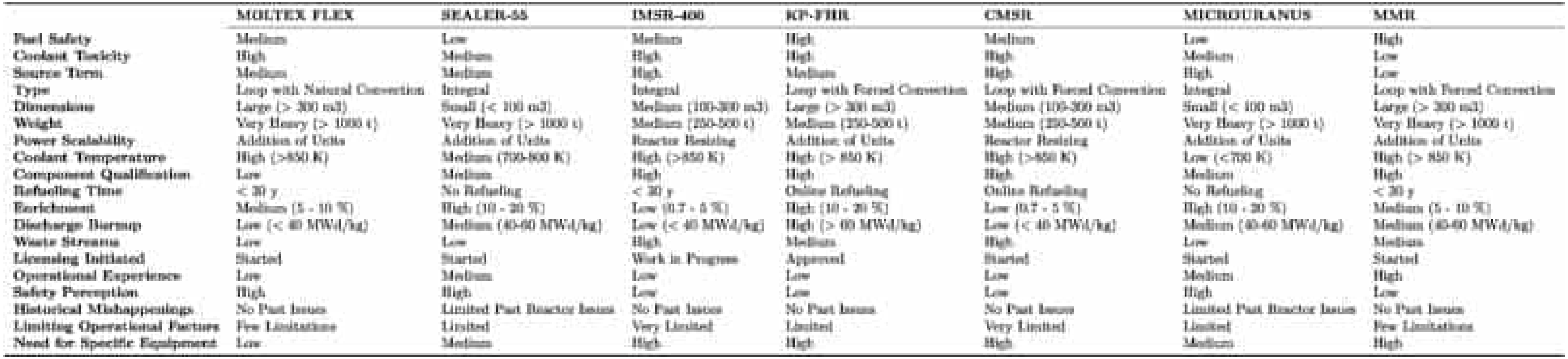
Figure 34 – *Need for Specific Equipment* rating scale.

2.2.6 Scoring of reactors

To obtain the final score of the selected reactor designs, their own characteristics for each sub-criteria must be evaluated through the respective rating scale. Therefore, it is a matter of classifying each reactor design in the rating scale for each sub-criterion, see Table 31. For this purpose, information was asked to the vendors of the seven reactor designs through email exchanges and telematic meetings. The rationale for the reactor score in qualitative criteria, with references to the conversations/email exchanges, can be obtained by request.

Finally, by the sum-product of the value in the rating scale with the global weight for all sub-criteria a total score is obtained for each reactor design.

Table 31 – Ratings selection for the 7 reactor designs.



	MOLTEX FLEX	SEALER-55	IMSR-400	KP-FHR	CMSR	MICROURANUS	MMR
Fuel Safety	Medium	Low	Medium	High	Medium	Low	High
Coolant Toxicity	High	Medium	High	High	High	Medium	Low
Source Term	Medium	Medium	High	Medium	High	High	Low
Type	Loop with Natural Convection	Integral	Integral	Loop with Forced Convection	Loop with Forced Convection	Integral	Loop with Forced Convection
Dimensions	Large (> 300 m3)	Small (< 100 m3)	Medium (100-300 m3)	Large (> 300 m3)	Medium (100-300 m3)	Small (< 100 m3)	Large (> 300 m3)
Weight	Very Heavy (> 1000 t)	Very Heavy (> 1000 t)	Medium (250-500 t)	Medium (250-500 t)	Medium (250-500 t)	Very Heavy (> 1000 t)	Very Heavy (> 1000 t)
Power Scalability	Addition of Units	Addition of Units	Reactor Resizing	Addition of Units	Reactor Resizing	Addition of Units	Addition of Units
Coolant Temperature	High (>850 K)	Medium (700-800 K)	High (>850 K)	High (> 850 K)	High (>850 K)	Low (<700 K)	High (> 850 K)
Component Qualification	Low	Medium	High	High	High	Medium	High
Refueling Time	< 30 y	No Refueling	< 30 y	Online Refueling	Online Refueling	No Refueling	< 20 y
Enrichment	Medium (5 - 10 %)	High (10 - 20 %)	Low (0.7 - 5 %)	High (10 - 20 %)	Low (0.7 - 5 %)	High (10 - 20 %)	Medium (5 - 10 %)
Discharge Burnup	Low (< 40 MWd/kg)	Medium (40-60 MWd/kg)	Low (< 40 MWd/kg)	High (> 60 MWd/kg)	Low (< 40 MWd/kg)	Medium (40-60 MWd/kg)	Medium (40-60 MWd/kg)
Waste Streams	Low	Low	High	Medium	High	Low	Medium
Licensing Initiated	Started	Started	Work in Progress	Approved	Started	Started	Started
Operational Experience	Low	Medium	Low	Low	Low	Medium	High
Safety Perception	High	High	Low	Low	Low	High	Low
Historical Mishappenings	No Past Issues	Limited Past Reactor Issues	No Past Issues	No Past Issues	No Past Issues	Limited Past Reactor Issues	No Past Issues
Limiting Operational Factors	Few Limitations	Limited	Very Limited	Limited	Very Limited	Limited	Few Limitations
Need for Specific Equipment	Low	Medium	High	High	High	Medium	High

2.3 Results and discussion

Out of the seven reactor designs belonging to feasible technologies, the three most ranked designs are selected for Stage 3 of the project. The result obtained for these three reactors (MMR, SEALER-55 and KP-FHR) is shown in Figure 35.

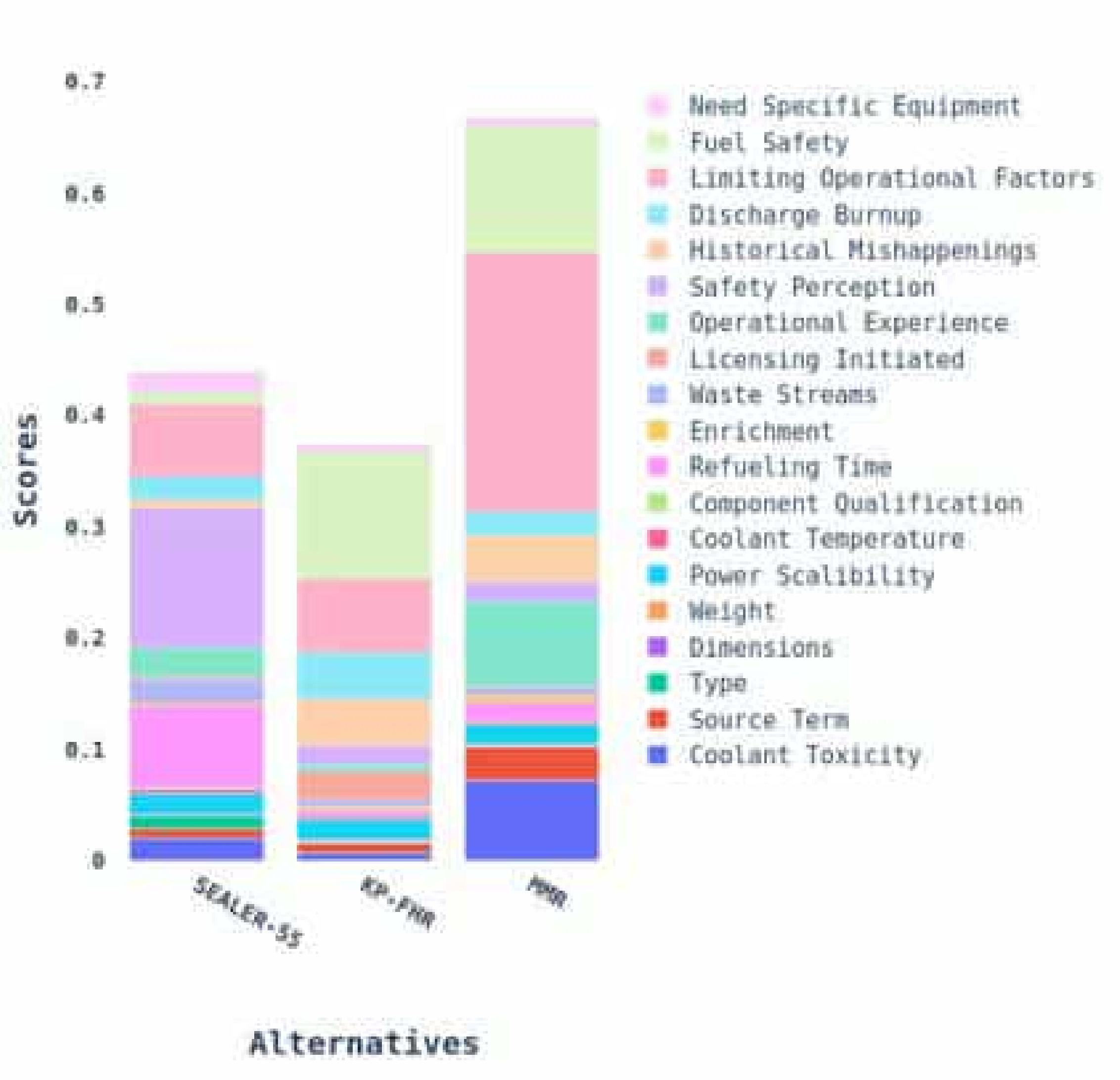


Figure 35 – Score for the top 3 reactors: MMR, SEALER-55 and KP-FHR.

The reactor with the highest score is the Micro Modular Reactor (MMR), a High Temperature Gas-cooled Reactor (HTGR) developed by Ultra Safe Nuclear Corporation. This reactor has a thermal power ranging from 15 to 45 MWth (5 to 15 MWe), depending on the enrichment of the fuel (which can vary from 9.99% to 19.75%). The fuel consists of Fully Ceramic Micro-Encapsulated (FCM) pellets that are stacked in columns in solid hexagonal graphite blocks and incorporate fuel formed of TRi-structural ISOtropic (TRISO) particles embedded in silicon carbide (SiC). The reactor is pressurized at 6 MPa, as the responsible for cooling down the TRISO prismatic array is Helium gas. This design, stands out with respect to the others since the configuration with no moving parts minimizes the effect of sea dynamics during reactor operation, being one of the main reasons of its high score in the sub-criterion *Limiting Operational Factors*. Furthermore, by using fuel in TRISO form, excellent fission product confinement is ensured giving its high score in the *Fuel Safety* sub-criterion. In addition, gas-cooled reactors, including High Temperature Helium-cooled Reactors, have been in operation for more than 60 years in several countries, providing sufficient *Operational Experience*. Finally, the use of an inert gas as coolant provides an excellent *Coolant Toxicity* score.

SEALER-55, which is in second place, is a Lead Fast-Cooled Reactor (LFR) developed by the Swedish company Blykalla. This reactor has a thermal power of 140 MWth and an electric power of 55 MWe. The reactor operates at atmospheric pressure and has a lead-cooled hexagonal core composed of Uranium Nitride pellets. Its cradle-to-grave approach, meaning that the reactor is fueled only once and can be dismantled as a whole unit, provides excellent scores on the sub-criteria *Safety Perception* and *Refueling Time*. However, given the potential problems in the marinization of the reactor (sub-criterion *Limiting Operational Factors)*, such as the possible coolant solidification during power ramp-downs below a certain level (30-40% of the nominal power), and the fact the reactor uses conventional oxide pellets as fuels (sub-criterion *Fuel Safety*) lower the overall score.

Finally, the third design in the top-3 is the Kairos Power Fluoride salt-cooled High temperature Reactor (KP-FHR), a high temperature Molten Salt Reactor (MSR) developed by Kairos Power. It has a thermal power of 320 MWth and an electric power of 140 MWe. The fuel consists of spherical pebbles filled with TRISO fuel particles. The reactor coolant is a chemically stable molten fluoride salt mixture $2LiF:BeF_2$ (FLiBe). Buoyancy makes the pebbles circulate through the reactor core from the bottom to the top. A fuel handling system extracts the pebbles from the active core and based on flow detection and burn-up measurement, either inserts them back into the active core or directs them to spent fuel storage. The reactor operates at near atmospheric pressure and an intermediate salt loop transfers the heat to the power conversion system through a steam generator.

Kairos Power has also developed a smaller version, the KP-HERMES, initially for demonstration purposes, but with potential commercial deployment for ship propulsion purposes. It has a thermal power of 35 MWth and an electric power of 14 MWe. Apart from power and size, the characteristics of this reactor are expected to be similar to the KP-FHR. Kairos Power obtained the construction permit for the KP-HERMES at the end of 2023 and is planning to start its operation as early as 2026.

As in the MMR, the excellent fission product confinement provided by the TRISO particles first, and, in this case, the molten salt coolant next, gives a high score on *Fuel Safety* sub-criterion. The fact that TRISO particles cycle through the core several times allows achieving a higher *Discharge Burnup.* Finally, its advanced status in licensing, with approved license for the construction of the Hermes test reactor, provides a high score in the *Licensing Initiated* sub-criterion. However, the potential problems in the marinization of the reactor (sub-criterion *Limiting Operational Factors)*, such as the challenges that online refueling (sub-criterion *Refueling Time*) can face from the security viewpoint, and the lack of operational experience with such designs (sub-criterion *Operational Experience*) punish the global score.

Later discussions and work seem to indicate that the refueling issue is better than first anticipated therefore making the final score of the reactor better than suggested here.

2.4 Conclusions and future work

Due to the innovative nature of the project, there is still lot of work to perform and issues to solve in order to make nuclear reactors a real and viable alternative to today's propulsion technologies. This is why the analysis captured in this document needs to be completed and developed in various aspects for a safe and effective deployment of the technology, leading to new process stages to be performed in the future. For example, given that, unlike land-based reactors, the reactors for ship propulsion will move through different jurisdictions, a crucial step, which is currently ongoing, is the engagement with national and international regulatory bodies and public stakeholders to begin discussions on the proper regulatory framework to facilitate the implementation of nuclear ship propulsion.

The next stage in the process involves engaging with various vendors of the selected reactor concepts, to discuss their technology in more detail as well as monitor new concepts. This process is key to verify that the publicly available information is still valid. If it is not valid due to design changes, updated information will be requested. These discussions may lead to the introduction of more selection criteria for Stage 2. Once the initial information gathering is performed, a new AHP can be executed, and a smaller set of reactor concepts can be chosen. This work is expected to be completed by yearend 2025.

Following this, the project will move into a detailed design analysis and cost study of the chosen reactors. As all three candidates are land-based technologies currently under design, the objectives will be to identify any design criteria that may need modification for the maritime version and to obtain a relatively reliable cost estimate after industrialization, which may take longer to gather, but is likely to be significantly lower than for the first prototypes. Then, these reactor concepts will be mapped onto various ship designs and operational modes identifying which will fit each ship type the best, considering technical and regulatory issues, competitiveness towards HFO and other fuels, impact on ship design, and other issues relevant for marine propulsion of merchant ships. This work will be performed in the next project, NuProShip II.

3.0 Ship safety, regulations and technical implications

The work done in WP2 is based on those considerations and selection of technologies has been made in WP1. The WP2 results presented in this report has been undertaken by several partners to the project, including the following main tasks and responsible resources, as organized in the sections as follows:

- Risk identification, see the results from the Risk Identification Workshop, a physical workshop resulting in a risk inventory.
- Safety-rules framework (as relevant for the nuclear technologies from WP 1).
- Regulatory roadmaps, given the technologies being considered and the risk identified.
- Additional technical aspects related to refuelling (Refuelling aspects.
- A shipbuilder's consideration of building nuclear powered ships.

3.1 Vessel design and risks

Initially in the NuProShip I project a risk identification workshop was carried out to identify risks related to the introduction of a nuclear reactor onboard a merchant vessel, increase understanding among stakeholders of the risks and challenges to be managed, and propose measures to address identified risks/challenges where applicable means of risk control can be indicated. In this chapter, an overview of the design properties and how they may affect the risk associated with the vessels has been included, then hazards as they were addressed in the risk identification workshop are being presented, together with considerations on some of the hazards arising with advanced reactors.

The detailed overview from the risk identification workshop can be obtained upon request.

3.1.1 The project and its design properties

With an emphasis on safety, there are certain features and design properties that will play a more important role than others. In WP1, the number of reactor designs has been attempted to be narrowed down to three, and in this chapter two categories of nuclear ships have been considered; NPS (nuclear powered ship, category 1) - representing a complete novel concept in modern regulatory terms, compared with a power producing facility as a FNPP (floating nuclear power plant, category 2). The requirements for the floating platform on which the reactor sits are derived from the location, the transport routes, and the reactor. While there are obvious technical issues that should be duly assessed for the construction of an FNPP, this is a project in continuation of the efforts to design SMRs (small modular reactors), which have considerable attention right now, as emphasized above. The operation of an FNPP will probably not include any production activities while under transport, possibly also having the fuel out of the reactor.

However, there is a large difference in using well-known light water technology, compared to advanced reactor technology not licensed onshore yet, as emphasized in Table 32 (No. 3) below. This aspect will also play a role in the environmental assessment of sinking, as siting on water, potentially also at different locations on water, has not systematically been addressed until now. The graded approach will come into play in relation to the nominal power (No. 2) of the facility, corresponding to how this plays out for the land-based SMR. If the FNPP is meant for remote locations, potentially the manning may represent a different issue compared to land-based power reactor facilities. However, as discussed below, choosing light-water technology may have ramifications for several properties, also manning. The PWR type is still an important candidate for the future small and medium reactor (SMR) onshore.

Regarding NPS, overall design properties, here listed from No. 1 to No. 5 are closely linked to how these projects may expect to be regulated, as they are closely linked to the issues of cost and time. There are arguments for having both one and two reactor units as part of a propulsion system (No. 1). Intuitively, the cost of two reactors increases compared to one. However, one can assume that the reactor is standardized to such an extent that the potential advantages having two reactors may outweigh the disadvantages, both in terms of cost, weight, and space vs. robustness and reliability. Regarding reactor(s) size (in nominal power (MW)) (No. 2), previous assessments have shown that approx. 40 MWe is sufficient for a 15,000 TEU container vessel, provided that for example a diesel generator sets are available for situations requiring higher speed. Several smaller reactors, with high degree of standardization, may play a significant role in the licensing of the vessel, considering the graded approach.

With respect to pressure and temperature (No. 3), these are fundamental in relation to the system complexity, as high pressure and temperatures requires a meticulous approach to safety (No. 4), another fundamental aspect for the realization of NPS. Again, given the need for as little complexity as possible, an inherent safe design and passive safety functions, the preference may be given to low-pressure systems for NPS. As this excludes several traditional light-water reactor types, this choice is fundamental with respect to how this can increase the licensing time. However, another aspect related to the choice of reactor technology is the safe manning, e.g. size and competence of the crew (No. 5). The overwhelming operating experience at sea has been gained in the operation of PWR-type reactors. However, this type of reactor requires extensive monitoring and several different types of remedial actions in the event of transients, which in turn may require a larger crew with a wide range of skills related to the reactor, possibly making this type of reactor less sustainable for a cost-efficient shipping industry. One may assume that only a limited number of crew members with appropriate competence will be available.

For any nuclear reactor, fuel qualification is a fundamental step, i.e. demonstrating that the fuel produced to a specification will perform as described in the safety case that forms the basis for the license application (No. 3). This can be a challenge, especially if the aim is to use fuel enriched to more than the 3-5% U-235 used in commercial power plants. However, higher enrichment can be rewarding as it allows for smaller reactor cores and potentially fewer fuel changes over the life of the vessel. Important factors are cost and security of supply, as nuclear fuel supply lines are already limited and shrinking with the growing need for independence from the well-supported Russian nuclear fuel industry. For options that are not based on light water technology, the path is even more complicated, as all materials used in the reactor as well as the fuel itself must be qualified for the entire fuel cycle (before, during and after operation). Together with the material qualification, an overall design must be prepared that describes the necessary fabrication, construction, testing and performance of the safety-related structures, systems, and components. A proposed non-light water design must be accompanied by a recognized methodological basis (e.g. event-specific analytical methods, reactor coolant analytical methods, core design methods and reactivity control methods).

A vital property is the time between refueling (No. 3), which can be as long as 5 years to fit a normal maintenance schedule, or even longer. When considering the fuel and fuel technology, the risk for proliferation is important. While fuel in a reactor is self-protected, any present fresh fuel at a vessel constitutes a significant security risk.

Table 32 – General design properties for SBNPP (NPS/ FNPP) vessels/ facilities.

	Main design properties[2]	Important aspect related to NPS (propulsion, large containership)	Important aspect related to FNPP (power production)	Note
No. 1	**# reactor/ overall properties/ dimension/ weight)**	One or two reactor units. Cost vs. space/ reliability/ operational redundancy (as compact as possible)	Several (more than one). Reliable power supply vs. cost/ reliability/ power generation redundancy	NPS and FNPP with unlike trade-off reg. fundamental properties as their overall purpose and function is not similar.
No. 2	**Reactor nominal power (MW), refueling frequency/ burn-up**	Up to one hundred MWe (single unit/ divided on two units) Complexity vs. simplicity (time and cost)	SMR-equivalents (up to three hundred MWe). External factors (ex. availability factor for power production)	The nominal power (MWe) is closely connected with other properties, such as # reactors, power need, type, fuel etc.
		As high/ long as possible (e.g. 5 y., at least in line with major maintenance periods), preferably longer	As high/ long as possible (in line with power need, major maintenance periods), preferably longer	Lack of access to fresh fuel more important for NPS than FNPP, similarly for length of refueling periods
No. 3	**Reactor type and characteristics (temp./ pressure)**	Emphasis on simplicity (basis for reliability and robustness (to maximize availability factor for propulsion and minimize risk) (Gen III/ Gen IV)	Emphasis on high efficiency (to maximize availability factor for power production), in addition to reliability and robustness (Gen III/ Gen IV)	Several reactor types may be relevant (fuel, coolant, moderator etc.), though more info needed for detailed evaluation (value chain (front/ back-end))
		Emphasis on simplicity (low pressure, in that case higher temperatures is manageable)	The most efficient design involves high temperature processes	Both simplicity and high efficiency are criteria that may involve several reactor types, taking external factors into acc.
	Fuel/ fueling mechanisms (non-proliferation)	High possible enrichment (burn-up) vs. fuel cost and refueling time. Limit access to fresh fuel	High possible enrichment (burn-up) vs. fuel cost and refueling time. Limit access to fresh fuel	Twenty percent U-235 a given limit; detailed assessment needed (value chain (front/ back-end))
No. 4	**Reactor safety**	Modern safety levels (Gen III/ Gen IV), emphasis on inherent safety, passive measures	Modern safety levels (Gen III/ Gen IV), emphasis on inherent safety, passive measures	Main difference reg. safety may be the need for surveillance (active parameters), e.g. inherent safety mechanisms
No. 5	**Other (crew, competence)**	Minimization of crew size and on-site competence (implications for the control systems and level of complexity)	Minimization of crew size and on-site competence, but not at the expense of power gen.	SMRs with more than 30+ employees pr. unit, is probably beyond the scope of NPS

A relevant assumption is therefore that any refueling, including adding fresh fuel to the reactor, must take place under secured circumstances, with few acceptable locations worldwide. The security issue at large suggests that the access to the reactor compartment is as limited as possible, which play well with designs

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[2] Reference to relevant papers has been included, also providing areas for future research.

providing a good basis for remote monitoring and with even the application of some autonomous functions. In any case, one may assume that a NPS will require a high degree of remote monitoring, suggesting that nuclear-propelled vessels will be of new design, fulfilling comprehensive obligations for information and secure communication on location and overall status of safety functions.

The overall conclusion is that there is uncertainty on what the design properties of future NPS in international commercial operation will be, and this will only be clear as specific initiatives, with their own background and external factors, are presented. Thus, for now we know some of the properties for NPS that will be important, but not to which level.

As for several other properties, for example requirements for an emergency preparedness zone when in port, accident inventory and source term, which differ between the various reactor types and sizes, each of these properties requires a separate assessment, as would be the case when designing and licensing the system, taking external factors into account. These factors may include societal, commercial, and industrial factors not directly related to the general properties mentioned in Table 32.

While there are probably proprietary and commercial activities underway in various countries, a more comprehensive approach is needed to understand the importance of the different properties within the relevant national context.

3.1.2 Hazards – the overall picture

Even though naval ships have been powered by nuclear reactors for decades, the experiences and any incidents related to the operation of these ships are not publicly known and available. The hazards considered, if any, forming the basis for the design and construction of these ships have not been established. There are also ice breakers that are powered by nuclear reactors. It is however not known what rules and regulations the design and construction of these ships have been based on.

An existing source of information that may provide input on relevant hazards to consider for nuclear powered ships is the IMO Nuclear Code. Even though restricted in its application to pressurized light water type reactors, the Code is considered relevant in many respects also for other reactor types of reactors, as there are few or no requirements that are directly relevant only for PWR-type reactors in this Code.

A HAZID workshop for nuclear powered ships was conducted in the NuProShip I project, as summarized in Annex IV of this report. The HAZID was mainly focusing on failures and incidents related to the ship construction and systems, and how a reactor incident in general may affect the safety of the ship. There could be merit in conducting further HAZID workshops going more into detail on the different types of reactors to identify relevant hazards that may affect their safety, as well as what hazards the different types of reactors may pose to the safety of the ship and the persons onboard.

Questions have been raised within the project to clarify hazards and consequences with regards to relevant types of reactors considered in this project:

- What are the consequences (short-term and long-term) for the different types of reactors (not for the ship) should a vessel with a reactor sink?
- Are there specific means and arrangements required for rescue and recovery related to the different types of reactors?
- To what extent does the safety for the different types of reactors depend on ship services, such as cooling water and electric power supply?
- How long can the different types of reactors maintain their safety without these services?

- In case of loss of a service, to what extent (e.g. capacity) does the service need to be restored to maintain the safety for the different types of reactors, e.g. fully or partial?
- May any of the types be prone to challenges with respect to conditions onboard a ship, such as shock, heel, roll, pitch, accelerations in general, vibrations, humidity, salt, voltage variations and transients, EMC, etc.?
- What are the required physical arrangements for containment in case of a reactor incident for the different types of reactors?
- Are the arrangements for maintaining the safety for the different types of reactors based active or passive arrangements?
- To what extent are the different types of reactors based on manual operation, monitoring and emergency interaction and are these onboard or onshore based?

The above questions remain to be clarified and are considered essential for establishing a complete identification of hazards relevant for nuclear powered ships.

When hazards related to nuclear powered ships have been sufficiently identified covering the different types of reactors, guidance on how to design ships and their system arrangements to address these hazards may be established.

3.1.3 Hazards – different reactor designs

A full overview of hazards related to the different types of reactors is still to be established. There are, however, some known or anticipated properties with the different types of reactors that should be further considered.

The risk spectrum associated with advanced reactors/Gen IV differs from that of reactors currently in operation, mainly because they have been further developed to offer nuclear technology with a lower accident risk, but also because they are still largely untested in practice. We must therefore assume that there will be further safety issues to be resolved for Gen IV – reactors when they reach a more mature stage of their development. However, as the technology is inherently different in some cases, there are some practically new risks that are discussed below.

A new problem relevant to all reactor types today is supply chain issues, as the global market for various fuel cycle services has been divided into two geopolitical spheres: those that still rely on Russia and those that want to avoid it. This will remain the case for the foreseeable future, as initiatives have been taken to steer industry in Western countries away from Russian services. Nevertheless, even in this case, Russia will continue to be important for large parts of the world for many years to come.

Another issue related to safety is the introduction of new technologies and the ability of regulators to respond appropriately and in a timely manner so as not to hinder industrial development, but this has been assessed in another chapter of this report.

3.1.3.1 Fast vs. thermal reactors – control of fission

Reactivity control for nuclear reactors is based on thermalization of the neutrons, i.e., the neutrons in the reactions are slowed down to allow new fissions to occur. In this way, the fission process can also be better controlled, as the delayed neutrons, which make up a large proportion of the neutrons used to control the fission reactor, are released between 1 and 50 seconds after the actual fission. Control systems for fast reactors of modern design have not yet been developed and tested. In this case, there is an inherent risk of ending up in a situation similar to that of today's reactors: the introduction of a technology that has not been adequately tested prior to its deployment. Some molten salt reactors and most lead-cooled reactors are designed for operation with fast neutrons. There are other reasons, including safety-related ones, for using the fast spectrum. However, the control system for fast reactors still needs to be developed and tested.

3.1.3.2 Challenges related to high temperature or flux.

The operating temperature is important to ensure a more efficient power generation system. The use of higher temperatures in some designs, such as high-temperature reactors (VHTRs), brings new challenges in terms of materials and technology compared to today's plants, and therefore also potential sources of error. For all Gen IV reactor types that have not yet been commercially tested, there are new and untested aspects that can bring new safety problems. Fast reactors have a different flux spectrum that can introduce new dimensions in terms of radiation damage. The materials intended for use have been tested and rejected in some cases, such as lead and sodium-cooled plants (USA, Russia, France) due to safety issues, while others still need to be tested experimentally with more modern materials or in large-scale plants.

3.1.3.3 Proliferation issues

For some of the Gen IV reactors to be economically efficient, they will have a closed fuel cycle that requires reprocessing of the spent fuel. Reprocessing was identified early in the history of nuclear energy as a potential source of proliferation of weapons-related material, and a significant number of countries have foregone this option due to the proliferation risk associated with this technology. This may be relevant for some types of molten salt reactors, lead-cooled fast reactors, and gas-cooled fast reactors, while the very high temperature reactor and the supercritical water-cooled reactor can only be operated in a once-through mode (no reprocessing).

3.1.3.4 Waste issues

In some cases, Gen IV reactors have been developed to reduce the waste problem associated with the use of nuclear energy. However, there are many safety issues associated with waste management, and optimization of e.g. half-life (reduction) can bring forward other issues related to chemical composition and vice versa. The nuclear waste management industry today is built for handling used fuel from conventional nuclear reactors. Where the reactor has been operating in moderated reactors, i.e., thermal reactors, and with the set of associated waste issues for fuel used in such reactors. Solutions include repositories in Sweden/Finland.

3.2 The safety rules framework

In this chapter we discuss statutory regulations, class rules and hazards with different reactor designs. This work will be continued in NuProShip II.

Given the broad variety of nuclear technologies that may be applied for sea-based nuclear facilities, from conventional water-water technology with high pressure and high temperature circuits, to unproven molten salt technology in a low-pressure system, the detailed regulations are not yet developed and the state-of-the-art regulations are considering only one type of technology (pressurized water technology). Below are the statutory regulations outlined.

3.2.1 Maritime framework

Similarly, large-scale accidents in international shipping, such as the sinking of Titanic in 1911, led to the establishment of the international convention Safety of Life at Sea (SOLAS). Other conventions addressing both the prevention of pollution, and the training of crew have been added, all of which are being regularly updated through the efforts of the International Maritime Organisation (IMO).

Regarding licensing of ships, the IMO, made up of representatives from the various flag administrations, administers the relevant conventions (UN Convention on the Law of the Sea (UNCLOS), the IMO Safety of Life at Sea (SOLAS) Convention and the IMO Convention on the Liability of Operators of Nuclear-Powered Ships and the Nuclear Ship Safety Code), being the basis for the statutory regulations as described below. The other main role, the classification societies, are important as part of the statutory system for shipping; when a classification society is assigned tasks by the administration of the flag state, which is ultimately responsible for certifying the safety of the ships it registers, it is referred to as a recognized organization (RO). Due to the international nature of shipping and the historical context in which it is necessary to systematically address the issue of safety, classification societies fulfil the role of an independent third-party organization in relation to, among other things, hull and stability, mechanical and electrical systems and fire safety both towards the yard, in the design and construction of the ship, as described also below.

3.2.1.1 Statutory regulations

An Administration means the Government of the state whose flag the ship is entitled to fly. Every ship registered in a flag Administration is a piece of that administration and only the relevant statutes, laws, provisions, rules, and regulations set out in the legal order of that administration will apply to the ship.

Although ships may be subjects of international law, ships themselves cannot incur responsibilities as individual legal persons. A flag Administration which is party to international instruments such as SOLAS, is responsible for implementing the obligations laid down in the relevant international instruments in its legal order. In Norway, for example, the country has a dualist legal system and must hence implement provisions of international law in national law in order to give the provisions full and complete effect.

3.2.1.2 IMO SOLAS Chapter VIII and the Nuclear Code

SOLAS Chapter VIII on Nuclear Ships was adopted on the 17th of June 1960 and entered into force 26th of May 1965. Since then, chapter VIII of SOLAS has not been amended, with the exception of the addition of a reference to Resolution A.491(XII) – The Code of Safety for Nuclear Merchant Ships in 1980 (hereinafter referred to as the “IMO Nuclear Code” or just the “Code”). The Code was meant as a supplement to the requirements of SOLAS Chapter VIII and superseded the recommendations applicable to nuclear ships that until then was found in attachment three to SOLAS 1974.

SOLAS Chapter VIII is yet to be implemented in Norwegian legal order. The decision not to take the steps necessary to give the present SOLAS Chapter VIII full and complete effect, is based on the fact that historically SOLAS Chapter VIII has not been relevant in the context of the Norwegian shipping industry. However, the Norwegian Maritime Authority (NMA) has the competence necessary for implementing the provisions set out in the SOLAS 1974 Convention into the Norwegian legal order. The Code has approximately eighty pages with eight chapters and 6 appendices which has been based upon established and accepted shipbuilding, marine and nuclear engineering principles. Application of the Code is restricted to conventional types of ships propelled by nuclear propulsion plants with pressurized light water type reactors, but few or no requirements are pure technical prescriptive for PWR. Purpose as stated in §1.1.1 of the code:

This Code is intended to provide a technical and regulatory reference for nuclear merchant ships. It supplements other applicable international conventions, codes and recommendations promulgated by the Organization and defines specific safety problems which should be addressed. Appropriate criteria are included to protect people and the environment from radiological hazard throughout all phases of the ship's life cycle: design, construction, commissioning, operation, and decommissioning.

There shall be four barriers to prevent release of radioactive products (in the Code developed for PWR, section 2.1.2: cladding, reactor primary pressure boundary, containment structure, safety enclosure). A nuclear ship should be designed, constructed, tested, inspected, operated and decommissioned under the quality assurance program (QAP).

The single failure criterion and reducing the probability of failure of essential systems in general, four important concepts should be incorporated in the design of systems for nuclear ships. These provisions are aimed at reducing the probability of system or component failure: Redundancy, independence, segregation, diversity.

With respect to risk acceptance there are specified 4 levels of Plant Process Conditions (PPC), see Table 33.

Table 33 – The levels of plat Process Conditions.

PPC	General description	Likelihood of occurrence	Consequence class
	Normal operation	Continuous or frequent	
2	Minor occurrences	Infrequent	2
3	Major occurrences	Remote	3
4	Severe accident	Extremely remote	4

Basic design criteria to ensure adequate safety during all PPCs:

A. Means provided to shield radioactive sources and to minimize the potential for the release of radioactive substances, so that exposure will be kept as low as is reasonably achievable.

B. Means provided to remove residual heat safely from the reactor core.

C. Means provided to control and shut down the reactor safely and to maintain it in that state as long as necessary.

Systems should be assigned a Safety Class (SC), based upon the importance of the consequences of the loss of the function performed by the system. There are 4 classes where SC-1 covers reactor protection system and the scram system etc. Within each safety class, every system or component should be assigned an appropriate Design Class (DC), ranging from DC-1 to DC-4.

The Nuclear Process Plant (NPP) has environmental and operational design requirements. A double bottom is to be provided under the reactor compartment, sufficient for the protection of the reactor and safety related systems, including high level radioactive material storage areas.

Chapter 4 in the Code covers the Nuclear Steam Supply System (NSSS) which includes the reactor and the complete steam system (primary and secondary system).

Chapter 7 in the Code covers manning, competence and certification, which may be a cost driver for commercial ships.

Survey during operational phase has a scheme which may be challenging for commercial merchant ships. It is a long list of systems and components which “should” be surveyed annually such as: Safety operations and functions shall have NDT and leak tests, including:

- Emergency cooling and emergency electrical systems etc..
- Hull structure in way of reactor and collision zones.
- High stressed parts of NSSS and reactor pressure vessel.

Every four year it is a more comprehensive test of NSSS. After 12 years in operation the whole reactor pressure vessel should be examined.

Note: The Code describes processes and requirements related to certification of a nuclear-powered ship by the administration. Certification of reactor design is not covered or mentioned in the Code.

While this code is specifically established for the pressurized water reactors, the code is modern in its focus on safety goals, with less prescriptive rules for how to fulfil the goals. However, since the Code has not been updated since its establishment, an important issue with the code is the integration of relevant security provisions reflecting the comprehensive role of security in modern installation regulations.

To present day it is not clear if the Code ever has been used to design a vessel. The robustness of the provisions set out in SOLAS Chapter VIII and the Code is hence up for debate. Considering the recent surge in interest for nuclear power and the technological advancements it is easy to argue that the Code is outdated. The IMO also acknowledges this, and whether the Code should be updated or not is on the provisional agenda for the forthcoming 110th meeting in the Maritime Safety Committee (MSC) scheduled for June 2025. Norway's position before the upcoming meeting is that we are positive to support a new output that targets a completely new revision of the Code.

More than 40 years after publication it is relevant to look at other reactor designs, which is recognized in the Code as it states a review will be necessary motivated by technology progresses. The independent organization World Nuclear Transport Institute (WNTI) has published a 350-page gap analysis of the Code which is sent to IMO Marine Safety Committee (MSC). The gap analysis promotes a technology neutral approach and will be handled at the forthcoming MSC 110.

3.2.1.3 IMO SOLAS Reg. I/5, Alternative design

Modern nuclear technology will in most cases challenge the present requirements because the present nuclear regulations are based on nuclear technology available at the time it was written. In such cases the regulations may restrain the level of innovation that is feasible. To not hinder technological advancement, SOLAS Reg. I/5 allows for equivalent solutions to be used to meet the requirements of the Convention given that it can be proven, through trial, that the equivalent solution is as effective as the solution required by the regulation. In order to comply with the requirements laid down in SOLAS Reg. I/5, the alternative design process as described in SOLAS Reg. II-I/55 must be executed. The purpose of SOLAS Reg. II-I/55 is to provide a methodology for the alternative design process. The regulation further links to MSC.1/Circ.1455 – Guideline for the approval of alternatives and equivalents as provided for in various IMO instruments which contains a description of the process and the tasks to be performed in order to prove equivalence.

The alternative design process is complex and relies on risk assessments. It is hence a risk-based certification process, rather than a prescriptive and rule-based certification process, with the governing principle that the equivalent solution shall be as safe, or safer, than the conventional solution. There may be different levels of approval depending on how challenging the proposed equivalent design is. Such designs may deviate from prescriptive requirements related to certain components, systems or functions, or the whole ship. Equivalent design and approval are expected to be carried out only for parts that either directly or indirectly proposes alternative ways of complying with prevailing regulations. The parts of the ship that do not challenge prevailing regulations shall be approved based on conventional design and standard approval principles. One approach to the approval of an equivalent design is to compare the alternative design to existing designs to demonstrate that the design has an equivalent level of safety. To demonstrate an equivalent level of safety, functional requirements and performance criteria should be established for essential ship functions, which then should be met by the equivalent design. An alternative approach could be to carry out a risk analysis of the equivalent design and compare it to overall risk evaluation criteria.

To prove and demonstrate that the required safety level is achieved is not an exact science. The design process may be iterative and many workshops focusing on quantitative and qualitative risk identification and analysis must be expected. A close co-operation between shipowner, designer, equipment providers and integrator, as well as class societies and administrations are hence crucial to the success of such projects.

3.2.1.4 Class rules

The objective of the class rules is to safeguard the ship, the persons onboard and the marine environment.

To meet this objective, the main class rules provide requirements to the availability of the ship's main functions to ensure the safety of the ship, and to the arrangement of the ship and the machinery systems to ensure the safety of persons onboard and the marine environment. The ship's main functions cover (among others) structural integrity, watertight integrity, propulsion, steering and power generation.

The main class rules are anchored in the general regulations in SOLAS Ch.II-1 and provide detailed requirements for the design, construction and testing of the ship structure and machinery systems.

The rule requirements are based on the relevant hazards for a ship and the persons onboard. In addition to the external hazards a ship may encounter (such as environmental conditions and navigational hazards), the rules also address internal hazards represented by the machinery installed, the fuels used, and the cargo carried that may affect the safety.

The hazards are considered in view of how they may affect the main functions of the ship, such as loss of propulsion, steering or power generation caused by failure in the machinery systems or their power sources, and loss of structural or watertight integrity caused by incidents with the fuel or cargo, such as fires or explosions. The rules also consider how the internal hazards may affect the safety for the persons onboard, such as injuries or loss of life caused by exposure to fire, explosions and toxic gases and smoke. The hazards are based on incidents experienced through decades, if not centuries, of ship operations. The hazards covered are thus those that are applicable for the conventional types of power sources, fuels, and cargo. When new types of power sources, fuels or cargo are introduced, potential new hazards related to these are not addressed by the rules and need to be identified and assessed to provide sufficient requirements to prevent or mitigate these new hazards.

For unconventional designs of major character, the ship classification is based on the same process as referred to within the statutory framework, see section 3.1.1.2, i.e., based on a process following IMO MSC.1/Circ.1455. A main part of such a process is to identify the hazards associated with the design.

Identification of hazards may be done in different ways. One way is to conduct HAZID workshops involving persons covering various competencies, such as manufacturers of the technology, ship designers, ship operators and regulators.

Another way is to study any existing rules or regulations on the subject that may not be directly applicable for the new technology, but to identify or interpret what hazards were considered forming the basis for the requirements for that technology. Such hazards may be relevant to consider also for the new technology.

A combination of these two ways of hazard identification should be applied.

3.2.2 Nuclear framework

The nuclear domain gradually grew after the second world war, with first only military, later also with civilian facilities. As the activities associated with these facilities have been considered to represent significant societal risk, the societal control (the regulation) has been anchored in regulatory agencies with regional or most commonly – national responsibilities. With a growing number of countries involved with nuclear activities, the international framework, collecting the national responsibilities together in conventions, has evolved to a large system covering nuclear safety, nuclear security, waste management and spent fuel handling and insurance, in some cases specifically limited to land-based facilities, though in most cases covering all types of activities. This international framework, established through the International Atomic Energy Agency, a UN organization, describe principles, roles, and responsibilities, while the detailed assessments with respect to for example safety rests with the national legislation. This legislation also set up the licensing process.

A licensing authority normally commissions a technical support organization (TSO) to carry out the detailed technical analysis required to ensure safe design, operation and all related activities. Certain aspects of nuclear activities, such as safeguards and oversight of nuclear material, are truly multinational and harmonized. However, fundamental, and complex issues like nuclear security and safety are assessed, decided upon, and enforced nationally. Fundamental aspects for a regulatory guide on nuclear ships are therefore:

- Is there a national legislation covering nuclear ships?
- Is there a national regulatory authority with a well-defined role for civilian marine reactors and fuel, with a TSO established?
- Has there been established international guidance documents or technical advice for the activities relevant for nuclear ships.

3.2.3 Differences in approaches and perception

The licensing of ships has evolved over a century based on the experiences made in all parts of the world, with the class systems slowly evolving, as the empirical basis for design, safety features and safety assessments has expanded. On the other hand, the nuclear licensing basis for commercial power plants with significant risk for the public are based on a strong analytical foundation, with probabilistic safety assessments at the core of the methodological approach. The safety analyses are carried out based on all possible and remote operating events and postulated initiating events that can be caused by external and internal hazards. There is probably a difference methodologically for how events are analyzed, and the different risks are perceived.

The licensing system of the nuclear system itself has been described by the IAEA generically and consists of site assessment (with environmental impact assessment), design, construction, commissioning, operation. Design is the process of determining the range of conditions and events that are explicitly considered in the design of the nuclear installation so that the installation can withstand them without exceeding the permissible limits.

The two most striking differences between the maritime and nuclear framework is the difference in a) approach and b) methodological basis. While the system approach appears to be similar in having a national fundament in international conventions and national regulatory authorities – or flag administrations, the true story is that there are vast differences between the two worlds.

3.3 Regulatory roadmaps

In this chapter we present av roadmap for the approval of the concept 'nuclear ship', then including maritime and nuclear regulatory aspects. This work will be continued in NuProShip II.

A regulatory roadmap has been established as regulatory barriers and challenges has been identified for other types of nuclear facilities, for example when considering SMRs. While the shipping industry has been in constant need of change and innovation for more than a hundred years, the nuclear industry has gradually matured to the point where it can cope with the current modus operandi of providing energy from large, centralized units. This situation has recently been challenged for the first time since the nuclear industry was founded by the latest conceptual nuclear power project: small and medium-sized reactors (SMRs). However, the development of SMRs has been hampered by various issues, of which regulatory issues (including licensing) is a key area. These issues have been raised on numerous occasions and have led to considerable debate and even political controversy, for example in the US where the lack of progress on advanced reactors or Gen IV has been a particular concern. Licensing efforts have been analyzed, with obstacles divided into 'licensing challenges' and 'licensing barriers.' While the term 'licensing challenge' has been defined as a problem that can be solved within ten years and where a single organization can bring about the solution, the term 'licensing barrier' has been used for problems that are likely to have an impact on deployment over a decade and require the cooperation of multiple organizations. The experience of setting regulations for SMRs therefore suggests that a thorough understanding of the regulatory basis can be important in understanding the challenges and barriers to nuclear ships. "The licensing barriers are: (1) existing legal and regulatory framework; (2) prescriptive regulatory framework; (3) novelty in the technology; (4) regulatory fragmentation; and (5) absence of in-factory certification. The licensing challenges are: (1) fees charged by regulators; (2) regulatory capability gaps; and (3) lengthy licensing duration. The identified barriers and challenges have implications on the project timeline and cost, consequently affecting the overall economics of the SMR."

Similarly, regulatory issues have created challenges in the maritime area. The introduction of alternative fuels, particularly those with a low flashpoint, such as efforts to create a code, which resulted in the International Code for the Safety of Ships using Gases or other Low Flashpoint Fuels (IGF Code), which became mandatory in 2017, began in the early 2000s. Some of the similar issues facing the nuclear industry in shipping today have been identified as important for the introduction of alternative fuels:

- Technical challenges, such as the different types of fuel, the lack of existing standards and the need for basic safety checks to address the obvious concerns regarding the use of natural gas, for example.
- International cooperation, as shipping companies, shipbuilders, engine manufacturers, fuel suppliers and governments, who also have conflicting interests, had to make a concerted effort to create a harmonised common framework.
- Infrastructural challenges such as the storage and bunkering of new fuels, in which players other than the shipping industry itself are also involved in order to bring about the necessary change.

In short, the concepts introduced above have outlined both the barriers to licensing and the challenges in the long-term efforts to introduce alternative fuels in international shipping, and a number of these elements would have formed an important basis for the establishment of a regulatory roadmap at an early stage of alternative fuel development.

3.3.1 Regulatory roadmap components

In order to translate regulatory challenges and barriers into a regulatory roadmap, the roadmap components are identified. The basis for the roadmap is that a project, with some specific design properties as described in Section 3.2, has been established. The project – the design properties of the reactor/ vessel/ project is, as discussed in Section 3.2, at the center for identifying the relevant risks. One important principle from the nuclear arena is the graded approach; "The resources devoted to safety … have to be commensurate with the magnitude of the radiation risks," which may also prove important as the magnitude of the radiation risk has yet to be established for nuclear ship. In other words, using a well-known and familiar technology require a different approach compared to a first-of-a-kind version. A regulatory roadmap shall therefore spell out the roles and responsibilities for a nuclear ship, with a description of the licensing process, taking all relevant legal instruments into account, with a graded approach in mind, providing due note of the complexities and the maturity of the parties and the technology involved.

The following components are then identified:

- The international safety framework as presented in Section 3.3 – international conventions and recommendations, national regulations, classification guidelines and rules, standards, all relevant for ship and reactor design, construction, operation, safety, and back-end management (well-to-wake), as discussed in Section 3.3.
- A responsible entity: The use of a reactor requires a clear responsibility for the overall installation from the very beginning, with the design, until the reactor and its fuel has been taken care of in line with the provisions of the relevant international framework for this. A licence must be granted for the licence holder, the reactor, and the fuel to be used in this reactor, as well as for all production facilities relevant to the manufacture of the reactor, its components, fuel, and the fabrication processes. Other main roles, in the maritime area the shipyard and the shipowner, needs to be clearly defined in relation to the licensee.

Thirdly, three different organizations with specific and well-defined roles have been identified in Section 3.3; a) the nuclear regulator, b) the maritime authority and c) the class society.

The regulatory roadmap consists of these activities along a timeline and their interdependencies components discussed separately and then pieced together in an overall roadmap for the realization of nuclear ships.

3.3.2 Establishing roadmaps for the licensing process

The regulatory roadmap describes the licensing process. When applying this system on the two main categories considered in this paper, the FNPP as described in Figure 36 and NPS as described in Figure 37, there is a large difference in how this may play out, as pointed out below.

The licensing process for non-nuclear conventional ships and nuclear reactors are very different. The former is a well-defined process where the classification societies have an important role both in relation to the shipyard and the shipowner. In the design and construction phase, the shipyard has a given role, cooperating closely with the class society that certifies that the ship's design complies with its technical standards and relevant international regulations. In the end, the final decision is made under which flag the ship will sail, and the flag state conducts inspections to ensure that the ship complies with its national laws and international conventions. In operation, there are additional requirements for e.g. pollution certificates, security certificates, one may expect port control when visiting foreign harbors and periodic surveys and inspections to maintain the certification. These inspections check the ship's condition, machinery, and equipment, and also crew requirements have to be fulfilled.

The nuclear regulatory licensing processes on the other hand, involving (at least) one license application, with safety cases in a safety report (nuclear), clearly demonstrating the status of the reactor for all possible operational modes for the reactor and all possible states of the vessel. Similarly, the potential effect on the status of the ship due to the reactor states must be duly demonstrated to the maritime authority/ classification society as part of the design and demonstrated during the follow-up activities during construction.

Given the possible large differences between FNPP and NPS – in particular if the basic design properties applied for FNPP is based on water-moderated and -cooled pressurized reactors – the licensing process may vary between 5-10 years on one hand, if the technology and concept is well-known and familiar, to 15-20 years if the technology and concept is new, the national resources and competence is lacking and there has been no agreement on how to harmonize the nuclear and the maritime licensing regime. This must address the roles, responsibilities and interaction between the regulatory authorities and the classification societies, to streamline the process to finalize the main elements, such as safety assessments and environmental impact assessments.

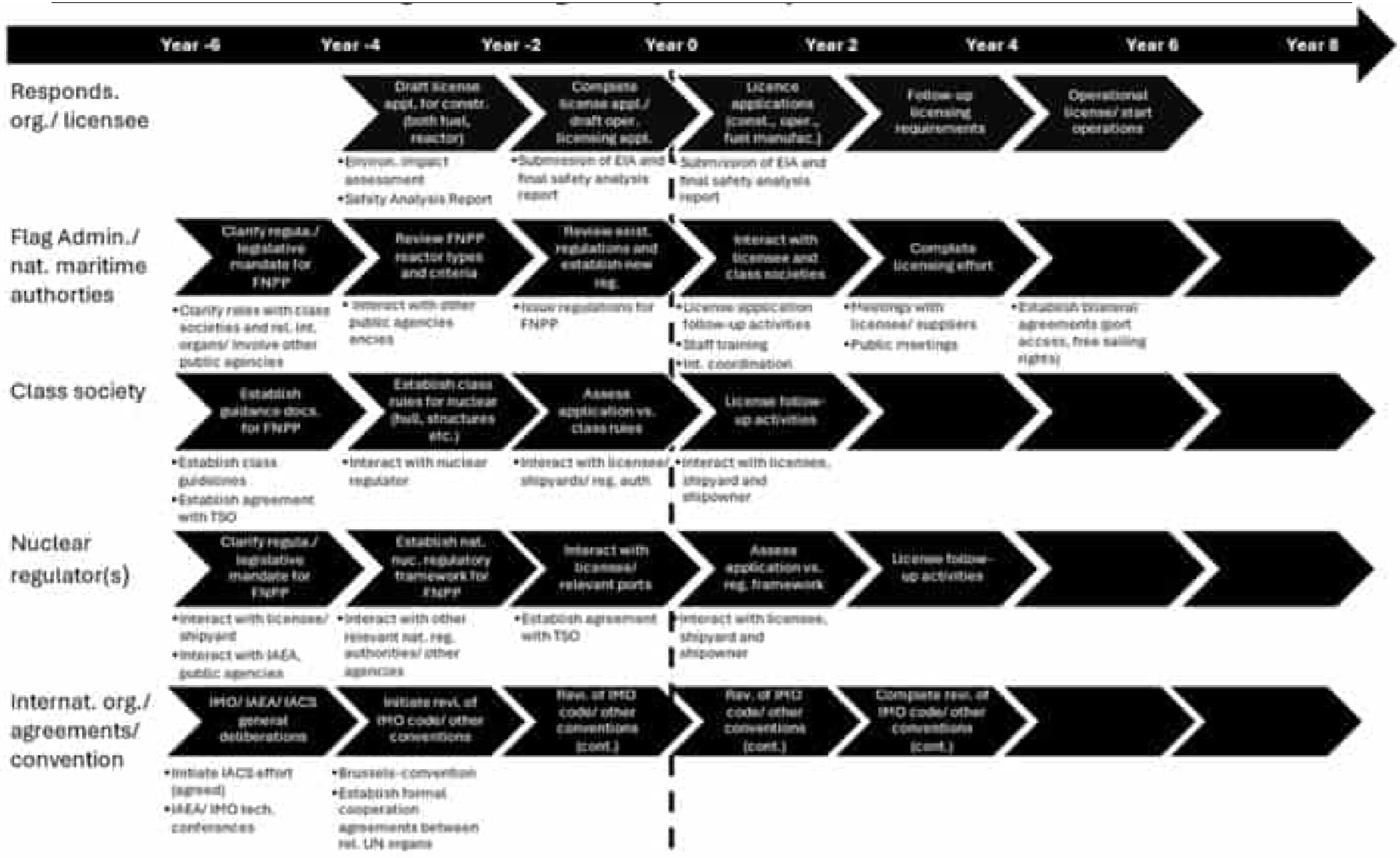


Figure 36 – A regulatory roadmap for a Floating Nuclear Power Plant (FNPP).

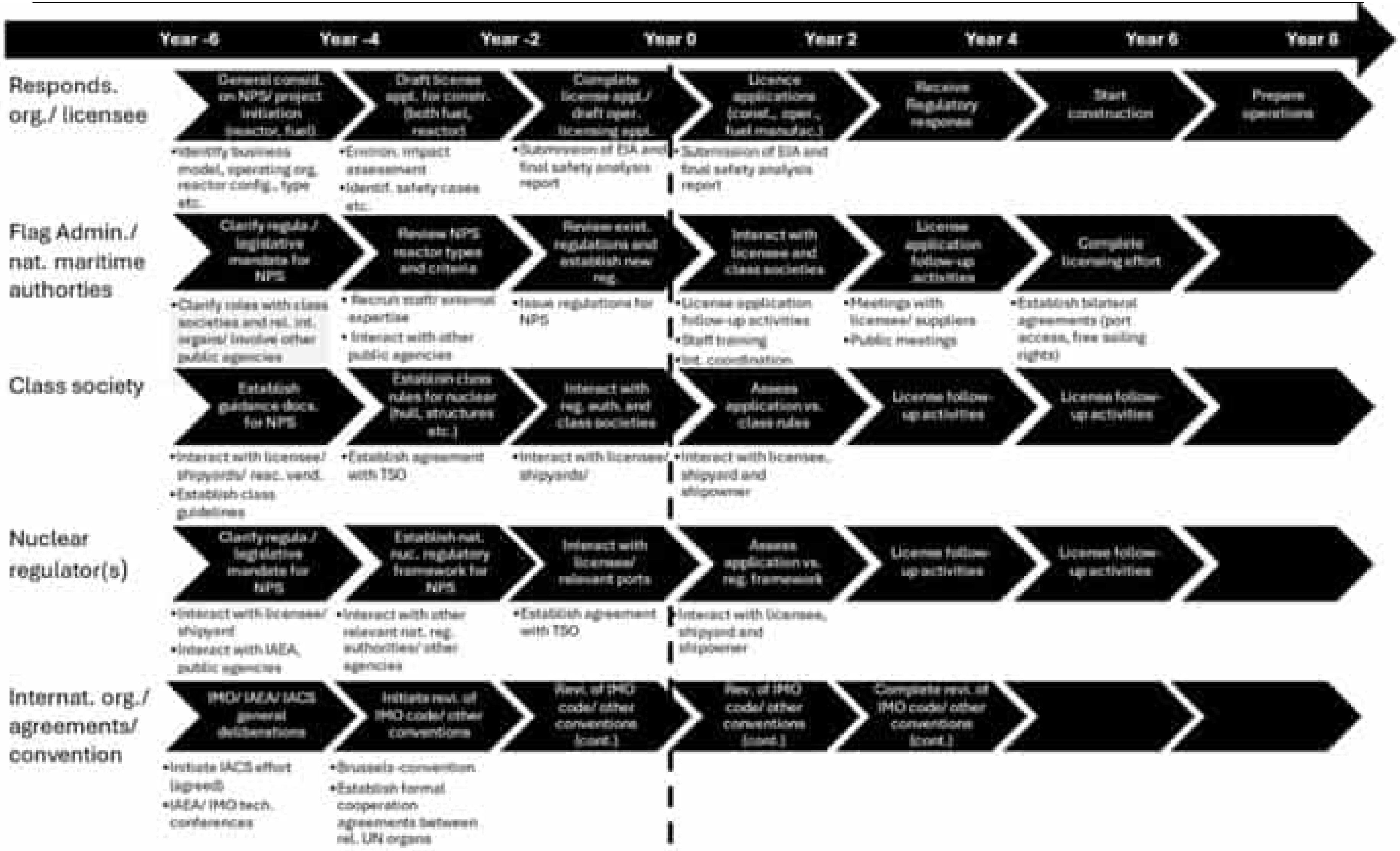


Figure 37 – A regulatory roadmap for Nuclear Propulsion Systems (NPS).

3.3.2.1 Floating power plants – a floating SMR

Regarding a FNPP, this is essentially a power production unit, which, if relevant, can be transported from site to site. The essential maritime unit may be a barge, being towed from site to site. The main activity will take place while in port, from a regulatory point of view, a similar activity to producing power at onshore facilities.

Regarding the regulatory roadmap as described in Figure 36 for the licensing of FNPPs, the licensing process will last for a decade, from the very beginning of the interaction with the regulator on pre-licensing activities until everything is in place to start normal operations. As the environmental impact assessment for a FNPP will have to be significant different for a FNPP, emphasis must be placed on having the requirements in place for this.

However, as we see in Figure 37, the national authorities/Flag administration, maritime and nuclear regulatory authorities, with the class societies, have a task to solve before the licensee may solve his part, since we may assume that there would at an early stage emerge a need for clarifying the roles. However, as there are international regulations established which essentially cover the transport between countries, while one may assume that the power production activities take place within a national jurisdiction, there should be minimal need for additional legal instruments internationally to cover the movement of a FNPP between countries. In this case, the responsible organization is probably a power producing entity.

When considering the real-life projects, the Prodigy are in the pre-licensing phase (phase 1 in Figure 36), assessing the site-characteristics, which essentially means the local infrastructure and environmental impact assessments. The timelines provided in Figure 36 indicate roughly a decade for the establishment of a concept, design and construction of a FNPP. This corresponds to the plan for the Prodigy facility, being planned in Canada, using one or more of the eVinci reactor, which shall be a transportable nuclear power plant (TNPP), relevant also for remote land areas.

3.3.2.2 Nuclear propulsion systems

The point of departure for establishing a regulatory roadmap in Figure 37 is then a project to establish a vessel with one or several reactors on board, of modern reactor design assuring the highest level of safety and security, as described in modern standards. Such a NPS is a commercial ship with a potential need for movement in international waters, e.g., needs a license to operate on more than one national jurisdiction. There is a limited number of crew to sustain efficient operations, with long refueling times, probably without the possibility of online refueling due to non-proliferation concerns. The project has been worked out by a competent organization with design knowledge and understanding, operational experience and capabilities and resources for surveillance and assistance in ports if necessary (emergency preparedness). The reactor technology is not first-of-a-kind, e.g., the technology has been licensed for use in a land-based reactor, however, not necessarily for use on a vessel.

Regarding the regulatory roadmap for NPS as set forward in Figure 37, many more challenging issues arise compared with the FNPP. NPS challenge many aspects of the current regimes for regulation of reactor and ships. The first and the main role is the establishment of a licensee, an organization with the purpose and objective to take the overall responsibility for the design, operation and decommissioning of the NPS. This organization shall be able to work out a license application, covering the vessel and reactor(s), including the fuel. In the regulatory roadmap, the process from establishing a business model with a suitable licensee and until an application for license has been submitted, has been assessed to 5-6 years. This organization must be able to cover the design, sustain the operational phase and guarantee for the post-operational phase (fuel, reactor).

The necessary foundation for applying for a license is that there are regulatory authorities with a formal mandate to handle the license application, covering both the reactor(s) and the vessels from idea to realization, which also covers the role of the classification societies. The clarification of mandate for a governmental agency may take considerable time and effort. As governmental agencies normally are reactive, the assumption for the roadmap has been that after clarifying the mandate for regulating NPS, approximately 4 years is needed to establish an infrastructure as part of and in relation to the agency. The most important tasks are to make sure that the relevant regulations are in place, clarify roles with class societies and relevant international organizations and have competent people in place to handle the application.

The class societies themselves are in a different situation, compared to the nuclear regulatory agencies, as they, despite their fundamental role in assuring safe design and operations, are in a competition for clients. We may therefore expect the class societies early on to establish guidance documents and class rules.

Given the situation above, that vital roles and responsibilities are in place, though with a limited international framework, the roles of the nuclear regulatory authority and the classification societies needs to be described. First and foremost, the nuclear regulatory must have a mandate for NPS. In any case, this mandate is probably limited to NPS in the national jurisdiction areas, but for sure that will in any case involve coastal areas and relevant ports. In addition to the issues already considered as part of a licensing effort for a land-based facility, release to sea and accidents caused by the national maritime environment and with consequences for the national maritime environment are relevant.

3.4 Refueling aspects

In this section we discuss different nuclear and commercial aspects of refueling, as well as some implications for shipyards potentially providing refueling of nuclear reactors.

3.4.1 Nuclear aspects

Refueling is one of the most critical processes in the operating life of a reactor. Regarding the understanding of the frequency and scope of refueling a merchant civilian reactor, there are three related installations we can gather experience from: land-based facilities (nuclear power reactors for the electric grid), military naval surface vessel facilities and Russian icebreaker facilities. In general, refueling a nuclear vessel would typically take weeks, months or even years, depending on several factors:

1. Type of Reactor: The only reactor type in active operation is the pressurized water reactor, which are designed for long refuelling intervals, typically 4 to 7 years.
2. Preparation: Before refuelling, the vessel is docked, the fuel cooled (weeks), and the relevant equipment is prepared (casks, specialized equipment).
3. Refuelling:
    a. The spent nuclear fuel is removed (days).
    b. The reactor interior is inspected (weeks).
    c. New fuel assemblies are installed (days).
4. Maintenance: Refuelling periods are used to perform maintenance, which can extend the overall downtime.
5. Regulatory follow-up activities: Inspections and tests will normally take place before the reactor can return to operation.

In summary, the actual refueling time is relatively short (a few days to a week), but the additional preparation, maintenance, and regulatory checks make the overall process longer. The differences between land-based nuclear power facilities and civilian commercial reactors are striking. Firstly, only part of the core is replaced in case of land-based facilities, while the overall position of the fuel elements is changed to maximize fuel burn-up. Secondly, previously spent fuel from the spent fuel storage facilities can be introduced into the reactor to also maximize burn-up, in the case of nuclear ships, in contrast to land-based facilities where the fuel is fully burned in that facility.

As for naval reactors located on military surface ships, these facilities are often taken out of service during refueling for an extended overhaul and refurbishment. Because the fuel has spent a much longer time in the reactor compared to civilian commercial reactors, or because the fuel is extremely enriched, or because the size of the nuclear fleet allows for longer refueling periods than is the case for commercially operated ships; refueling may only occur once or twice, if at all, during the ships' lifetime. For civilian Russian icebreakers, the refueling procedures could possibly mirror the expected procedure for civilian merchant ships; the ship and reactor are designed for a fuel change, the refueling process itself is not a complicated process that normally takes place every five years (give or take a few years) depending on the reactor's operational history. However, since refueling would require docking the ship, cooling the reactor for weeks and then replacing the fuel – a complete reactor core – fuel consumption (the level of burn-up, how much of the fissile material that could be used) would be significantly worse than for a land-based reactor where the fuel can be redeployed.

In terms of refueling infrastructure, this would be dependent on shipyards having facilities and permits for fuel storage and associated management equipment. While there are normally facilities for spent fuel storage near an operating reactor, the Russian design for a floating power plant for export indicates that such storage facilities have not been included in the overall design. The immediate interpretation is that concern for the safety of spent fuel storage has led the Russian draft to omit this part entirely from its latest proposals. This leaves out the issue of spent fuel safety and the safety of mobile facilities. The IAEA is currently working on a publication on the safety of floating power plants planned for 2026, which will address this issue. Such a position would mean that the storage of fresh fuel assemblies, which pose a greater safety and proliferation risk than spent fuel, could also be considered less relevant, and that fresh fuel storage facilities onboard Storage of fresh fuel could in principle face major obstacles when national regulations and international recommendations are considered. The interesting question is then online refueling, which is a planned feature for some reactor types. This type of arrangement would necessary be carefully scrutinized before being accepted as part of merchant reactor systems.

A relevant assumption, if not considering technologies with specific requirements regarding refueling, is that every vessel would need to be refueled every fifth year. Due to requirements from classification societies that often leads to ships drydocking around every five years. The yard offering refueling would need to be licensed for that operation in accordance with the general IAEA recommendations for fuel cycle facilities, where security considerations have a special emphasis.

An additional element with respect to operation of nuclear vessels, would be if new types of fuel are being commissioned, for example TRISO-fuels, which also can be used in land-based reactors after being taken out of marine reactors. In principle, this is a logical consequence of a more versatile fuel geometry (e.g. spheres) with the barrier for leakage of activity implemented as part of the fuel. However, this would require a special infrastructure that would only be relevant for certain reactor types. Finally, taking the commercial aspects into account, the overall time spent on refueling have to be as short as possible, but must be based on availability of fuel and relevant facilities (yards), in addition to the sailing routes.

3.4.2 Commercial aspects

Merchant ships operate under different types of commercial contracts, and the most common types are:

1. Time Charter (TC), where a charterer hires the ship for a given time period. Today, the shipowner usually covers fuel costs.
2. Spot, where a charterer hires a ship for a given voyage on short term notice. Usually, the charterer pays for the fuel.
3. Contract of Affreightment (COA), where a shipowner promises to transport a certain amount of cargo at given times in the future. E.g., will transport 10 million tons of iron ore from a given port in Brazil to China in 2025. Charterer usually pays for the fuel.

The commercial contracts under which the ship operates will have an impact on the ideal refueling philosophies and frequency of nuclear-powered ships, that in some cases can operate for years without refueling. The refueling frequency may have to be adopted for a given ship, depending on the contract it is trading under. For example, it might be beneficial to do refueling between two different Time Charter contracts. It may also be the other way around, that for a given nuclear-powered ship with a given nuclear technology setting certain constraints on refueling, that this nuclear ship is better suited for some contract types than others.

Some nuclear-powered vessels today use lifetime cores, which means they only need to be fueled once, and some cannot be refueled at all. Others, on the other hand, refuel after a certain amount of energy in the core is used, i.e., after a given burn-up is reached. There are several aspects to consider in finding the optimal frequency.

There are clear differences here in different reactor and fuel technologies, with differences in today's PWR reactors of different designs, and with greater differences for newer designs of reactors that also include GenIV reactors. Some reactors have online refueled, probably allowing for higher flexibility in terms of refueling frequency. While most proposed reactors will have to be opened to replace fuel rods, requiring more time to do the refueling operation itself.

If the refueling operation for a given reactor type is very time consuming, it will be preferable to do the refueling while the ship already is undergoing major maintenance including dry-docking, which usually is at given five-year intervals. If the refueling procedure is not so time consuming, one can consider more frequent refueling.

The economic aspects, not considering time to refuel, also have an impact. Even though nuclear fuel is significantly less costly than conventional fossil fuel, buying all the fuel in year one has a much higher Net Present Value than gradually buying the fuel over time.

Consider this example calculation:

- A 15,000 TEU container vessel, having a total annual fossil fuel consumption today of 24,500 tonnes of LSFO (low sulfur fuel oil).
- The internal combustion engines on such a ship have higher thermodynamic efficiencies (48%) than a nuclear to steam reactor (35%). The nuclear-powered ship would require nuclear fuel with an energy content (the energy the reactor can convert to thermal energy) of 48/35 * 24,500 = 33,600 tonnes of LSFO equivalent energy.
- Today, LSFO prices are in the range of 500-650 USD/tonne, while heavy fuel oil (HFO) is in the range of 400-525 USD/tonne.
- Nuclear fuel is going to be significantly cheaper than fossil fuels, with annual fossil fuel costs for the case ship of between 12.3 and 15.9 MUSD (using LSFO). If, as an example calculation, the nuclear fuel costs 100 USD per tonne of LSFO equivalent energy, then the annual fuel costs for the nuclear reactor will be 3,36 MUSD.

- If the case ship sails for 15 years and fuels all nuclear energy when it is built, the Net Present Value of the fuel is 50.4 MUSD. This must then be considered as part of the CAPEX.
- If the ship instead fuels every five years (year 1, 6 and 11), the NPV with a discount rate of 8% is 46.8 MUSD.
- If the ship instead fuels every year, the NPV with a discount rate of 8% is 31.1 MUSD.

With an expanding and developing nuclear industry, the cost of nuclear fuel could very possibly drop in the future, if the technology is successfully developed and scaled. This could lead to even lower nuclear fuel prices going forward, further increasing the benefit of gradual fueling rather than a single lifetime fueling.

Another important variable is the introduction of leasing mechanisms in the fuel value chain, either for the fuel or even for the whole reactor installation. One option is to consider a contractual model where the ship owner leases fuel from a larger supplier, where there could be an annual fee for the fuel regardless of refueling rate. In the early years of nuclear in shipping, it is likely that refueling takes place in a very few yards globally. This would mean a constraint in operations, so the fewer constraints, the better. The annual fee could be set higher for lower number of actual refueling. This approach also makes for a safer and easier-to-monitor fuel industry, since fewer and possibly governmental or semi-governmental companies would set the agenda.

3.4.3 Shipyards

Using nuclear power as energy source onboard ships means that shipyards globally must be equipped and certified for commissioning, refueling, and decommissioning of maritime reactors. The handling of the nuclear fuel and commissioning of the reactor are specialized procedures, and there are two options for the industry going forward:

1. All shipyards building ships above a certain size are certified to handle nuclear fuel and to ensure safe operations throughout the vessel life cycle.
2. All shipyards build the ship and performs the reactor and support systems installation, and then a few, selected shipyards install the fuel and commissions the reactor. The same shipyards handle refueling and decommissioning when the time comes for that.

Since a reactor installation is quite conventional until the fuel is introduced, alternative no. 2 above seems most reasonable and likely. It also simplifies safety and security aspects and reduces the number of locations necessary for spent fuel treatment and safe deposit. This approach also reduces the need for transportation of nuclear fuel both to and from the different shipyards, either on land or at sea.

These selected shipyards must be subject to approval according to specific regulations, and regular audits performed. Since most of a shipyard is a shore facility it should be treated like any shore nuclear power plant or fuel treatment facility, and consequently the present regulations for these can be used also for shipyards with only minor revisions. Each nation's nuclear regulatory body could handle the approvals and audits.

To reduce time and thereby costs, a type-approval approach should be adopted for reactor installations. To support this, it is important that the total nuclear reactor installation and support systems are module based as far as possible.

3.5 A shipbuilder's considerations on NuProShip I for installing a nuclear propulsion system in an LNG carrier

This section in the report summarizes the work Vard Design AS has performed as partner in the project NuProShip I, and it focuses on identifying challenges and possibilities related to the integration of a 4th generation MSR as energy source onboard an LNG carrier. It also proposes main principles to be followed when planning the integration of the reactor(s).

The vessel “Iberica Knutsen” has been used as case for potential retrofit to nuclear power, and this report considers two locations:

- A new elongation section with the nuclear power plant in it.
- A retrofit in the existing engine room.

3.5.1 Possibilities & Challenges

A nuclear-powered vessel should have redundancy in energy generation and in propulsion. The energy generation redundancy could be solved either by having two independent nuclear energy systems with their own separate reactor and auxiliary systems, or with one nuclear energy system backed up by different energy source/carrier. The following advantages / challenges for this arrangement is discussed subsequently.

3.5.1.1 General comments, regardless of location

In general, all auxiliary systems serving the reactor systems shall be dedicated systems not combined or integrated with vessel’s existing systems.

A dedicated sea water cooling system to be arranged for cooling of reactor freshwater cooling system. Shipyard shall install necessary number of sea water cooled heat exchangers, sea water cooling pumps, control systems etc.

The systems shall include a high level of redundancy. The level of required redundancy to be decided together with the classification society.

The heat exchangers shall be designed for a sea water temperature of 32°C.

The reactor freshwater cooling system to be included in the scope of delivery from the reactor supplier of the reactor module. This includes all circulation pumps, thermostatic valves, flow control valves etc.

A separate firefighting system for the reactor compartment to be installed.

Type of systems to be defined during concept design process.

- Separate bilge water system with dedicated bilge water collecting tank. Requirements for capacity etc. to be defined during concept design process. Considerations to be made for treatment/disposal of the bilge water with regards to contamination etc.
- A new electric power balance to be carried out on order to define the electrical power demand. This must include operation of all new systems installed, including AC compressors, boil-off gas liquefaction system, cooling water systems and other new auxiliary systems.

In order to have sufficient redundant electrical supply, considerations to be made about what type of electric power sources to be installed.

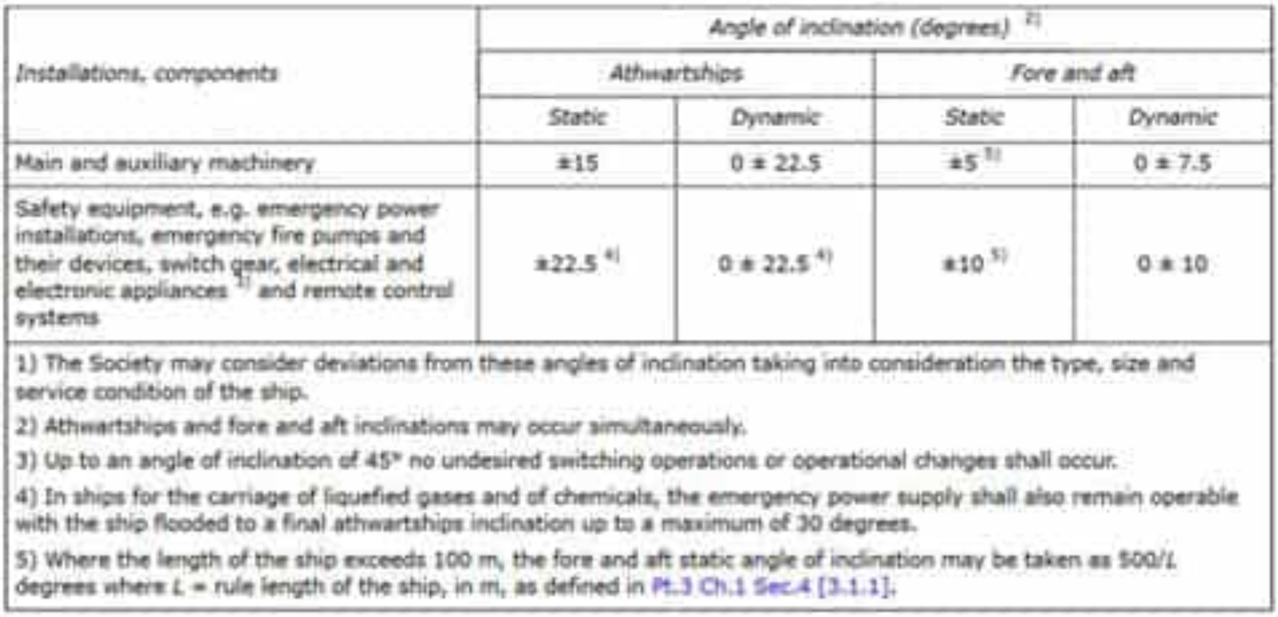
3.5.1.2 Ship motion considerations

The following motions need to be taken into account when designing ship systems:

1. DNV Rules for ships Part 4, Chapter 1, Section 3 specify the motions given below in terms of maximum angles, to be taken into account when designing the machinery systems for general cargo ships, see Table 34.
2. The Code of Safety for Nuclear Merchant Ships, paragraphs nos. 2.2.8, 2.3.10, 3.4.7, 4.3.1 and 5.2.5 contain requirements that deviates from the above.

3. The Code will be amended by IMO in the coming years, so the eventual revision of these requirements needs to be followed and taken into account in the engineering of the nuclear energy system.

Table 34 – List, rolling, trim and pitch. Source: DNV Rules for ships Part 4, Chapter 1, Section 3.



Installations, components	*Angle of inclination (degrees)* 2)			
	Athwartships		*Fore and aft*	
	Static	*Dynamic*	*Static*	*Dynamic*
Main and auxiliary machinery	±15	0 ± 22.5	±5 1)	0 ± 7.5
Safety equipment, e.g. emergency power installations, emergency fire pumps and their devices, switch gear, electrical and electronic appliances 3) and remote control systems	±22.5 4)	0 ± 22.5 4)	±10 5)	0 ± 10

1) The Society may consider deviations from these angles of inclination taking into consideration the type, size and service condition of the ship.

2) Athwartships and fore and aft inclinations may occur simultaneously.

3) Up to an angle of inclination of 45° no undesired switching operations or operational changes shall occur.

4) In ships for the carriage of liquefied gases and of chemicals, the emergency power supply shall also remain operable with the ship flooded to a final athwartships inclination up to a maximum of 30 degrees.

5) Where the length of the ship exceeds 100 m, the fore and aft static angle of inclination may be taken as 500/*L* degrees where *L* = rule length of the ship, in m, as defined in Pt.3 Ch.1 Sec.4 [3.1.1].

3.5.2 Locations

There are two alternatives to consider, as discussed in the subsequent sections.

3.5.2.1 Reactor located in elongation section

By choosing a solution with hull elongation, one will keep much of the existing engine room as it is today, which is the main advantage of this alternative. This will potentially reduce conversion costs and increase redundancy. Here are some alternatives to consider:

- All experience indicates that new systems do not work optimally from the start, they may even fail and stop. For that reason, one should think about keeping as many of the existing systems intact as possible to avoid operational interruptions on the ship.
- One can without risk remove the systems for heavy oil and only run the boilers on diesel if needed. For handling boil-off from LNG cargo tanks, systems for liquefaction and systems for delivering this back to the cargo tanks must be installed. This will prevent unwanted release of gaseous LNG into the atmosphere.
- Should the liquefaction system fail, it may be an idea to install Dual Fuel auxiliary engines or to maintain Dual Fuel burners on the existing boilers.
- If you have an engine room that is "intact", it would provide redundancy and thus a higher level of safety than if you have only two reactors. External influences can easily knock out both reactors at the same time.

However, placing the reactor installation in a separate elongation section will require a higher number of auxiliary systems.

- Sea chests, with high and low suction for separate firefighting systems and sea water cooling systems.
- Separate firefighting systems for the reactor compartment.
- Separate bilge water system with dedicated bilge water collecting tank, and systems to treat the bilge water if needed. In case of elongation, the vessel's existing bilge and firefighting systems must be

checked due to vessels new main dimensions, including capacity of emergency fire pump end emergency power generator.

- Vessel's ballast system. Tankers normally dimension the capacity of the ballast water system based on the filling / discharge rate of the cargo system. This means that if you need for example 5 hours to fill the cargo tanks you also need to discharge ballast water within the same timeframe. When increasing the length of the hull you also increase the buoyancy, which might lead to a need for upgrading the ballast water system. In order not to change the capacity of existing ballast system, a separate ballast water system with ballast water treatment could be installed in the new compartment of the hull. This to be clarified with regards to regulations and stability/load line.
- A room for Chilled water compressors to be arranged. Compressors to be installed for air condition of compartments in vessel's reactor area. The compressors also to be arranged for free sea water cooling systems at low sea water temperatures. Compressors to have electric power supply from separate switchboards for redundancy. If the main switchboard does not have sufficient number of main bus breakers, this has to be upgraded. In worst case, the switchboard room must be increased in size. In order to have a proper zero-emission vessel, the main electric power should not be produced by the auxiliary engine.
- It is important to evaluate and clarify any influence on existing Gas Dangerous Zone on open deck. Do we need to consider Gas Dangerous Zone on cargo deck in all conditions or just during bunkering / discharging? This has to be clarified with the Class.
- Ventilation systems. It is assumed that we need to consider and define a Dangerous Zone around ventilation inlets / outlets from the reactor compartments. Most likely these must be routed to a high level above vessel's wheelhouse. Class or flag authorities must define or calculate any size and shape of such zone, based on input from reactor supplier.

3.5.2.2 Reactor installed in existing engine room

By choosing a solution where the reactor module shall be installed in the existing engine room compartment you will get the advantages of minimum interference with the vessel's:

- Hull structure (longitudinal hull strength)
- Cargo systems
- Fire and bilge systems
- Ballast systems

Matters that one should be aware of:

Installing such a large component in an existing engine room means in practice that you must remove most of the existing equipment to free up space and to give the opportunity to install new solutions.

Based on experience, because in an engine room everything is connected to everything, so starting with changes will quickly have a significant domino effect.

Therefore, the general advice is to take out as much equipment as possible and then put it back where there is room / space and where it will work appropriately.

In an engine room there are some main principles that have to be respected:

1. The engine room is defined in SOLAS as machinery space of category A. These are the spaces and trunks to such spaces which contain:
    a) Internal combustion machinery used for main propulsion; or

   b) Internal combustion machinery used for purposes other than main propulsion where such machinery has in the aggregate a total power output of not less than 375 kW; or any
   c) oil-fired boiler or oil fuel unit.
2. Even if we remove the oil-fired steam boilers, the category A will remain since there is an auxiliary engine installed.
3. The reactor module therefore be designed, built, equipped and approved by classification and maritime authorities for installation in machinery space category A.
4. Further, the dimensioning of casing for exhaust gas piping from boilers and engines, and air inlet ducts for ventilation of the engine room must be evaluated.
5. It is assumed that ventilation for the reactor module or reactor compartment must be separated from the general engine room ventilation systems.

3.5.2.3 Required interface information from reactor supplier

Number of cooling circuits:

1. Flow requirement, m^3/h (Max. seawater temperature = 32°C).
2. Heat to be removed, kW.
3. Outlet / inlet temperatures.
4. Any requirements for connections to the reactor module.

Ventilation – general requirements for the reactor module, figures as relevant for:

1. Number of ventilation systems.
2. Figures for any air cooling to be specified.
3. Number of air changes.
4. Any requirements for connections to the reactor module.

Steam system:

1. Principal flow diagrams steam systems, defining interface shipyard / Reactor supplier.
2. Any requirements for connections to the reactor module.

Other:

1. Electrical single line diagram for main electric power distribution to / from reactor module.
2. Technical specifications / requirements for module foundation and fastening to ship structure.

4.0 Operational safety, crew and maintenance

The work produced was mainly considering the review of existing regulations for nuclear merchant ships:

1. IMO Resolution A.491 (XII), Code of Safety for Nuclear Merchant Ships, 1981.
2. Marine Guidance Note for Nuclear Ships, MGN 679 (M), MCA, UK, 2022.

This documentation constitutes the basis for the development of new rules and regulations for the future nuclear-powered ships.

The research project, Nuclear Propulsion of Merchant Ships I (NuProShip I) intend to identify Generation IV SMRs for ship propulsion that can contribute to achieving emission reduction targets for deep-sea merchant fleet. Furthermore, and directly relevant to this work package, is that the project proposes to analyze relevant regulations, training requirements, ship design, maintenance, operational safety, staffing and waste management [27].

We agree with [28] that the regulatory framework is very complex. Experts of nuclear power for merchant shipping must interpret and comply with a vast number of different rules and regulations, both international and national [29]. The primary international organizations concerned in this matter are the IAEA and IMO. The IAEA's safety guides and standards regarding qualification and training of personnel for nuclear power plants and nuclear safety present best practices and have been partly developed in collaboration with the EU and other international and national organizations. National regulatory examples are the United States - U.S. Nuclear Regulatory Commission (U.S. NRC), France - Nuclear Safety Authority (ASN), Japan - Nuclear Regulatory Authority (NRA), United Kingdom - Office for Nuclear Regulation (ONR), Norway – Norwegian Radiation and Nuclear Safety Authority (DSA), all members of the IAEA.

Since there are significant differences between conventional-powered ships and nuclear-powered ships, this implies that the existing education and training of seafarers for nuclear vessels is not sufficient [28]. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW 78 as Amended) revised in Manila, 2010 [30] does not cover manning and training for merchant nuclear-powered ships, thus supplementary education and training for seafarers of nuclear-powered ships is extremely necessary [28, 31]. Moreover, it must be stressed that different nuclear reactor types require different education and training programs [28].

The IMO adopted in 1981 [31], also known as the 'Nuclear code', which created the international framework for the design, construction, operation, maintenance, and decommissioning of nuclear-powered merchant ships. The initial application of the Nuclear Code was restricted to nuclear propulsion plants with PWR but this resolution was not implemented by any of the member states at the time [10].

When [31] was adopted, IMO recognized that the technology for nuclear powered ships was evolving and authorized the Maritime Safety Committee (MSC) to "amend the Nuclear Code in due course as necessary in the light of future development in the field of nuclear-powered merchant ships". To the present date, the Nuclear Code has not been amended, and it needs to be comprehensively updated to reflect and accommodate new technology developments in the nuclear field [32].

In 2022, the British government turn effective the IMO resolution A.491 [33]. The UK Maritime and Coastguard Agency (MCA) developed the Marine Guidance Note for Nuclear Ships, MGN 679 (M), which provides guidance on the application of the Merchant Shipping (Nuclear Ships) Regulation in 2022, see [34]. Both the [33] and the [34] provide recommendations, rules and regulations for the manning and training of crew members for nuclear-powered merchant ships. The IAEA, developed several publications covering the education, training and manning of traditional nuclear power plants and SMRs. Furthermore, there are international organizations working on developing higher education and training in nuclear science, technology and engineering, such as the ENEN (European Nuclear Education Network).

Several countries have nuclear power as propulsion in their navy fleets, both in submarines and surface ships. As examples, the US navy has 73 submarines and 11 aircraft carriers, the Russian navy has 21 submarines and 1 battle cruiser, China has 14 submarines, the British navy has 10 submarines, France has 9 submarines and 1 aircraft carrier, and the Indian navy has one submarine. Further, Russia has six icebreakers in operation [27]. There have been a few experimental merchant ships with nuclear propulsion in the past, namely, the NS Savannah, 1959 – 1972, The German NS Otto Hahn, 1968, and the Japanese Mutsu, also a pilot project, in 1974. All three ships were pioneers in the area of merchant nuclear-powered ships and were powered by pressurized water reactors [10].

4.1 Overview about safety and training of seafarers of nuclear-powered ships

The overview presented is based on the work of IMO and MCA.

4.1.1 The IMO Regulatory Policy and Recommendations for Merchant Nuclear Ships

As mentioned above, IMO, developed in 1981 the resolution A.491 (XII), The Code of Safety for Nuclear Merchant ships. The purpose of the code was to give guidelines and recommendations for flag states. According to chapter seven in the code, crew members should have sufficient competence to perform their assigned duties on board the vessel and fulfil the requirements in the operating manual for the relevant reactor to be used on board the vessel. In the case of merchant ships with nuclear propulsion, the following additional skills listed below are requirements for the engineering officers and should be part of an education and training program approved by the administration [31] pages 87-88:

i) Principles of nuclear engineering and nuclear reactor theory.

ii) Radiation physics, including radiological effects on health and the environment, principles of radiological protection and radiation monitoring.

iii) Design and operating principles of the Nuclear Steam Supply System (NSSS), its monitoring, control and protection systems; engineered radiation safety features of the ship and nuclear propulsion plant (NPP), and particulars of the ship’s hull structure.

iv) Detailed study of a NSSS of the type fitted on the ship for which the officer is being trained and study of the Safety Assessment, Operating Manual and operating instructions for the NPP equipment.

v) Practical training in start-up, shutdown and control of the NSSS, in normal and simulated emergency conditions, including maintenance, checking and survey procedures.

vi) Principles for safe operation of NPP including maintenance inspections, surveys, core refueling and waste management.

The code highlights that practical training should be performed on the type of nuclear power plant that the trainee will be qualified to operate. Such training can be achieved by using intensively specific simulators or on-the-job training on an existing reactor. The trainee should be able to perform reactor start-ups and shutdowns during normal and abnormal conditions. The code also states the importance of updating skills and emphasizes retraining in the operation of the nuclear power plant on board the ship [31]. The code is a supplement to existing qualification requirements for seafarers in the STCW.

4.1.2 The MCA Regulatory Policy and Recommendations for Merchant Nuclear Ships

These recommendations are substantiated by the Maritime and Coastguard Agency (MCA) as reflected in the Marine Guidance note [34], which provides guidance for the application of the [33]. In addition to IMO's recommendations, MCA recommend study of national and international safety requirements applicable to nuclear ships and their nuclear propulsion plant. All considered training courses (36) should be approved by the administration. MCA also states that education and training of staff should be in accordance with the operating manual of the specific reactor to be installed and operated on board the vessel [34].

According the MCA program, the master and qualified officers should hold certificates commensurate with their duties. They should have successfully completed a special training course approved by MCA, the curriculum of which includes the following minimum requirements:

i) The basic principles of nuclear energy and its application to ships.

ii) The particulars of the structure and performance of a nuclear ship.

iii) Knowledge of the possible consequences of navigational accidents to the ship and to the environment.

iv) Basic principles of radiation hazards and radiological protection.

v) Action to prevent or alleviate postulated emergency situations.

Engineering officers should successfully complete training which includes the following minimum requirements:

i) The principles of nuclear engineering and nuclear reactor theory.

ii) A course in radiation physics, including radiological effects on health and the environment, principles of radiological protection and radiation monitoring.

iii) Design and operating principles of the nuclear steam supply system (NSSS), its monitoring, control and protection systems.

iv) Engineered radiation safety features of the ship and of the nuclear power plant (NPP).

v) Particulars of the ship's hull structure.

vi) Detailed study of a NSSS of the type filled on the ship for which the officer is being trained and study of the Safety Assessment (section 4 of [34]), Operating Manual (section 6 of [34]) and operating instructions for the NPP equipment.

vii) Practical training in start-up, shutdown and control of the NSSS, in normal and simulated emergency conditions, including maintenance, checking and survey procedures.

viii) Principles for the safe operation of NPP including maintenance inspections, surveys, core refueling and waste management.

ix) Study of national and international safety requirements applicable to nuclear ships and their NPP.

The certificate of qualification for engineer officers should record the completion of the special training course and the chief engineer and qualified engineer officers should hold certificates commensurate with their duties and should be subject to retraining and re-examination for each type of NSSS they may be required to operate.

All NSSS operators should have successfully completed a special training course approved by the MCA and should hold an appropriate operator's certificate. The degree of detail of course content should be commensurate with the duties of the operator.

All members of the ship's crew required to undertake specific or general tasks in the event of a radiation accident, should be trained in radiation protection to a level commensurate with the duties they would be expected to perform. This training should be periodically updated and repeated at a frequency sufficient to ensure a continued awareness and understanding of the radiation protection requirements.

The personnel responsible for radiation protection should:

i) Be trained in radiological protection and dosimetry to a level satisfactory to the MCA.

ii) Have successfully completed a detailed training course approved by the MCA and possess a qualification certificate indicating the types of NSSS and radiation protection equipment for which they have been trained.

iii) A ship's doctor, if carried, or other medically trained crew member, should have received adequate training in treating the effects of radiation exposure.

Other crew members involved in the operation of the NPP should be given operation theoretical courses and practical training commensurate with their official duties in the operation of the NPP and their muster list duties, as well as instructions on the use of personal health protection equipment. This training may be given in a training center or onboard ship by qualified engineer officers. The qualifications of the crew members referred to in this subsection should be to the satisfaction of the [34].

Crew members not involved in the operation of the NPP should be acquainted with the established procedures for entering controlled areas of the ship and with their muster list duties. They should also be familiar with the measures necessary to ensure their personal protection in the event of accidents resulting in high radiation.

All persons on board, including non-crew members, should have received instruction on health physics and radiation protection procedures before entering the controlled areas of the ship.

The practical training in NSSS control should be carried out on special simulators, or on ship or land-based facilities having NPP installations of the type the trainee will operate. Trainees should, without assistance, perform a sufficient number of reactor start-ups and shutdowns to demonstrate to the satisfaction of the MCA their competence to suitably control reactor operation under all PPCs.

Appropriate officers and NSSS operators should be regularly retrained, to update their qualifications in theory and in the safe operation of the NPP. The frequency and level of requalification training should be to the satisfaction of the MCA.

The qualifications and skills of crew members, in performing their assigned duties, should be exercised and improved by carrying out ship emergency and radiation alarm drills to the satisfaction of the MCA. The radiation alarm drills should simulate the probable damage and consequences of postulated accidents involving the NPP [34].

4.1.3 The Report on gap analysis of the Code of Safety for Nuclear Merchant Ships

A group of experts on nuclear reactor technology and safety standards at the World Nuclear Transport Institute (WNTI), the Nuclear Safety Task Force, has undertaken a detailed and thorough gap analysis of resolution A.491(XII) to demonstrate how [31] may be revised to be applicable to nuclear merchant ships, while meeting current international practice relating to nuclear safety standards set by the IAEA [34].

The WNTI Nuclear Safety Task Force gap analysis identifies, in particular, that the [31], in its current form, is not in line with current international practice based on a goal-setting approach to safety requirements and that it should be technology-neutral to accommodate emerging technologies. Furthermore, it identifies a range of other requirements for a revised Nuclear Code that will be fit for purpose in guiding the design and safety assessment of nuclear merchant ships.

The gap analysis provides a framework for creating a revised [31] that is consistent with current practice and follows a non-prescriptive, technology neutral approach. This includes the current nuclear safety requirements given in IAEA Safety Standards, International Commission on Radiological Protection recommendations, and SOLAS convention.

WNTI brought an outline of the Nuclear Safety Task Force gap analysis to the attention of the Correspondence Group on Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels due to its relevance to one of the terms of reference given to the Correspondence Group: namely, to “develop a record for safety obstacles and gaps in the current IMO instruments that may impede the use of the alternative fuel or new technology” [32].

The gap analysis undertaken by the WNTI Nuclear Safety Task Force has taken years to complete and gone through several thorough peer reviews prior to finalization. As promised, during WNTI’s engagement with the Correspondence Group referenced in the above paragraph, WNTI presented the gap analysis which identifies the sections of the [31] that require updates for it to be consistent with current international safety standards as they would apply to nuclear-powered merchant ships. This report is published [32].

4.1.4 Summary of findings

Education and training in the military or naval nuclear fleet of European countries like United Kingdom (UK), are part of one organization that is responsible for the whole life cycle of the nuclear propulsion program, ranging from research and development activities to construction, commissioning, maintenance, operation and disposal. Secondly, there are many indications that the education and training are given at a higher academic level that corresponds with the first and second cycles of the qualification’s framework for the European Higher Education Area (EHEA).

These education and training programs consist of teaching and learning activities, such as classroom lessons, laboratory work, simulator training and on-the-job training. Unfortunately, the literature available does not clarify the specific learning outcomes and objectives in terms of knowledge, skills and competence, but rather outlines the subjects that are taught.

Regarding the rules and regulations for the education and training of engineering officers on nuclear-powered ships, in addition to the STCW, [31] apply. The [34] has adopted [31] in [33]. However, IAEA has several updated publications and safety standards addressing the education and training of nuclear power plant personnel e.g., [35] and [36]. Considering that IMO will update [31], the foregoing standards and publications could have a significant impact on the education and training programs of engineer officers for nuclear-powered ships.

Thus, considering the available information and traditional training programs in maritime higher education institutions, should be considered the following proposals of education programs for engineer officers in nuclear-powered ships:

i) Specific Master of Science (MSc) program in Maritime Nuclear Operations in order to align with STCW Code Table A-III/2 – management level requirements (Specification of minimum standard of competence for chief engineer officers and second engineer officers on ships powered by main propulsion machinery of 3,000 kW propulsion power or more).

ii) Reviewed and modernized bachelor's degree (BSc) in marine engineering incorporating STCW requirements for engineer officers and the prerequisites for Master programs in nuclear engineering to align with STCW Code Table A-III/1 – operational level requirements (Specification of minimum standard of competence for officers in charge of an engineering watch in a manned engine-room or designated duty engineers in a periodically unmanned engine-room).

It is important to verify whether nuclear reactors like SMRs considered in NuProShip I project will have significant consequences for any education and training program [20]. Due to the safety aspects of the nuclear power and maritime industries and considering that shipping is an international concern, it will be natural for the existing rules and regulations of the maritime and nuclear domains to be revised and harmonized, particularly emerging nuclear technologies. The results of such initiatives may have a material impact on the design of education and training programs for engineering officers on nuclear-powered merchant ships.

There may also be a need to elucidate the contrast existing between work cultures of the maritime industry and the nuclear power industry, especially regarding safety culture. Further, solutions to alleviate such contrasts should be generated for the benefit of the upcoming nuclear-powered merchant fleets [27].

It is crucial to develop detailed learning outcomes, teaching and learning activities and assessment tasks with ECTS that fulfil the needs of the industry and the regulatory bodies of the maritime and nuclear domains. This initiative assumes that the preferred reactor technology, like SMRs is in place, together with the associated regulatory framework. Before a detailed program description for the education and training for seafarers of nuclear-powered ships can be developed, efforts should be made by national and international authorities concerning maritime and nuclear regulations for achieving updated and harmonized international rules and regulations.

4.2 Recommendations for qualifications of engineering personnel of nuclear-powered ships

The section presents summary recommendations, based on task analysis, concerning training and other qualification requirements appropriate for personnel to serve on future new commercial nuclear ships. Training content and type (classroom, shoreside practical/simulation, onboard) are recommended for 12 personnel functional areas. The study described in this section is seen as an initial step in the process of developing marine nuclear personnel requirements.

Pertinent existing standards and legal requirements are taken into account in the recommendations; however, the need for regulatory guidelines specific to the Merchant Marine environment is identified. The task data presented offer a basis for specific training curriculum development once the regulatory guidelines are defined. In addition to the task data and summary recommendations, the report is a compendium of reference materials including description of the design proposals for new nuclear commercial ships; discussion of nuclear hazards; description of existing standards and legal requirements; and summaries of nuclear personnel requirements for the utilities, the U.S. Navy, and on the prototype ship NS SAVANNAH.

4.2.1 Maritime education and training for nuclear powered ships

All maritime education must follow the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers 78 as Amended (STCW) and additional national requirements. In Norway, the regulation FOR2011-12-22 nr. 1523 Forskrift om kvalifikasjoner og sertifikater for sjøfolk applies. National requirements cover STCW requirements and additional national requirements beyond the international requirements from STCW.

The International Maritime Organization, IMO, sets the regulatory framework through STCW. The STCW Convention and Code defines the international regulatory framework for education of seafarers in all positions across the world.

Standard competencies are covered by the educational programs, while specialized competencies must be achieved as an addition to the educational program.

Requirements on extended competencies for specialized vessels such as e.g. tankers, passenger vessels, etc. are defined through own regulations and competency tables within the STCW Convention and Code. These regulations and tables define the required competence for e.g. tankerman certificates.

Requirements from STCW Convention for officers:

- Deck officer, operational level – STCW regulation A-II/1, section A-II/1 and table A-II/1.
- Deck officer, management level – STCW regulation A-II/2, section A-II/2 and table A-II/2.
- Engine officer, operational level – STCW regulation A-III/1, section A-III/1 and table A-III/1.
- Engine officer, management level – STCW regulation A-III/2, section A-III/2 and table A-III/2.
- Electrotechnical officer (ETO), operational level – STCW regulation A-III/6, section A-III/6 and table A-III/6.

4.2.2 Norwegian maritime education framework

In Norway, there are several ways of completing maritime education and becoming a deck or engine officer:

- High school (maritime) + apprentice on board + vocational college + cadet on board (2 years + 2 years + 2 years + 6 months) – the majority of deck and engine officers in Norway have completed this educational path.
- High school (maritime) + apprentice on board + vocational Bachelor of Nautical Science or vocational Bachelor of Marine Engineering + cadet on board (2 years + 2 years + 3 years + 6 months).
- High school (study specialization) + Bachelor of Nautical Science or Bachelor of Marine Engineering + cadet on board (3 years + 3 years + 12 months).

In addition to completing the educational program for the relevant position, it is necessary to complete tankerman training when working onboard specialized vessels, such as a tanker.

Tankerman training is divided into two different levels, where personnel participating in operations must complete the basic training or have 90 days sea time and personnel leading operations must complete the advanced training (basic training is a prerequisite for the advanced training). In addition, it is necessary to have 90 days sea time on tankers to apply for the tankerman certificate.

Tankerman advanced training + 90 days sea time = Certificate of Competence (CoP) tankerman highest grade.

The existing complete list of certificates for familiarization and specialization for the three types of tankers (oil, chemical and gas tankers), are the following:

Familiarization training according STCW Convention:

- BASIC TRAINING FOR OIL AND CHEMICAL TANKERS, in compliance with the contents of paragraph 1 in section A-V/1-1 (table A-V/1-1-1);

- BASIC TRAINING FOR LIQUEFIED GAS TANKERS, in compliance with the contents of paragraph 1 in section A-V/1-2 (table A-V/1-2-1).

Specialization training according STCW Convention:

- ADVANCED TRAINING FOR OIL TANKERS, in compliance with the contents in section A-V/1-1 (table A-V/1-1-2);
- ADVANCED TRAINING FOR CHEMICAL TANKERS, in compliance with the contents of section A-V/1-1 (table A-V/1-1-3);
- ADVANCED TRAINING FOR LIQUEFIED GAS TANKERS, in compliance with the contents of section A-V/1-2 (table A-V/1-2-2).

4.2.3 Norwegian vessels for which the INTERNATIONAL CODE OF SAFETY FOR SHIP USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE) applies

IGF basic training or CoP tankerman for Gas Tankers + valid health declaration and CoP safety training (basic or advanced) = CoP IGF Basic.

There are several alternatives to qualify for IGF advanced. All alternatives require valid health declaration and CoP safety training (basic or advanced), training (several alternatives) and practical experience/sea time (several alternatives).

The complete list of certificates for familiarization and specialization for vessels for which the IGF Code applies, are the following:

- Familiarization training according STCW Convention:

  BASIC TRAINING FOR SHIPS SUBJECT TO THE INTERNATIONAL CODE OF SAFETY FOR SHIP USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE), in compliance with the contents in table A-V/3-1.

- Specialization training according STCW Convention:

  ADVANCED TRAINING FOR SHIPS SUBJECT TO THE INTERNATIONAL CODE OF SAFETY FOR SHIP USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE), in compliance with the contents in table A-V/3-2.

4.2.4 Certificates and documentation

In shipping industry, there are several types of documentation which is included in a seafarer's total documentation:

1. Certificate of Competency (CoC) – the CoC is a certificate issued and endorsed for masters, officers and GMDSS radio operators in accordance with the provisions of Chapters II, III, IV or VII of the STCW which entitles the lawful holder of the certificate to serve in the capacity and perform functions involved at the level of responsibility specified therein (STCW 78 as Amended).
2. Certificate of Proficiency (CoP) – the CoP is a certificate, other than a certificate of competency issued to a seafarer, stating that the relevant requirements of training, competencies or seagoing service in the Convention have been met (STCW 78 as Amended).

3. Documentary evidence - documentary evidence is documentation, other than a certificate of competency or certificate of proficiency, used to establish that the relevant requirements of the Convention have been met (STCW 78 as Amended). Documentary evidence can e.g. be a course certificate, course diploma, etc.

4.2.5 Nuclear powered vessels

In the tanker trade today, the regulatory framework is fixed. In addition, there are several other requirements which also come into force, from industry, charterers, makers and own company. This means that the certificate and course matrixes in the tanker trade are quite complex. In addition to the already existing requirements, it will be necessary to include vessel specific training for nuclear powered vessels.

In order to find the correct level for vessel specific training, it is important to secure a regulatory framework for Nuclear Powered Vessels. This regulatory framework can be included in STCW Chapter V which contains the standards regarding special training requirements for personnel on certain types of ships or be developed as a separate code (based on a highly necessary revision of the existing nuclear code). As followed by IMO for tankers and vessels for which the IGF Code applies, the regulatory framework must encompass two training levels: basic and advanced training, and two certification levels: lowest and highest grade.

Based on the regulatory framework, training needs to be developed. In order to be in line with the hierarchy of the STCW, we suggest the following:

- CoP for Nuclear Powered Vessels – highest grade and lowest grade – maritime education in collaboration with maker provide advanced training for personnel on nuclear powered vessels, and maritime education institutions provide basic training for personnel on nuclear powered vessels.
    - CoP Nuclear Powered Vessels – highest grade – advanced technical and operational understanding and competence on nuclear powered vessels.
    - CoP Nuclear Powered Vessels – lowest grade – basic technical and operational understanding and competence on nuclear powered vessels.
- CoP for Safety Training in Nuclear Powered Vessels – highest and lowest grade.
    - CoP for Safety Training in Nuclear Powered Vessels – highest grade – advanced safety knowledge, skills and understanding relevant for nuclear powered vessels.
    - CoP Safety Training Nuclear Powered Vessels – lowest grade – basic safety knowledge, skills and understanding relevant for nuclear powered vessels.

In the certificate matrix of a given nuclear-powered vessel, such requirements can look like the one found in Table 35. Please note that one engine officer position and one engine rating position is removed compared to ordinary LNG tanker manning, as per info discussed in the subsequent paragraph.

Table 35 – Certificate matrix that can be applicable.

		POSITIONS																				
Certificates	Validity	Master	Chief officer	2nd Officer	3rd Officer	Senior Deck cadet	Deck cadet	Chief engineer	Cargo engineer	2 engineer	3 engineer	Engine cadet	Electrician ETO	Electrician cadet	Bosun	Pumpman	AB	OS	Fitter	Motorman	Ch. Steward/Cook	Messman/Boy
CoP Nuclear powered vessels highest grade	5y							M		M	M	M	M	M								
CoP Nuclear powered vessels lowest grade	5y	M	M	M	M				M						M	M	M	M	M	M		
CoP Safety training nuclear powered vessels highest grade	5y	M	M	M	M			M	M	M	M		M		M	M						
CoP Safety training nuclear powered vessels lowest grade	5y					M	M					M		M			M	M	M	M	M	M

When established the regulatory framework for personnel working on nuclear powered vessels, it will be important to look into the manning requirements for such vessels. From our point of view, it may be possible to reduce manning in the engine department by at least one engineer and one rating, as the equipment on board a nuclear-powered vessel will require less maintenance than the equipment found on board vessels today.

4.2.6 Nuclear powered vessels – Emergency Response Management Team

In addition to establishing requirements for the on-board personnel, competency requirements for the shore organization’s Emergency Response Management Team (ERMT) must be developed. We suggest that the shore organization ERMT must have at least two members with competence on CoP Nuclear Powered Vessels highest grade and CoP in Safety Training for Nuclear Powered Vessels highest grade or similar. It would be beneficial if own courses for the ERMT is developed in order for the whole team to be well prepared in case of emergency situations.

4.3 Remote operation of nuclear-powered ships

One of the challenges of nuclear power in commercial shipping is the need for personnel with a high level of competence in case of nuclear accidents. Even with the safest type of reactors there could arise situations that require expert knowledge of nuclear physics. The problem is that these experts’ knowledge would not be needed in the daily operation of the ship and the situations that their competence would be needed will be extremely rare. Earlier, when commercial nuclear-powered vessels where in operation like Savannah, Otto Hahn and Mutsu, the training regime of the engineers were quite extensive. The reason for this is because these ships were operational in the 1960’s and 70’s.

This era, without modern communication technology required the crew onboard to have the necessary skills and competence to handle any situation that could emerge onboard the ship. They were in open waters and without any means of support from outside resources. Today, this has changed. Technology allows remote support, remote control and other means of accessing competence that means it is not necessary to have personnel with rarely needed expert competence physically located onboard the ships. This technology could be an important factor in making nuclear propulsion a viable solution for the merchant shipping fleet by removing the need to train the ship engineers to a high level of competence in nuclear physics that would be costly and very time-consuming activity.

The term ‘remote operations’ is not easily defined. It is often seen as interchangeable with remote control and autonomous operations, but it is also used as a description of operations that involves personnel located at a distant location [37]. For the case of nuclear propulsion, this definition of remote operations, as a method of conducting an operation where outside personnel are involved in the work and decisions, is an interesting approach.

A likely scenario for nuclear powered merchant vessels will be experts located in an onshore control room that monitors the reactor for any issues and advice the engineers onboard if there are any actions needed. This situation has several common features with what is known as integrated operations that has become a standard operating method in the oil and gas sector. Integrated operations in the oil and gas sector have evolved over the last 20 years and in some areas, like the North Sea, it involves remote control and unmanned platforms. It is therefore useful to investigate lessons learned from the oil and gas industry for relevant information for the shipping industry.

In Norway a start of implementing integrated operations can be traced back to 2003 when the Norwegian oil and gas association (OLF) recommended that integrated operations (IO) should be implemented to increase safety and efficiency. Even though this seems like IO was decided it was also a consequence of a series of emerging technologies that made the transition possible [38, 39]. Two types of technologies can be highlighted in respect to the relevance for the operation of nuclear propulsion. One is the fiber optic communication lines that were installed in late 1990's to oilrigs and production platforms in the North Sea. These communication lines allowed broadband communication platforms like video conferencing and high-speed data transfer allowing people onshore access to the same information as people offshore.

The second technology that were important were more advanced real-time instruments that gave experts better understanding of the geology that were drilled and allowed them to make decisions in real time. The experts that can make these decisions are scarce, even in large organizations like oil companies and they are located onshore in the main headquarters. Consequently, both as a result of technological development, and as a strategic decision to improve operational efficiency, the use of onshore control centers became a natural part of the drilling operation.

This concept known as integrated operation have continued to evolve over the years since the beginnings in the early 2000's and it has led to a significant amount of research and development of standards for such operations. As there are significant benefits for both efficiency and safety there are also many pitfalls and complex challenges that needs to be overcome. One major challenge is the fact that such operations is not just a technological development, but it also requires the involved personnel both onshore and offshore to have a shared cognitive understanding of the operation. This means that work processes, responsibilities and competences need to be adapted to facilitate such operations. For the oil and gas industry this transition to IO took several years and now they describe the transition as Generation 1 and Generation 2.

During the first generation the onshore control centers started as a support organization and the majority of decision and control were still located offshore. As technology developed and the quality of digital cooperative tools increased the role of the onshore control center became more important. New offshore installations were designed to have control centers that could accommodate collaboration with onshore control centers.

This led the ground for Generation 2 where Integrated operation became Remote Operations. The start of this transition to remote operations happened around 2015 when skepticism and fear of job loss caused by moving jobs from offshore to onshore had subsided. The focus among companies involved changed from technical challenges involved in remote control to viewing remote operations as socio-technical systems [40]. This means that operational considerations which include technical solutions, organization and competence were included in the concept of remote operations.

Another aspect of the transition from integrated operations to remote operations is the transition from collaboration between an offshore control center and an onshore control center to collaboration between a network of centers. Drilling operations involves an extensive number of companies and partners, and it is not practical nor useful to have them present at all times in one control centers. This means that remote operations currently involve several centers that monitors and perform their work and collaborates as needed with the other supplier centers and offshore locations [40, 41].

The way forward for remote operations seems to focus on integrating the “remote” part of the operation and to focus on issues of safety that the inclusion of several remote centers introduces. The primary safety concerns using several locations are connected to cyber security and using “open” networks that is not point to point. This means that the possibility of hostile interests can gain access to information and even gain control of critical operations becomes a possibility that needs to be controlled.

Remote operations as a way of organizing nuclear propulsion on merchant ships can benefit from experiences from the oil and gas industry. The first finding is that remote operation of complex technology is indeed an option and that it increases efficiency by utilizing expert competence available onshore and reduces safety issues as it can reduce human presence in harmful environments.

The second finding is that the process of turning an operation that were performed offshore with experts at the worksite to a remote operation with experts located at different physical places was challenging and took a long time. For the oil and gas industry the transition has taken two decades and it is still ongoing [40].

A third finding is that cybersecurity is an ongoing challenge when using ICT in remote operations. A starting point when evaluating remote operations for operating nuclear propulsion for merchant shipping is to study how remote operations have been used in other areas like drilling operations. Identifying success factors and learnings from comparable applications can reduce uncertainty and establish a successful approach. This might reduce the time and effort to establish remote operations as the principal way of operating nuclear reactors onboard merchant ships. It is also very important to consider the risks of cyber threats and incorporate safety mechanisms as an integral part of the operation [42].

4.4 Remote connections and use of big data in vessel fleet operations

The Knutsen group has several systems on its ships available for remote service and monitoring. Some are engine manufacturers, turbo charger manufacturers, ballast treatment manufacturers and automation systems. We can divide our remote connection into following main groups:

- Performance monitoring
- Remote assistance and fault finding
- Condition monitoring

We consider all the above as highly relevant in conjunction with use of nuclear-powered machinery.

4.4.1 Performance monitoring

Most of our assets are equipped with ship performance monitoring systems to ensure efficient operation and monitoring of energy and fuel consumption. Those systems are also linked up to fleet performance overview, etc. and we can grant access to charters and other when needed.

4.4.2 Remote assistance and fault finding

The ship automation system for machinery and cargo equipment has been remote serviced for years and enables Knutsen to grant vendor access within minutes when required. This significantly reduces any downtime and potential consequences for the vessel’s operation and equipment.

Key factors for this success are to select an appropriate vendor with the capacity to provide assistance 24/7, knowledge to advise and attention to cyber security.

Combined with strict internal procedures managed by our cyber security team we have a system that is safe and effective for troubleshooting and upgrades on our systems.

4.4.3 Condition monitoring

The vessels are equipped with vibration monitoring on key equipment, for the equipment deemed most critical the vibration measurement together with other key data is lived streamed to an operation center that monitors the condition 24/7 and contact vessel and office personnel via phone or email, depending on the severity of the situation.

Dedicated teams of experts are available to embark on any vessel to perform planned maintenance and emergency repairs in collaboration with the crew. With their years of experience and training they ensure the highest quality and lowest down time for the vessels.

Logs are extracted from our systems and sent to experts ashore for analysis at regular intervals, giving advice on service and the functioning of the systems.

4.4.4 Knutsen Group in the future

Knutsen is currently collecting near real-time sensor data from its vessels. All sensor data will be stored together enabling Knutsen Group to apply machine learning, AI, algorithms, trends and alarms across its vessels. The consolidation of all data provides the opportunity to learn across vessels with the same maker, conditions, and equipment type, enabling the prediction of failures before they occur. Combining all the data with augmented reality glasses for each ship, we have quick access to assist or service the vessels with subject experts onshore together with a well-trained crew onboard.

4.5 Regulatory and organizational challenges in implementing nuclear propulsion in deep-sea shipping – simulator for crew training

The main topic of discussion of his study is centered around past, existing and future training requirements and how maritime universities can incorporate essential courses on traditional nuclear technology alongside high-fidelity digital twin models that can also be used to control predictive maintenance and develop model-based full detection systems for innovative advanced reactor designs. Hence, this study will focus on today’s digitalization, communication and automation technologies that can use computation as a direct tool to shorten the development cycle of new nuclear propulsion technologies as well as reduce crew size and operational requirements, making the transition to nuclear propulsion in deep-sea shipping less demanding. Furthermore, the current status on availability of trained mariners and the maritime industry’s ability to supply the amount of skilled crew necessary for nuclear propulsion should be also addressed at the end.

4.5.1 Proposed Methodology

Basically, the method proposed herein consists in using PWR as a case study first, so that high-fidelity digital twin models can be developed for the time being as a nuclear propulsion simulator. Next step proposed herein is to adapt, modify and calibrate the PWR nuclear propulsion simulator to special reactors such as X-energy and Kairos Power pebble bed reactors or even the TerraPower that is developing a liquid metal cooled travelling wave reactor as well as a molten chloride fast spectrum reactor.

According to [43], advances in parallel computing have made possible the development of high-fidelity tools for the design and analysis of nuclear reactor cores, and such tools require extensive Verification, Validation and Uncertainty Quantification (VVUQ). In [43], a new multi-cycle full-core PWR depletion benchmark is described. This study conducted at MIT was based on two operational cycles of an American commercial nuclear power plant that provided a detailed description of fuel assemblies, burnable absorbers, in-core fission detectors, core loading patterns, and numerous in-vessel components.

This benchmark enabled analysts to develop extremely detailed reactor core models that could be used for testing and validation of coupled neutron transport, thermal-hydraulics, and fuel isotopic depletion. The benchmark also provided measured reactor data for Hot Zero Power (HZP) physics tests, boron letdown curves, and three-dimensional in-core flux maps from fifty-eight instrumented assemblies. It should be noted however, that not all the necessary data are presented in this document, and therefore, even for the purpose of development of a PWR propulsion simulator, it will be necessary for nuclear energy experts to make appropriate judgements, assumptions and adaptions from a land-based power plant to a marine propulsion plant.

Namely, it is proposed to have a resource and a protocol in place between ENIDH and Instituto de Plasmas e Fusao Nuclear of Instituto Superior Tecnico (IPFN/IST) and a company specialized in 3D geometric modelling of vessels and marine systems (e.g., KDS Offshore) to proper address these nuclear engineering aspects in the demonstration of a simulator for crew training to be developed during NuPropShip II. In particular, requirements on the crew that must be thoroughly identified and analyzed via the traditional approach to assess Reliability, Availability, Maintainability and Inspectability (RAMI) of a generic nuclear power plant. These should be based on Block Sim regulations and codes of practice as those proposed by ReliaSoft.

However, in these generic codes of practice many simplifications need to be introduced. In particular, a new approach to assess RAMI characteristics based on Digital Twin (DT) models of the entire vessel and the machinery and nuclear reactor spaces along with high-fidelity Virtual Reality (VR) simulations tools must be developed to allow a new simulation-based design technique called direct analysis of crew performance and RAMI characteristics to address this practical need. Further refinement of different nuclear power options requirements by updating criteria and creating preliminary life-cycle maintenance and inspection plans should be devised. The selection process of the most favorable reactor technology for marine purposes will culminate with the release of an updated OPEX estimate from the crew performance and RAMI studies conducted by ENIDH.

After the initial step in the development process of a marine propulsion simulator described above, it is time to also implement the Physical Inventory (PhI), the so-called Perimeter Intrusion Detection System (PIDAS) and the Security-by-Design (SbD) features. Note that, according to [44], in the PhI, all the nuclear plant command & control systems must provide tracking historical inventory, reconciling records with physical inventory, digitally tracking special nuclear material, simulating what-if scenarios of missing or defective items, and ensuring that physical inventories meet regulatory acceptance criteria. In respect to PIDAS, the following safety features are required: 1) automated classifying of nuisance alarms across different sensor modalities, 2) leveraging sensor self-diagnostics to meet regulatory requirements for periodic testing, 3) detecting anomalies and 4) predicting sensor failures.

Finally, in respect to SbD, the following security features are deemed as required: 1) identifying gaps in addressing design basis threats, 2) incorporating security by-design into the facility, 3) planning and preparing for changes in design basis threat and 4) upcoming security scenarios. Still according to [44], these features require extensive use of Data and Information Management (DIM) and Model Based Design (MBD) principles in developing these sophisticated DT models, whose architecture is illustrated in Figure 38. Notice should be given to the formal definition of a DT as a virtual representation of an entity, process, or system, synchronized at a frequency and fidelity sufficient to maintain state concurrence. Moreover, a DT must leverage various types of models, data, and frameworks to produce knowledge/insights about the represented entity, process, or system to fulfill an intended purpose.

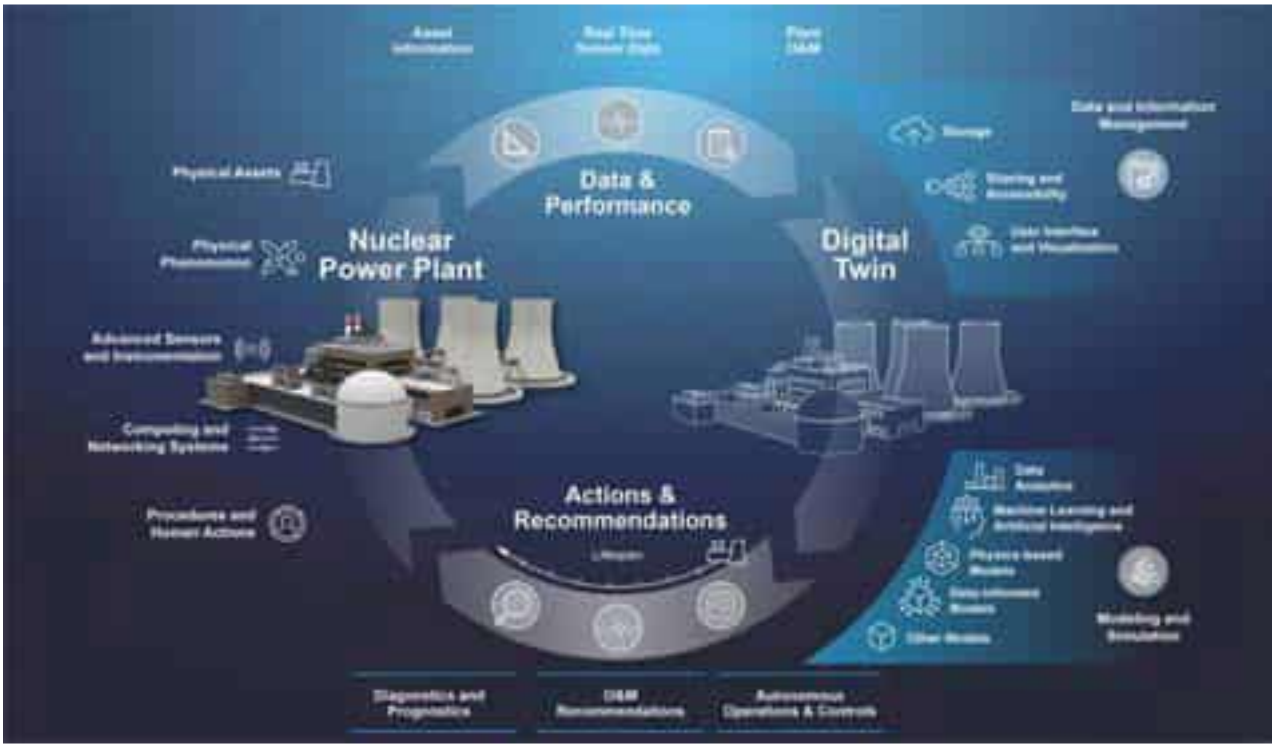


Figure 38 – Description of digital twin for nuclear power plant applications. Source: [44].

As illustrated in Figure 39, the main four characteristics of a Nuclear Power Plant (NPP) digital twin are:

i) Exists in digital form: The technologies and information that form part of a DT must exist in a digital form that can be managed, processed, communicated, and executed using digital technology. It is important that this characteristic be explicitly defined for applications in the nuclear industry, which has a legacy of information sharing via non-digital formats (e.g., paper).

ii) Maintains state concurrence: The DT must be able to update dynamically to represent the current state of a physical entity or phenomenon, and it must be able to maintain that state. This vital condition differentiates a DT from an existing modeling or simulation capabilities that can run in digital form but do not maintain concurrence with the actual system in real time.

iii) Ensures state cognizance: The DT must be able to provide new and integrated sets of insights, information, relationships, and outcomes—all pertaining to the physical entity being twinned, and all made possible, feasible, or efficient with DT technology. State cognizance is an important characteristic that ensures DTs do not simply recreate preexisting capabilities but add a unique and novel value to the selected application.

iv) Serves an underlying purpose: The technology must have an underlying purpose related to an NPP life cycle activity, and that purpose should inform decisions about the system or component represented.

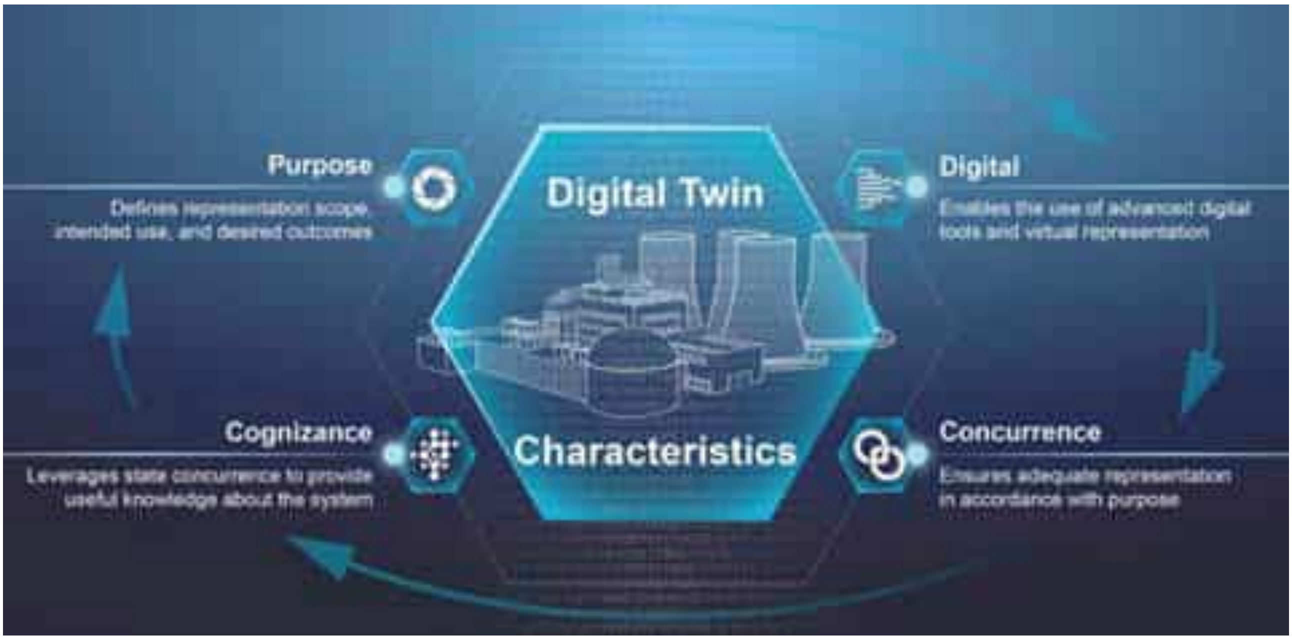


Figure 39 – The four characteristics of a nuclear digital twin system digital twin. Source: [44].

Finally, as illustrated in Figure 40, the envisaged seven capabilities of a Nuclear Propulsion Digital Twin System (NPDTS) adapted/extended from [44] and proposed in this preliminary study are:

i) Communication: Propagates information among the various DT-enabling technologies and among nuclear DT stakeholders to facilitate deeper insights and new cognizance of plant states.

ii) Information: Provides new and improved plant information that is trusted, timely, on-demand, correct, and complete enabled by state concurrence and state cognizance.

iii) Analysis: Leverages analytical products to produce, process, and represent information about a plant's current, past, and future states.

iv) Control: Combines classical and novel frameworks that leverage advance technologies such as Machine Learning/Artificial Intelligence, state prediction, advanced and virtual sensors multiple real-time input and output systems to enable operations that are adaptive, optimal, robust, and autonomous.

v) Integration: Establishes a centralized hub and enabler for the integration of a variety of data, information, models, and analytics to address the underlying DT purpose in a reliable and accurate manner.

vi) Simulation: In addition to five capabilities above, allows advanced analytical tools to produce, process, and represent information about a plant's current, past, and future states, as well as provide insights to support decision making and risk assessments.

vii) Training: Allows via simulation operators to train all life cycle activities, and for that purpose should inform decisions about the system or component represented in a fully interactive manner.

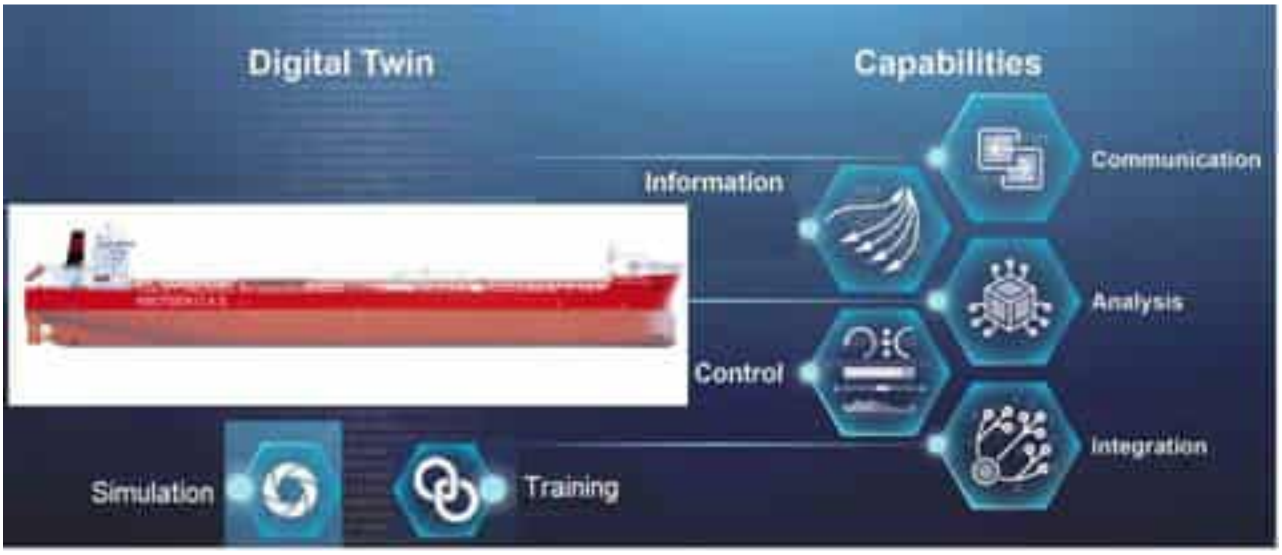


Figure 40 – The seven envisaged capabilities of a nuclear propulsion digital twin system. Adapted from [44].

4.5.2 Discussion

In terms of training of personnel for nuclear power plants and nuclear safety, the International Atomic Energy Agency (IAEA)'s safety guides and standards regarding qualification and training [36], present best practices and have been partly developed in collaboration with the European Union (EU) and other international and national organizations. Moreover, the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) does not cover manning and training for merchant nuclear-powered ships. Therefore, supplementary and fully dedicated education and training programs for the crew of new merchant nuclear-powered vessels is absolutely necessary.

It is believed that such education and training programs can be more rapidly and economically attained via a specific NPDTS jointly developed by the nuclear reactor manufacturers and the ship designers after the system being approved by the regulatory bodies. Note that over the last five decades, education and training of the US Navy personnel comprised teaching and learning activities such as classroom lessons, laboratory work, simulator training and on-the-job training aboard a nuclear vessel for the duration of one year at the end of the teaching block. Unfortunately, the syllabus of these courses devised by the US Navy and the US Department of Energy are confidential and therefore there are no outlines available of the subjects that are taught to assist the task of clarifying the specific learning outcomes and objectives in terms of knowledge, skills and competencies although these can be envisaged by more experienced nuclear professionals.

To conclude the discussion about the simulator for training nuclear propulsion in deep-sea shipping after extensive VVUQ process has been conducted, notice should be given to the fact that existing Modelling & Simulation (M&S) tools may have limitations such as incorporating nuclear plant operational cost estimates, human factors, operator actions, realistic data, and effects of environmental and meteorological and oceanographic (meteocean) conditions. However, addressing these limitations could also result in benefits, such as more accurate cost estimates and M&S results, higher reliability, reduced uncertainty, and a faster decision-making process. Enhancing the M&S capabilities to address limitations in developing a NPDTS could be a complex task owing to limited information and historical data and sometimes not understanding a certain physical phenomenon. One of the gaps to increase realism in M&S lies in developing DT-enabling technologies, such as sensors and instrumentation, real-time data acquisition systems, and communication technologies. Despite all that, information and data from such DT-enabling technologies (MBD and DIM) could be applied toward increased qualitative and quantitative insights in operational models, as well as component performance and reliability data to narrow this fidelity gap.

Providing economic viability of the nuclear propulsion in deep-sea shipping is attained in the future, then it is believed that training simulators of nuclear propulsion systems can be readily developed using high-fidelity digital twin models to train crew personnel, control predictive maintenance and develop model-based full detection systems for innovative advanced reactor designs.

5.0 Closure remarks

The NuProShip I project is now commencing into the NuProShip II project where all the questions that are not addressed fully in this report will be researched further. The fact is that the objective of providing nuclear propulsion for merchant ships is a major undertaking that this first project report only starts addressing. In fact, we believe that the transition to nuclear propelled ships will become as monumental as from sails to fossil fueled propulsion systems.

The most important outcome so far is the selection of reactor technologies and the realization that we need different reactor technologies for different ship types depending on their operational modes and sizes.

We have also started on the very complex road of regulations, classification, ship design, crew requirements and more. These issues are very complex and will probably be ongoing issues for years to come. However, we have a very clear outcome in that we have a firm understanding of what has been done so far, upon which we can build and develop.

Most importantly, we have managed to start working constructively towards our objective at a speed that is highly satisfying. Provided that we are able to secure the right amount of funding in years to come, we foresee that demonstration projects should be launched sometimes between 2030 and 2035.

6.0 Acknowledgment

We highly appreciate the funding provided by the Research Council of Norway for conducting this project (project ID is 336539).

In particular, we value to excellent cooperation we have had with our vendors:

- Kairos Power – Per Peterson, Robey Clark, Zach Marquez and Jeff Olson.
- Ultra-Safe Nuclear Corporation – Francesco Venneri, Paolo Venneri, Wesley Deason and Hallgeir Juliebø.
- Blykalla – Janne Wallenius and John Lund.
- Sempre – Robert Spalding.
- Burges Salmon – Ian Salter.

We would like to express our gratitude towards Knutsen OAS for providing information about its LNG tankers, particularly the Cadiz Knutsen, including General Arrangements and much more, that has enabled proper discussions and work on real ships.

We would also like to thank the vendors that provided us with material after the initial exclusion round, so we could complete the final selection round. They are Terrestrial Energy, Seaborg Technologies, Moltex Energy and MicroURANUS Corp.

Finally, we would like to thank people that we have met with and discussed nuclear propulsion for merchant ships over the years.

7.0 References

1. UNCTAD, *Review of Maritime Transport 2023*. 2023, United Nations, United Nations Conference on Trade and Development (UNCTAD): New York. p. 126.
2. Olmer, N., B. Comer, B. Roy, X. Mao, and D. Rutherford, *Greenhouse Gas Emissions from Global Shipping, 2013–2015*. 2017, International Council on Clean Transportation (ICCT): Washington, DC. p. 27.
3. King, A., *Emissions-free sailing is full steam ahead for ocean-going shipping*, in *Horizon - the EU Research & Innovation Magazine*. 2022, European Commission. Accessed 2023-10-15 from https://ec.europa.eu/research-and-innovation/en/horizon-magazine/emissions-free-sailing-full-steam-ahead-ocean-going-shipping.
4. Forskningsrådet, *Maritim21-strategi*. 2022, Norges Forskningsråd (Research Council of Norway): Oslo. Accessed 2022-01-15 from https://www.maritim21.no/siteassets/maritim21_final.pdf.
5. Argyros, D., C. Raucci, N. Sabio, and T. Smith, *Global Marine Fuel Trends 2030*. 2014, Lloyd's Register Group Limited (LR) and the University College London (UCL): London. p. 59.
6. Concawe, *Marine Fuel Facts*. 2017: Brussels. Accessed 2024-04-20 from https://www.concawe.eu/wp-content/uploads/2017/01/marine_factsheet_web.pdf.
7. Jacoby, M., *The shipping industry looks for green fuels*, in *Chemical & Engineering News*. 2022, American Chemical Society. Accessed 2023-04-23 from https://cen.acs.org/environment/greenhouse-gases/shipping-industry-looks-green-fuels/100/i8.
8. Emblemsvåg, J., *Fremtiden til grønne maritime drivstoff i Norge – en energianalyse.* Naturen, 2025. **150**: p. Accepted for publication.
9. Emblemsvåg, J., *A Study on the Limitations of Green Alternative Fuels in Global Shipping in the Foreseeable Future.* Journal of Marine Science and Engineering, 2025. **13**(79): doi.org/10.3390/jmse13010079.
10. Schøyen, H. and K. Steger-Jensen, *Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications.* Journal of Cleaner Production, 2017. **169**: p. 152-160.
11. Kamei, T., *Implementation Strategy of Thorium Nuclear Power in the Context of Global Warming*, in *Nuclear Power: Deployment, Operation and Sustainability*, P. Tsvetkov, Editor. 2011, InTech: Rijeka. p. 365-382.
12. Emblemsvåg, J., *How Thorium-based Molten Salt Reactor can provide clean, safe and cost-effective technology for deep-sea shipping.* Marine Technology Socieity Journal, 2021. **55**(1): p. 56-72.
13. IAEA, *Advances in Small Modular Reactor Technology Developments - A Supplement to: IAEA Advanced Reactors Information System (ARIS)*, in *IAEA Nuclear Energy Series*. 2022, International Atomic Energy Agency (IAEA), Department of Nuclear Energy, Nuclear Power Technology Development Section (NPTDS): Wien. p. 343.
14. Kelly, J.E., *Generation IV International Forum: A decade of progress through international cooperation.* Progress in Nuclear Energy, 2014. **77**: p. 240-246.
15. Saaty, T.L., *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*. Third ed. 2001, Pittsburgh: RWS Publications. 335.
16. Saaty, T.L. and E. Forsman, *The Hierarchon: A Dictionary of Hierarchies*. 1992, Arlington, VA: Expert Choice, Inc.
17. Bhutta, K.S. and F. Huq, *Supplier selection process: a comparison of the Total Cost of Ownership and the Analytic Hierarchy Process approaches.* Supply Chain Management: An International Journal, 2002. **7**(3): p. 126-135.
18. Cheng, E.W.L. and H. Li, *Analytic Hierarchy Process: An Approach to Determine Measures for Business Performance.* Measuring Business Excellence, 2001. **5**(3): p. 30-36.
19. Emblemsvåg, J. and L. Tonning, *Decision Support in Selecting Maintenance Organization.* Journal of Quality in Maintenance Engineering, 2003. **9**(1): p. 11-24.

20. Emblemsvåg, J., C.H. Ordoñez, C.G. Tamm, T. Strand, H. Thoresen*, et al.*, *Criteria for Selecting Nuclear Reactors for Merchant Shipping*, in *31st International Conference on Nuclear Engineering (ICONE31)* 2024, American Society of Mechanical Engineers (ASME): Prague. ICONE31-135177.
21. Emblemsvåg, J., T. Strand, H. Thoresen, C.H. Ordoñez, C.G. Tamm*, et al.*, *Selecting and ranking nuclear reactors for merchant shipping*, in *International Conference on Small Modular Reactors and their Applications*. 2024, International Atomic Energy Agency (IAEA): Vienna, 21–25 October. Accepted for publication.
22. Daniels, A.S.J., *After Fukushima: What We Now Know - A History of Nuclear Power & Radiation*. 2016, Charleston, SC: Amazon. 378.
23. Kim, S.I. and K.J. Lee, *Investigation on the Polonium Problem in Lead-Bismuth Coolant for Nuclear Reactors* in *Proceedings of the Korean Nuclear Society Spring Meeting* 2003, Korean Nuclear Society: Gyeongju, Korea, May 2003.
24. US DOE, *TRISO Particles: The Most Robust Nuclear Fuel on Earth*. 2024, United States Department of Energy, Office of Energy Efficiency & Renewable Energy: Online. Accessed 2024-12-10 from https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth.
25. EPRI, *Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance - Topical Report EPRI-AR-1(NP)*. 2019, Electric Power Research Institute (EPRI): Palo Alto, CA. p. 192.
26. Saaty, T.L. and L.G. Vargas, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*. International Series in Operations Research & Management Science. 2012, New York, NY: Springer. doi.org/10.1007/978-1-4614-3597-6.
27. Morland, E., *Competence, education and training for nuclear merchant marine propulsion - an integrative literature review*, in *Faculty of Technology, Natural Sciences and Maritime Sciences*. 2023, University of South-Eastern Norway: Borre, Vestfold.
28. ABS, *ABS advisory on decarbonization applications for power generation and propulsion systems*. 2021, American Bureau of Shipping (ABS): Spring, TX. p. 75.
29. Pareliussen, B., E. Morland, L. Baptista, R. e'Silva, E. Ovrum*, et al.*, *Regulatory and organizational challenges in implementing nuclear propulsion in deep-sea shipping* in *1st International Conference on Sustainable Initiatives in Maritime Sector: Main Challenges and Future Trends, June 17-19, 2024*. 2024: Oeiras, Lisboa.
30. IMO, *International Convention on Standards of Training, Certification and Watchkeeping for Seafarers*. 2011, International Maritime Organization (IMO): London.
31. IMO, *RESOLUTION A.491(XII) adopted on 19 November 1981 Code of Safety for Nuclear Merchant Ships*. 1981, International Maritime Organization (IMO): London.
32. IMO, *Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships using New Technologies and Alternative Fuels*. 2024, International Maritime Organization (IMO): London. p. 19.
33. HM Government, *The Merchant Shipping (Nuclear Ships) Regulations 2022, UK Statutory Instruments 2022 No. 1169*. 2022, HM Government, The National Archives: London. https://www.legislation.gov.uk/uksi/2022/1169/contents/made.
34. MCA, *Guidance MGN 679 (M) Nuclear Ships*. 2022, HM Government, Maritime & Coastguard Agency (MCA): London. https://www.gov.uk/government/publications/mgn-679-nuclear-ships/mgn-679-m-nuclear-ships.
35. IAEA, *Systematic Approach to Training for Nuclear Facility Personnel: Processes, Methodology and Practices*, in *IAEA Nuclear Energy Series No. NG-T-2.8*. 2021, International Atomic Energy Agency (IAEA): Wien. p. 171.
36. IAEA, *Recruitment, Qualification and Training of Personnel for Nuclear Power Plants*, in *IAEA Nuclear Energy Series, No. SSG-75*. 2022, International Atomic Energy Agency (IAEA): Wien. p. 62.
37. Hepsø, V. and E. Monteiro, *From Integrated Operations to Remote Operations: Socio-technical Challenge for the Oil and Gas Business*, in *Proceedings of the 21st Congress of the International Ergonomics Association (IEA)*, N.L. Black, W.P. Neumann, and I. Noy, Editors. 2021, Springer: Cham. p. 169–176.

38. Haavik, T.K., *New Tools, Old Tasks: Safety Implications of New Technologies and Work Processes for Integrated Operations in the Petroleum Industry*. 2013, London: CRC Press. 184.
39. Haavik, T.K., *Sensework - Conceptualising Sociotechnical Work in Safety-Critical Operations.* Computer Supported Cooperative Work, 2014. **23**: p. 269-298, doi.org/10.1007/s10606-014-9199-9.
40. Hepsø, V. and E. Parmiggiani, *From Integrated to Remote Operations: Digital Transformation in the Energy Industry as Infrastructuring*, in *Digital Transformation in Norwegian Enterprises*, P. Mikalef and E. Parmiggiani, Editors. 2022, Springer: Cham.
41. Mathur, R.K., J. Macpherson, S. Krueger, and A. Goel, *A step change in drilling efficiency using remote operation*, in *Offshore Technology Conference*. 2020: Houston, TX. doi.org/10.4043/30890-MS.
42. Bodsberg, L., T.O. Grøtan, M.G. Jaatun, and I. Wærø, *HSE and Cyber Security in Remote Work*, in *2021 International Conference on Cyber Situational Awareness, Data Analytics and Assessment (CyberSA)*. 2021: Dublin. p. 1-8, doi.org/10.1109/CyberSA52016.2021.9478249.
43. Horelik, N., B. Herman, B. Forget, and K. Smith, *Benchmark for evaluation and validation of reactor simulations (BEAVRS)*, in *2013 International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering*. 2013: Sun Valley, ID.
44. Yadav, V., R. Christian, A. Shields, M. Schanfein, G. Reyes*, et al.*, *Digital Twins for Nuclear Safeguards and Security Applications*, in *13th Nuclear Plant Instrumentation, Control & Human-Machine Interface Technologies (NPIC&HMIT 2023)* 2023, American Nuclear Society: Knoxville, TN. p. 730-739.
45. IAEA, *Status of Molten Salt Reactor Technology*, in *Technical Reports Series No. 489*. 2023, International Atomic Energy Agency (IAEA): Wien. p. 315.
46. Grape, S. and C. Hellesen, *Chapter 10 - Nonproliferation and safeguards aspects of the MSR fuel cycle*, in *Molten Salt Reactors and Thorium Energy*, T.J. Dolan, Editor. 2017, Woodhead Publishing: Cambridge, MA. p. 261-279.
47. Worrall, A., J.W. Bae, B.R. Betzler, S. Greenwood, and L.G. Worrall, *Molten Salt Reactor Safeguards: The Necessity of Advanced Modeling and Simulation to Inform on Fundamental Signatures*. 2019, Department of Energy, Oak Ridge National Laboratory: Oak Ridge, TN. p. 12.
48. Holcomb, D., B. Cipiti, L. Cheng, V. Igantiev, B. van der Ende*, et al.*, *MSR Proliferation Resistance and Physical Protection White Paper*. 2020, Department of Energy, Sandia National Laboratories: Livermore, CA. p. 37.
49. Hosik, Y., J.-h. Seo, N.-Y. Lee, J.-h. Lee, M.-s. Koh*, et al.*, *Methodology for evaluating proliferation resistance of nuclear systems and its case study.* Progress in Nuclear Energy, 2017. **100**(September): p. 309-315, doi.org/10.1016/j.pnucene.2017.06.017.
50. Cirera, B., S. Mirmiran, F. Fuente Espel, P. Norborg, and I. Rodriguez Ruocco, *Toward developing a novel combined Licensing & Safety approach for advanced nuclear reactors based on the international maritime and nuclear safety framework. Case study of the CMSR Power Barge*, in *International Conference on Topical Issues in Nuclear Installation Safety: Strengthening Safety of Evolutionary and Innovative Reactor Designs*. 2022, International Atomic Energy Agency (IAEA): Wien.
51. Al-Dbissi, M., *Preliminary Safeguard and Security Analysis of Seaborg's Compact Molten Salt Reactor (CMSR)*. 2019, Chalmers University of Technology: Göteborg.
52. Scott, B. and T. Beard, *An investigation into the potential of the molten salt reactor for the propulsion of surface ships*, in *Scaling Decarbonisation Solutions - Reducing Emissions by 2030*. 2022, RINA: Rotterdam.
53. IAEA, *Applicability of IAEA Safety Standards to Non-Water Cooled Reactors and Small Modular Reactors*, in *Safety Reports Series No. 123*. 2023, International Atomic Energy Agency (IAEA): Wien. p. 277.
54. Fialkoff, M.R., *The Floating Chameleon: Floating Nuclear Power Plants and the Nexus of Maritime and Nuclear Security Law.* Journal of Maritime Law and Commerce, 2020. **51**(2): OSTI ID: 1649247.
55. Kuchinov, V.P., M.N. Lysenko, and A.V. Khlopkov, *International legal interaction between the state of manufacture and the host state on the use of floating small modular reactors*, in *First International Conference on Nuclear Law: The Global Debate*. 2022, International Atomic Energy Agency (IAEA): Wien. Paper ID: IAEA-cn-299-72.

56. IAEA, *Legal and Institutional Issues of Transportable Nuclear Power Plants: A Preliminary Study*, in *IAEA Nuclear Energy Series No. NG-T-3.5*. 2013, International Atomic Energy Agency (IAEA): Wien. p. 95.
57. IAEA, *Classification of Radioactive Waste for protecting people and the environment: General Safety Guide*, in *IAEA Safety Standards No. GSG-1*. 2009, International Atomic Energy Agency (IAEA): Wien. p. 48.
58. IAEA, *Practical applications of short-lived radioisotopes.* International Atomic Energy Agency Bulletin, 1963. **5**(1): p. 24-26.
59. IAEA, *Status and Trends in Spent Fuel and Radioactive Waste Management*, in *IAEA Nuclear Energy Series No. NW-T-1.14 (Rev. 1)*. 2022, International Atomic Energy Agency (IAEA): Wien. p. 88.
60. IAEA, *Storage and Disposal of Spent Fuel and High Level Radioactive Waste*. 2007, International Atomic Energy Agency (IAEA): Wien. Accessed 2024-12-12 from https://www.iaea.org/sites/default/files/gc/gc50inf-3-att5_en.pdf.
61. OECD/NEA, *Management and Disposal of High-Level Radioactive Waste: Global Progress and Solutions*. 2020, Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency (NEA): Paris. p. 45.
62. IAEA, *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*. 1997, International Atomic Energy Agency: Vienna. p. 36.
63. IAEA, *Fundamental Safety Principles*, in *IAEA Safety Standards Series No. SF-1*. 2006, International Atomic Energy Agency (IAEA): Wien. p. 21.

ANNEX I: Proliferation risk and safety, the MSR case and port entry requirements

The Molten Salt Reactors (MSR) technology, has it beginning in late 1940, since that moment some countries have been investing resources in research and development of the technology. This technology offers significant advantages over conventional water reactors, due to the use of molten salt to contain the fuel and as the coolant [45]. However, the technology presents some technical challenges regarding reducing the proliferation risk and increasing safety since the fuel s dissolved directly in the salt for a number of MSR reactor designs. To face this challenge, it is necessary to establish a safeguard system for MSR [46, 47]. The main points where the Safeguard needs to focus are:

- Fuel cycle [48]. Not reprocessing spent fuel is less problematic than a cycle that includes this process. During the reprocessing step, the material could exit the reactor system and increase the proliferation risk. Therefore, designs that minimize or eliminate the separation of fissionable species may be more proliferation resistant.
- Reactor design [48]. Online refueling makes it possible to access the fuel during reactor operation and changing conditions during the lifetime of the reactor imply new methodologies and tools to control and measure the power distribution and mass of fuel.
- Fuel [49, 50]. Liquid fuel makes it more difficult to account for all materials, and the potential variability of the continuous or batch addition of fissionable, fertile, or fissile material makes the power monitoring and control of the material balance more challenging. Some MSR designs require the addition of fuel throughout the lifecycle, avoiding the need for refueling. This makeup fuel must be delivered in sealed containers which can be easier to steal than the reactor itself. Besides, this type of reactor must ensure that the risk deviation of nuclear material that can be faced is reduced to a minimum (for example, IMSR does not require large fuel additions at a single time so the diversion would need to take place over an extended period).

How a safeguards system for a future MSR would be designed can therefore not be answered today. This comes from the difficulty of measurements of molten salts as the total bulk salt mass for the entire system must be measured. An MSR will have a unique geometry for the core, heat exchangers, pipes, and salt processing systems and therefore, be very challenging to determine total salt mass with precision [50]. However, at a minimum, one can expect the safeguards to monitor in detail the material balance of U, Pu, and other actinides. It means, establishing discrete counting units to measure its composition before and after the cycle. In this context, for MSR, the appropriate counting unit could be the reactor as a whole [51], especially if it is completely sealed during the whole operating cycle.

Most of the articles, IAEA reports and specialized chapter books mention that the detailed measure of the vector of fuel spent is an activity important to develop. Some of the suggestions include:

- Use the existing codes to simulate the vector at the end of the cycle (Mishra, et al., 2023).
- Develop new modeling tools to predict the inventories of nuclear material [47].
- Some upcoming techniques for novel safeguard approaches, such as stand-off reactor monitoring using neutron detection, alpha spectroscopy, spectroelectrochemistry, voltammetry, and laser-induced breakdown spectroscopy may provide solutions to this issue of maintaining continuity of knowledge with a direct physical sampling of the core [46]. These techniques could guarantee the

knowledge of core content in the case of sealed reactors, leading to increased safeguards standards. Besides, the highly corrosive environment that molten salt reactors present is a potential drawback, making the maintenance of safeguards monitoring instrumentation challenging. On-line instruments in direct contact with salt may not last long.

- Safety seals: In today's nuclear power plants, the regulatory body, after commissioning and subsequent inspections, establishes a series of seals to ensure that nuclear material is not tampered with or diverted [52]. According to [53], seals are a simple and effective means of meeting an important verification need. Metal seals, used worldwide, are an important part of an inspector's toolkit to verify that nuclear facilities and materials remain in peaceful use. A passive seal ensures continuity of knowledge regarding nuclear material. If the seal has not been tampered with, the inspector knows that the equipment or material it contains remains intact. A passive seal is also used to ensure the integrity of IAEA on-site verification instruments and equipment, such as surveillance cameras.

However, there is still no established technique for this control and monitoring. The IAEA has not had the opportunity to implement safeguards on MSR. Currently, there are no plans for the NRC to develop a modified approach for MSRs and no Fundamental Nuclear Material Control (FNMC) template for MSRs. Nonetheless, MSRs are bulk facilities and will very likely need to develop, submit, and implement FNMC plans, dividing the facility into 3 differentiated Material Balance Areas, concerning the front and back end of the process, and monitoring these and their connections raises a fundamental need.

An agreement between all involved parties should be considered: the supplier State of the reactor, the State owner of the ship, the host State, and the State owner of the territory where the ship transits [54]. The current state of international regulations needs to be updated to consider all nuclear reactor technologies and the weather disturbances that a ship could experience [55, 56].

Some important safety points to explore are:

- Measures designed to prevent weapons or any other dangerous substances and devices.
- Identification of the restricted areas.
- Measures for the prevention of authorized access to the ship.
- Procedures for responding to security threats or breaches of security.
- Procedures for auditing security activities and periodic review.

ANNEX II: Handling Po-210

One of the main challenges regarding lead-cooled fast reactors is the generation of one of the most toxic substances for humankind, Polonium-210. In LFRs, Po-210 is produced mainly by neutron capture of Bi-209 in the coolant; which with a half-life of 5 days decays into Po-210. While the Bi-209 in Lead-Bismuth Eutectic (LBE) cooled reactors is present in high concentrations as an alloying element, in lead cooled reactors Bi-209 is present in low concentrations as impurity, as well as produced by neutron capture of Pb-208. Therefore, the Po-210 activity is about 104 times lower in lead cooled than in LBE cooled reactors.

This isotope is a high-energy (5,3MeV) α-emitter with a half-life of 138 days that presents a radiation hazard only if taken into the body, for example, by ingestion, because of the low range of alpha particles in biological tissues. As a result, external contamination does not cause radiation sickness [1]. Polonium's effectiveness as a poison relies on its chemical characteristics only to the extent that they determine the isotope's distribution and retention in organs and tissues; the alpha particles are responsible for the lethal effect [2]. The biological half-time (the time for the level of Po-210 in the body to fall by half) is approximately 50 days. If taken into the body, Po-210 is subsequently excreted, mostly through feces but some is excreted through urine and other pathways. People who come into contact with a person contaminated by Po-210 will not be at risk unless they ingest or inhale bodily fluids of the contaminated person [3].

In the human body, Po-210 causes two major effects: somatic, which can be early and late (depending on the absorbed dose and time of exposure), and genetic. Somatic effects are similar to irradiation disease and are expressed through asthenia, alopecia, lymphopenia, gastrointestinal nausea, vomiting, abdominal pain, etc. The poisoning symptoms of Po-210 are similar to the final stage of neoplasia. Liver and kidney have major lesions, nausea, vomiting, massive dehydration, diarrhea, hair loss…

The genetic effects secondary to the action of radiation on deoxyribonucleic acid (DNA) are major and concern the entire genome. Radioactive isotopes are genotoxic, causing breakdown of DNA structure, with chromosomal mutations and underlying carcinogenic effects [2].

Good supportive care is essential and should be directed at controlling symptoms, preventing infections but treating those that do arise, and transfusion of blood and platelets as appropriate. Gastric aspiration or lavage may be useful if performed soon after ingestion. Chelation therapy is also likely to be beneficial, since it reduces retention in the body and improves survival, although increased activity in some radiosensitive organs has also been reported with some chelating agents. Dimercaprol (with penicillamine as an alternative) is currently recommended for Po-210 poisoning, which is also an agent used in mercury, gold, bismuth and lead poisoning.

The behavior of Po-210 in aqueous systems is generally dominated by adsorption onto surfaces, although incorporation into colloids, biovolatilization and precipitation in sulfides can be important in some circumstances. After ingestion, Po-210 is accumulated on soft tissues of marine organisms such as shrimps, prawns and fish [4].

Due to all these potential consequences for humans and environment in case of an accidental coolant leakage in LFRs, investigations have been performed in order to isolate and reduce the effect of polonium both in operation and dismantling/refueling stages. These investigations have shown different approaches that will be presented below.

II.A Polonium isolation or reduction strategies

There are three main strategies today. All the methods that are presented and explained in this section have been tested on small scale experiences performed in controlled environments. However, the new LBE-cooled test reactor MYRRHA [9], strives to corroborate these results on a large scale.

II.A.1 Lead enrichment

One of the ways for diminishing the consequences of an accident is via isotopically enriched materials. Although isotopical tailoring option requires tremendous technical and economical efforts, its application can be first of all assumed for those structural and functional materials which generate very hazardous radionuclides under irradiation [5]. While this strategy is not possible in reactors using LBE, since Bi-209 is the only naturally occurring isotope of bismuth, it is possible with pure lead cooled reactors due to the presence of Pb-208 isotope. Pb-206 enrichment practically solves the polonium problem as in 1 kg of pure Pb-206 the activity of Po-210 is reduced in 5 orders of magnitude compared to 1 kg of natural Pb [5].

II.A.2 Polonium filters

Diverse experiments have studied polonium evaporation phenomena and its adhesion characteristics to different metals. Through this, the possibility of developing filters that can capture evaporated Po-210 from neutron-irradiated LBE can raise as a solution to this issue. One of the experiments showed that both Stainless Steel 316 and Nickel have similar Po-210 adhesion capabilities under certain pressure and temperature conditions [6]. In a final experiment performed, some metallic filter configurations were interposed between two samples. Results showed a reduction of more than 88% for single filter configuration and more than 97% for double filter configuration in the Po-210 going through the metallic array. Larger decreases of polonium are expected by using finer meshes [6].

II.A.3 Alkaline Extraction

Chemistry also provides a solution to be implemented in lead-cooled reactors in order to control and remove accumulated Po-210. Alkaline extraction is based on the formation of sodium polonide (Na2Po) occurring from the reaction of molten sodium hydroxide (NaOH) with Po-contaminated LBE (PbPo) [7]:

$PbPo + 4NaOH \leftrightarrow Na2Po + Na2PbO2 + 2H2O$

It must be noted that under normal atmosphere conditions the coefficient of polonium extraction from bismuth decreases sharply, which is why the alkaline extraction process should be carried out in inert gas atmosphere [8]. Besides, results of experiences showed that presence of lead does not affect the level of polonium removal.

However, this reaction can produce residues that reduce coolant quality after the alkaline extraction. This is why this process requires the development of a system of control and coolant purification from alkaline residues [8].

II.B Polonium containment

After the separation/extraction of polonium, it has been demonstrated that solidified lead can be the most expedient way to contain the polonium, as up to 250,000 Ci of polonium may be retained in a ribbed container of 100 liters volume [8].

ANNEX III: Radioactive Waste Management

One of the main concerns of nuclear energy is the generation of radioactive waste. Radioactive waste is produced in different kinds of facilities, and it may arise in a wide range of concentrations of radionuclides, physical and chemical forms. These differences result in an equally wide variety of options for the management of the waste, dependent on the storage prior to disposal time (short- or long-term). This, added to the radioactive activity and heat removal needs, constraints the final disposal site, ranging from near surface to deep geological disposal [57].

III.A Different categories of radioactive waste

Different types of waste must be grouped according to their characteristics. For example, waste containing radionuclides with short half-lives (usually defined as those whose half-life is reckoned in seconds, minutes or hours [58]) may be separated from waste containing radionuclides with longer half-lives, or compressible waste may be separated from non-compressible waste. Thus, according to its activity and half-life, radiological waste may be classified in 6 different groups, see Figure 41:

1. Exempt Waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes.
2. Very Short-Lived Waste (VSLW): Waste that can be stored for decay over a limited period of time, up to a few years, and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. Radionuclides with very short half-lives, often used for research and medical purposes, fall in this category.
3. Very Low-Level Waste (VLLW): Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface facilities with limited regulatory control. Typical waste in this class includes soil and rubble with low levels of activity concentration.
4. Low-Level Waste (LLW): Waste that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near-surface facilities. This class covers a very broad range of waste including short-lived radionuclides at higher levels of activity concentration, and long-lived radionuclides at relatively low levels of activity concentration.
5. Intermediate-Level Waste (ILW): Waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs limited or no provision for heat dissipation during its storage and disposal. ILW may contain long-lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near-surface disposal during the time for which institutional controls can be relied upon. Therefore, waste of this class requires disposal at greater depths, in the order of tens of meters to a few hundred meters.
6. High-Level Waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations, usually several hundred meters or more below the surface, is the generally recognized option for disposal of HLW.

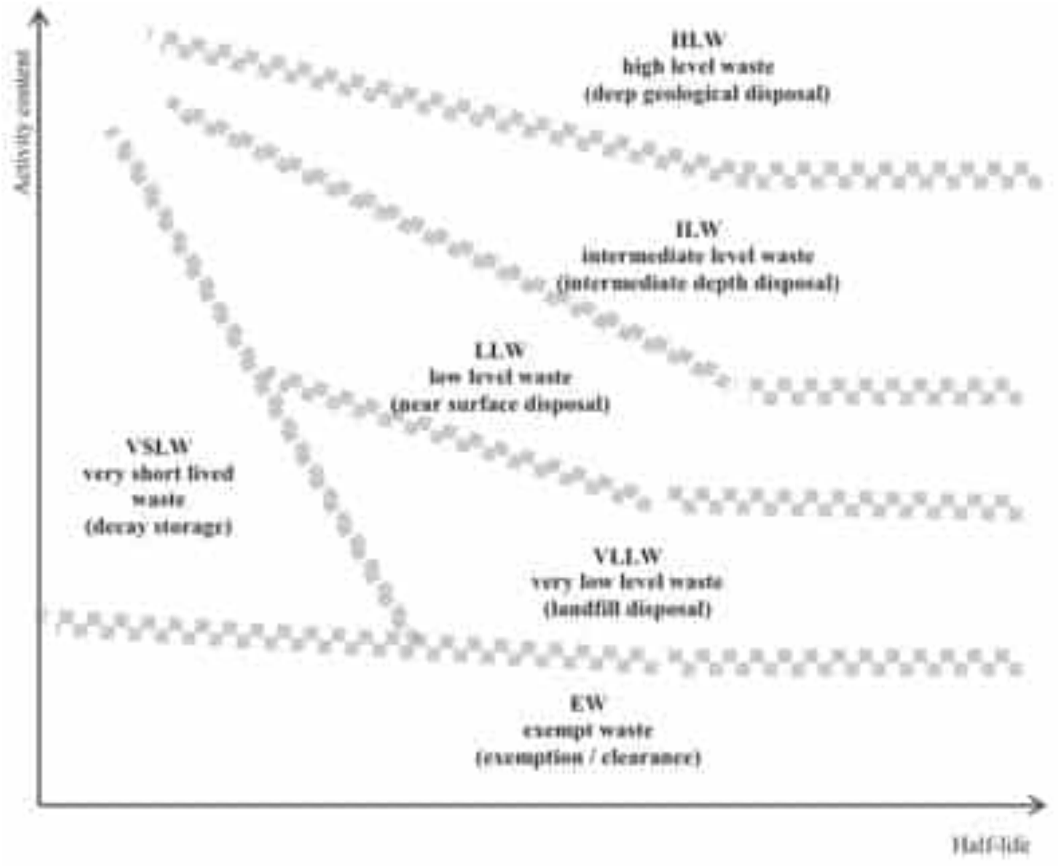


Figure 41 – Waste classification scheme according to IAEA [57].

Even though it is not strictly waste, Spent Fuel may also be included in this classification as in the case of not being reprocessed it constitutes a waste by itself.

7. Spent Fuel: Refers to the nuclear reactor fuel that has been used to the extent that it can no longer effectively sustain a chain reaction for electricity generation. However, it is still hot, highly radioactive, and potentially harmful, thus, falling in the category of High-Level Waste. Therefore, until a permanent disposal repository for Spent Nuclear Fuel is built, licensees must safely store this fuel at their reactors (wet storage of Spent Fuel in water pools). Depending on the policy and strategy of the Member State, Spent Nuclear Fuel can be partially reprocessed to recover fissile and fertile materials in order to provide fresh fuel for reuse. According to inventory estimates of Spent Nuclear Fuel as of the end of December 2016, there is an estimated 265,000 tonnes of Heavy Metal (t HM) of Spent Fuel in storage worldwide and 127,000 t HM of it has been sent to be reprocessed [59].

Figure 42 shows the share of different classes of radioactive waste in total volumes in storage and disposal from the inventory data of 2016. It is noticeable that more than 90% of the waste belongs to LLW and VLLW, and only 0.13% belongs to HLW.

While the national arrangements for ensuring that Spent Fuel and radioactive waste are safely managed vary from country to country, there are some common features. The national legislative assembly is usually responsible for enacting legislation, which generally includes the establishment of a regulatory body, and in many cases an implementing body for Spent Fuel and radioactive waste management, as well as defining the essential elements of the national policy and other related governance.

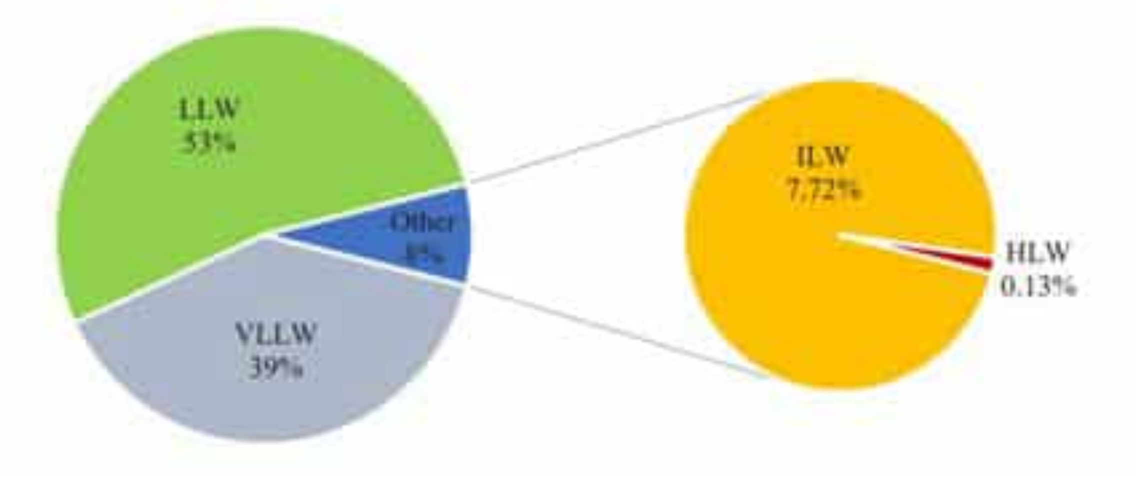


Figure 42 – Share of different classes of radioactive waste in total volumes in storage and disposal, based on 2016 inventory data from [59].

Nevertheless, management of the radioactive waste and Spent Fuel does not necessarily fall on the States´ responsibilities. In some countries, for example, the owner or license holder of a Spent Fuel and radioactive waste management facility is a private entity and thus is responsible for ensuring safety. In other countries, the owner or license holder might not be completely distinct from the government and so the responsibility for ensuring the safety of Spent Fuel and radioactive waste management essentially rests with the State.

III.B Spent Fuel Storage and Disposal

Two different management strategies are used for Spent Nuclear Fuel, as previously stated. One approach is reprocessing fuel to extract usable material (uranium and plutonium) for new fuel production. The other one considers Spent Fuel simply a waste, storing it prior disposal. If the Spent Fuel is to be reprocessed, it is shipped to a reprocessing facility where the fuel elements and fuel rods are chopped into pieces, to be chemically dissolved, and the resulting solution is separated into four basic outputs: uranium, plutonium, High-Level Waste (HLW), and various other process wastes. In terms of cooling and shielding, the HLW, which contains fission products and actinides, needs to be handled similarly to Spent Fuel of the same age.

Regardless of the strategy chosen, Spent Fuel management always involves a certain period during which the Spent Fuel is stored. For initial cooling and shielding, all Spent Fuel needs to be stored under water in storage pools at the reactor facility directly after its removal from the reactor and prior to being transported off-site. This initial storage period lasts a minimum of 9–12 months to allow both the radiation level and heat level to decay sufficiently. In most cases Spent Fuel is stored in these on-site pools for several years, and sometimes up to tens of years, depending on the storage capacities of the pools [60].

There are two storage technologies in use today: wet storage in pools and dry storage in vaults or casks. There are now more than 50 years of experience with wet storage of Spent Fuel in water pools. Wet storage is a safe technology, and likely will continue to be used for many years. However, as delays are incurred in implementing plans for geologic repositories and for reprocessing, storage of Spent Fuel for extended durations of several decades is becoming a reality.

This trend of more storage for longer durations is expected to continue, and some countries are now considering storage periods of 100 years or more. While no significant problems are anticipated with extended wet storage, it is important to monitor these facilities, learn from experience and apply the results in designing and operating new facilities, from the beginning, for extended storage.

Dry Spent Fuel storage is a technology with over 30 years of operating experience that has developed substantially over the past twenty years. It is more limited in heat dissipation capability than wet storage, but has the advantage of being modular, which spreads capital investments over time, and, in the longer term, the simpler passive cooling systems used in dry storage reduce operation and maintenance requirements and costs.

While most of the radioactivity decays away after a few hundreds of years, certain long-lived radionuclides will persist for thousands of years. For the longer term, final disposal in Deep Geological Repositories (DGRs) is today recognized, after decades of research and demonstration in Underground Research Laboratories (URLs), as the best solution [61].

Remarkably, only Sweden and Finland have opted for the storage of radioactive waste in specially designed underground facilities, where their long-term isolation is guaranteed.

The fundamental design objective of geological repositories is to confine and isolate the waste from the environment. Adequate long-term safety must be provided without reliance on active controls or ongoing maintenance. Geological repositories are therefore designed to be passively safe, such that continued indefinite institutional control is not required to assure safety. Nonetheless institutional control will likely be maintained for a long initial period to provide additional reassurance and to comply with current safeguards and security requirements [62]. To comply with those requirements, the governments must incorporate the following basic technical principles in their national approaches:

- Encapsulation of Spent Fuel or HLW in a tight canister with a very long expected lifetime.
- Assurance that the conditions in the repository will allow the canister to remain intact and tight for as long as possible (mechanical stability, stable geochemical conditions and very limited ground water movement that could bring corrosive agents in contact with the canisters).
- Backfilling of the repository with appropriate materials and locating it in geological media that, together with the backfill, strongly limit water movement and, eventually, waste movement when the integrity of the canisters finally breaks down.

Figure 43 shows the multi-barrier concept for Spent Fuel disposal in Sweden. It has barriers at three levels. First is the waste matrix and initial waste package. Second are engineered barriers, i.e., the copper canister with a cast iron insert, surrounded by compacted bentonite. Third is the host formation of the extensive crystalline bedrock.

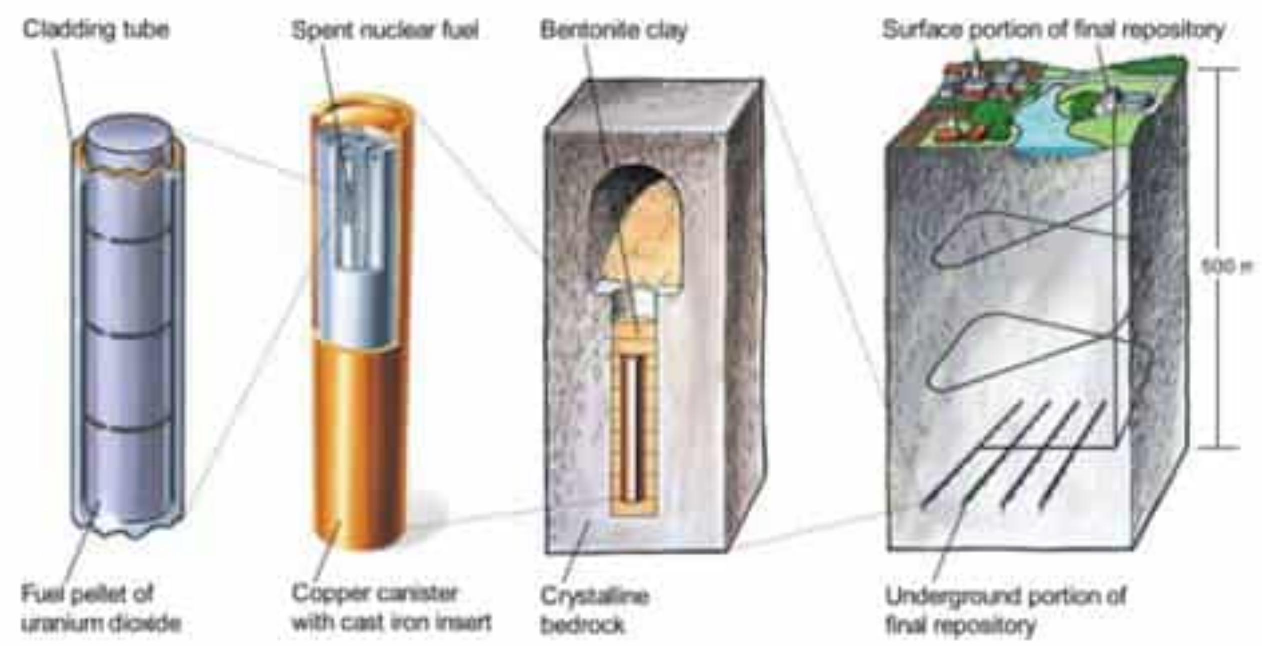


Figure 43 – The Swedish concept for the disposal of Spent Nuclear Fuel as an illustration of the multi-barrier concept [60].

III.C The Shipping Case

The implementation of nuclear reactors in merchant ships poses new challenges on how these wastes are handled. On the one hand, the moment when the vast amount of radioactive waste is generated is critical in a ship. While it can be expected that all reactor designs will produce small amounts of Low- and Mid-Level Waste during the operation, for example, coming from the coolant purification systems that would collect activated impurities found in the coolant, that will have to be securely stored onboard until its unload on harbor during maintenance/load-unload stops; the differences on refueling needs of different reactor designs will lead to different management scenarios for the Spent Fuel:

- In Harbor Refueling: In this case, Spent Nuclear Fuel is generated each time the reactor concludes a refueling cycle. The stops for refueling will have to match the stops of the ship for maintenance, which will require specialized harbors including new areas where refueling following IAEA standards can be performed. Independently of the form of the Spent Nuclear Fuel (conventional fuel assemblies, molten salt, TRISO), the Spent Nuclear Fuel extracted from the reactor is expected to be reprocessed to generate new nuclear fuel, in line with sustainability objectives.
- Online Refueling: Reactor designs with online refueling belong to this case. In this case, depleted fuel will be generated, burnt, collected and encapsulated in sealed casks during the operation of the reactor. These casks are later transferred to a reprocessing facility or a land-based reactor with the objective of achieving full burnup, in order to extract the remaining energy. This is a consequence of the load profile of the reactor working as a propulsion system with constant load changes to adapt the speed of the ship, in contrast to land-based reactors working at full load for electricity production. The transfer of this partially burnt fuel must ensure its compliance with the highest safety standards. As online refueling may be performed in high seas, fresh fuel should also be present on the ship with the objective of replacing the outcoming fuel. Inconveniencies due to the fact that both fresh and Spent Fuel need to be stored and managed in the ship come as a safety and security related issue.
- No Refueling: Some reactor designs are able to operate their whole lifetime without the need for refueling. This involves having all Spent Fuel and most radiological waste just at the end of the life of the reactor, which makes this the most convenient and safe scenario from the waste management point

of view. These reactors are designed so that the whole reactor can be directly disposed in canisters after decommissioning.

The most notorious challenge faced regarding waste management in new generation reactors is the uncertainty in the type of Spent Fuel and radioactive waste that will be generated as well as in the quantity, time and place of this generation. As these new concepts remain in a preliminary design status, the amounts and specific characteristics of the waste remain unknown and only approximations under certain conditions can be made, forcing the need of strong research in this field. However, observing the proportions in waste inventories (Figure 41), a similar proportion might be expected for Gen IV reactor designs, with small inventory variations due to concept differences. For example, impurities in irradiated molten salt from MSR will likely be classified as LLW, while part of the fuel, regardless of its form (TRISO, solid pellets, molten salt fuel) will be HLW and consequently vitrified and disposed in a deep geological repository.

All nuclear reactors generate radioactive waste, but SMRs can help address this challenge. Although SMRs are based on new technologies, countries with nuclear power plants already have established solutions to store and manage spent fuel. Due to their smaller size and fuel requirements, they can offer less waste management and could be attractive for maritime propulsion.

While for land-based reactors is easier to establish the responsibility for the Spent Fuel and radioactive waste management and disposal (assumed by both public and private entities depending on the agreements), in the case of reactors moving all over the world, lines of responsibility become blurred. The question is whether it will be the reactor operator, the shipping company, the country owning the ship, the shipping company country that will be responsible of this management.

Several international bodies, establish that the prime responsibility for ensuring the safety of Spent Fuel and radioactive waste management relies on the license holder as a basic prerequisite [62, 63]. However, agreements between new nuclear reactor design development companies, shipping companies and regulatory bodies must be ensured for cooperation and responsibility distribution.

IAEA encourages cooperation between countries in nuclear waste management. It facilitates the exchange of information, collaboration in research, and joint development of technologies.

Besides, due to the long-time frame of waste disposal, in certain cases it is practical to establish Waste Management Organizations (WMOs) owned and operated by private/public waste generators. This could be an interesting approach for maritime reactor operators to enable the management of the waste in a more international approach with facilities located across the most active countries. To this extent, organizations such as the International Maritime Organization (IMO) could emerge as candidates for the regulation and standardization of nuclear-powered ships and the management of the generated waste and Spent Fuel.

In the context of maritime propulsion, the management of radioactive waste must be considered due to environmental concerns associated with heat release and potential discharges of radioactive materials into the sea. Factors such as operational security and efficient logistics play a significant role. Consequently, specialized facilities are necessary for the temporary storage of these wastes, taking into account their indoor capacity.

ANNEX IV: RISK IDENTIFICATION WORKSHOP

As part of Work Package 2 (WP2) a "Joint Risk Identification Workshop" was carried out.

IV.A Objective

The objective of the risk identification workshop was to:

- Identify risks related to the introduction of a nuclear reactor onboard a merchant vessel,
- Increase understanding among stakeholders of the risks and challenges to be managed, and
- Propose measures to address identified risks/challenges where applicable means of risk control can be indicated.

These objectives are intended to support further work on demonstrating that a nuclear propulsion concept can obtain an acceptable level of safety enabling construction and operation of such a vessel concept.

IV.B Scope, limitations and assumptions

The proposed methodology for the risk identification workshop mainly considers the normal operation of a nuclear propulsion system that could have consequences for crew or third parties. Types of risks as described in this report are provided as expert judgement by the workshop participants.

Main assumptions for the workshop were as follows:

1. Reactor is approved by a competent authority in terms of functionality and safety prior to entering into operation.
2. Assuming a "black box" approach to the reactor itself, meaning that the focus will be at applicable interfaces between the reactor and ship, and what risks occurring in this interface may represent.
3. The methodology mainly focuses on single failures for connected ship systems (reactor itself is assumed handled within point 1).
4. Operation of the reactor is only carried out by qualified personnel that should be able to address process deviations with an appropriate course of action to de-escalate potential situations that may arise.

IV.C Methodology

The approach used for the workshop was a modified HAZID approach, as explained in this section.

IV.C.1 HAZID Methodology

HAZID is a structured approach where documentation/drawings and a set of guidewords form basis for a structured brainstorming for identifying hazards (i.e., potential accidental events) with respect to an operation or the use of equipment and/or systems. HAZIDs are commonly used throughout various industries for all types of safety and risk assessments.

The key objectives of a HAZID are to:

- Identify hazards and hazardous events that may give rise to serious and immediate risk to personnel, environment, and assets.
- Identify causes and consequences of hazardous events.

- Identify safety measures (e.g. measures to prevent the hazardous events from occurring and engineering or operational controls to help prevent escalation) that are already included in design for managing the risks associated with the identified hazards.
- Assess risks semi-quantitatively by using a risk matrix; and
- Recommend any potential new measures to be implemented in design and/or during operation.

For assessment of a vessel with nuclear propulsion, safety measures may depend on specific design, thus identifying such measures becomes less feasible as no specifics on the design is available and the assessment is approached from a generic point of view, as outlined in the “black box” approach. As a result, risk ranking also becomes less relevant, and consequently, these two items (point three and four in the list above) has been omitted.

The relationship between the hazard, hazardous event, cause, consequence, and safety measures are shown below in Figure 44.

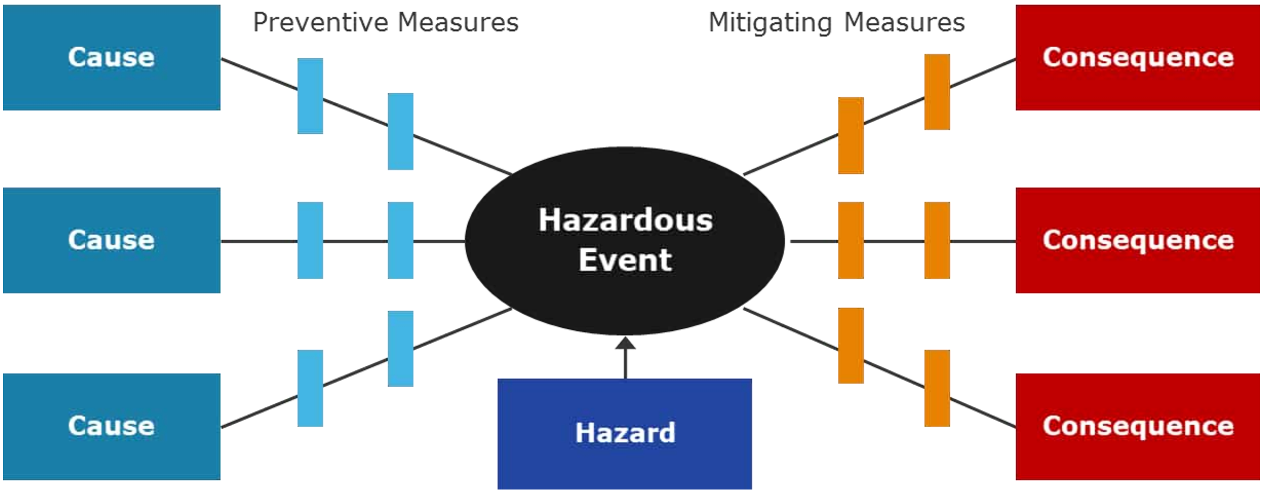


Figure 44 – Bowtie diagram.

IV.C.2 Procedure

HAZID study for the feasibility of a nuclear-powered propulsion system was carried out as a brainstorming exercise in the HAZID workshop attended by a multidisciplinary team (i.e. HAZID team).

The detailed procedure applied in the workshop followed the steps outlined below and is schematically presented in Figure 45.

1. *Identification of HAZID Nodes:* To assess the specifics of each individual area or operation, the areas and operations were broken down into the series of nodes listed in Table 36 below. For each node, the following steps were performed.
2. *Node Briefing:* For all HAZID team members to obtain a common understanding of the intended operation of the node, a brief introduction of the node in question has been given.

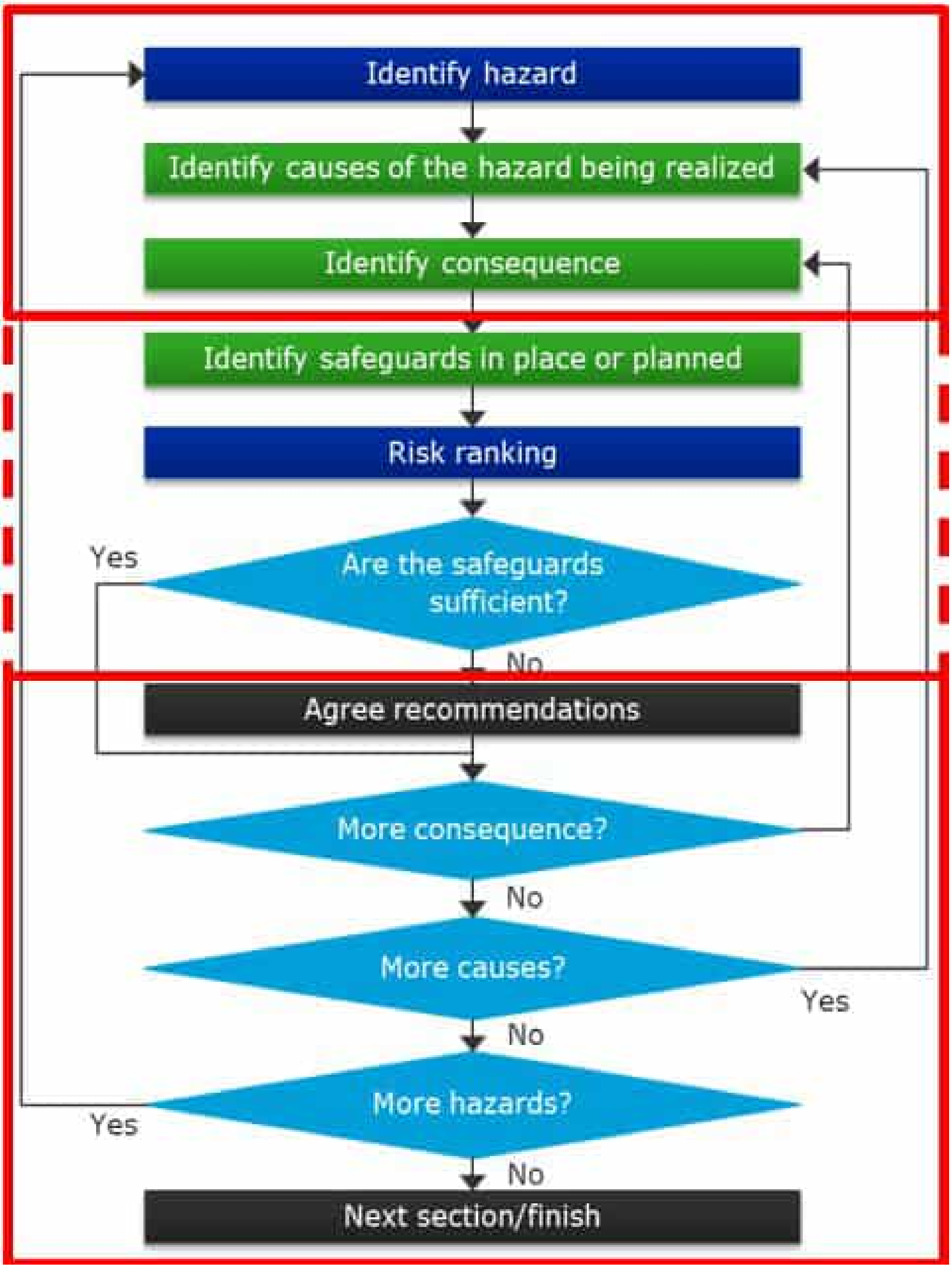


Figure 45 – HAZID procedure flow chart.

3. *Identification of Hazards and Hazardous Events:* Hazards and hazardous events were identified by the HAZID team. The HAZID team considered each node in turn based on the documents and drawings provided and previous experience.
4. *Identification of Causes:* For each hazardous event identified, all potential causes of the hazard being realized were identified and discussed if relevant. However, double jeopardy which is a combination of multiple independent events occurring at the same time was not considered during the HAZID workshop.
5. *Identification of Consequences:* For each hazardous event and cause identified, all potential consequences were identified without taking credit for preventive or mitigating measures in place. Consequences were not limited by the HAZID node definitions or scope boundaries in evaluating the consequences of a given event.

6. *Identification of Preventive and Mitigating Measures (Safeguards,):* For each identified accident scenario, existing measures expected to prevent a hazardous event from occurring (i.e. preventive measures) as well as those intended to control its development or mitigate its consequences (i.e. mitigating measures) were identified.
7. *Identification of Recommendations:* In case that the current provision of preventive or mitigating measures was considered insufficient to manage risks, or that further assessments are required to obtain a better understanding of hazard/hazardous event, recommendations were raised during the HAZID workshop. These recommendations were assigned to responsible parties.

IV.C.3 HAZID nodes

As the focus of this workshop was more on the interaction between the reactor assembly and the vessel, including onboard interface to onboard systems, the nodes for this workshop were selected on basis of hazard categories or types rather than nodes based on systems/sub-systems or operational steps.

The nodes selected to enable a structured approach to identification of hazards are presented in Table 36 below. According to the scope of work, the nodes presented in the table were used to provide structure to the workshop.

Table 36 – HAZID nodes.

Number	Node
1	Forces and accelerations - Ship motions - Slamming - Mechanical impact, ++
2	Marine environment - Water ingress - Salt/moisture - Other environmental effects
3	Technical hazards (Interdependency w/ connected ship systems) - Secondary cooling - Electric power supply - Reciprocating effects w/ propulsion system
4	Emergencies/Escalating events - External fire (adjacent areas) - Collision/Grounding - Flooding
5	Control - Remote operation - Safety systems

IV.C.4 Recording

For each hazard, the following aspects were discussed and recorded:

- Node.
- Hazardous events.

- Potential Causes.
- Potential Consequences.
- Planned safety measures.
- Proposed Additional Safety Measures (Actions/Recommendations).
- Comments and Notes.

IV.C.5 Workshop

The risk identification workshop was held as an in-person workshop in DNV's offices at Høvik, Norway, on the 17th of June 2024 and attended by a multidisciplinary team of specialists from the NuProShip I partners, with DNV Maritime Advisory facilitating the workshop. Participants were as listed in Table 37.

Table 37 – List of workshop participants.

Name	**Organization**	**Expertise**
Bjørn Mikkel Rygh	Norwegian Maritime Authority	Marine safety and regulations
Helge Thoresen	NTNU	Nuclear technology
Jan Emblemsvåg	NTNU	NuProShip project manager
Jessica Sabrina Chow	NTNU	
Even Bjørnevik	Knutsen OAS	Ship owner
Terje Strand	NTNU	Radiation physics
Thomas Olsvik	Vard	Ship building
Cesar Hueso	IDOM	Nuclear engineering and reactor technology
Lars Laanke	DNV	
Karl Hovden	DNV	
Ole Reistad	DNV	Nuclear regulations and reactor technology
Erik Brodin	DNV	
Magnus Høiberget	DNV	
Torill Grimstad Osberg	DNV	Piping systems
Eirik Ovrum	DNV	NuProShip WP 2 leader
Facilitator		
Magnus Jordahl	DNV	Maritime Risk & Safety
Scribe		
Åsa Snilstveit Hoem	DNV	Maritime Risk & Safety

IV.D Results

The workshop identified thirty-eight hazardous event scenarios, with total of thirty-four recommendations made by the HAZID team. Recommendations are summarized in Table 38 for an overview of the workshop output, for the complete log sheet, please refer to section 3.6.3.

Please note that the recommendations are based on a general approach to ship design and what aspects an unspecified reactor and associated systems would have to be able to handle. These are aspects that should be kept in mind and addressed when developing specific marine nuclear propulsion power concepts.

Table 38 – List of recommendations.

No.	Recommendation	Risk ID
1	Consider means of structural support (or other means of integration) for the reactor to dampen forces transferred to reactor support structure	1.1
2	Ensure reactor and steam system is designed to enable handling of transient loads, e.g. by means of buffer systems which may handle rapid increase or decrease in load demand.	1.2
3	Define acceptance criteria for ship motions a reactor needs to be able to handle and consider a higher acceptance level / design criteria for list and trim (roll and pitch).	1.3
4	Consider additional means of power in case the reactor has to shut down due to excessive ship motions and determine what level of redundancy should be required for a NuProShip.	1.3
5	Define acceptance criteria for static inclined loads of the reactor in terms of static inclination of the vessel and consider implementing resulting limitations in loading manual/calc. of the vessel.	1.4
6	Ensure that reactor- and support system design considers low-frequency cyclic motions represented by ship motion in waves as well as high-frequency vibrations represented by rotating equipment.	1.6
7	Consider alternative means for backup control power (decide on the need). Draw up the logic for backup power (different events to be evaluated) to meet potential requirements for safe return to port.	3.1
8	Consider redundancy in instrumentation and design of HMI to prevent accidental incorrect operation of reactor systems.	3.2
9	Consider secondary barriers for secondary cooling loop to reduce likelihood of releasing radioactive matter in case of a leakage from contaminated secondary cooling loop.	3.3
10	Consider potential toxicity of primary coolant and means of mitigating a potential leakage.	3.3
11	Ensure that the system design, including selection of equipment, is able to withstand operational temperatures that may occur in the system process	3.4
12	Define critical reactor systems that may need to be supplied from an emergency means of power to prevent loss of reactor cooling and control	3.5
13	Consider power supply segregation philosophy to reduce the likelihood of ending up in a dead ship situation that may result in a loss of safety systems-situation as well.	3.5
14	Consider potential solutions for back-up power to mitigate a potential loss of power supply to reactor.	3.5
15	Consider enabling the control room-with a safe return to port option (a minimum requirement for certain ship types). Principles in Pt.6 Ch.2 Sec.11 are relevant.	3.6

No.	Recommendation	Risk ID
16	Determine whether flooding of a single compartment or multiple compartments should be the design basis for a NuProShip vessel (not necessarily related to collision, but flooding of compartments in general)	4.2
17	Consider means for ensuring the ship folds around the reactor compartment in case it suffers substantial mechanical impact damage	4.3
18	Ensure reactor compartment is located in such a position that it will be outside of the likely affected area of a powered grounding.	4.4
19	Consider designing the reactor compartment for watertight integrity to potentially withstand total submersion	4.6
20	Consider including salvaging operation plans for the worst-case conditions within the expected operating area in the emergency response plans	4.6
21	Consider cargo properties and the probability of fire in adjacent spaces, ref. IMO Safety code, and consider whether additional fire protection could be applicable for protection of the reactor and associated systems.	4.7
22	Investigate the possibility to have "total flooding"-arrangement of adjacent spaces for additional fire protection of reactor and support systems.	4.7
23	Ensure a Safety analysis for loss of coolant scenarios is carried out (Likely to be required in licensing/approval process)	4.7
24	Spraying seawater when fresh water supply has ended may be harmful to certain equipment/systems, it may be considered to only use fresh water in some compartments (typically rooms with electronic/control equipment)	4.8
25	Consider relevant onboard competence requirements to enable mitigation of foreseeable operational challenges related to the reactor that may occur without being able to communicate with onshore personnel.	5.1
26	Consider means of tamper-proof independent tracking of vessel/reactor to ensure overview is maintained in case of a potential take-over of vessel/reactor	5.2, 5.3
27	Consider independent mitigation layers to counteract potential cyber-attacks and virtual take-over of reactor	5.2
28	Consider means for restricting unauthorized access to reactor compartment (while maintaining required access for required maintenance operations) to reduce the likelihood for unauthorized access to radioactive material.	5.3
29	Establish clear control protocols and switchover routines and guidelines between local and remote control in case a change of control is to take place, to prevent accidental events arising from potential misunderstandings between local and remote operators	5.4
30	Determine adequate level of training for onboard personnel to enable operation of vessel in remote areas without access to communication with onshore personnel.	5.5

No.	Recommendation	Risk ID
31	Ensure a secondary means of reactor control is located in a separate location on board, sufficiently away from control room to prevent total loss of control of reactor in case of accidental events external to the reactor systems	5.6
32	Design criteria to consider relevant electrical fault scenarios and mitigating measures to prevent damage to the system	5.9
33	Consider system segregation, not only for redundancy, but also to account for electrical system malfunctions.	5.9
34	Ensure sufficient software change management is applied to prevent introducing reactor system errors by update of software	5.10