European Maritime Safety Agency

POTENTIAL USE OF NUCLEAR POWER FOR SHIPPING

BY ABS, TEXAS A&M UNIVERSITY & ARCSILEA

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Executive Summary

The European Union with the adoption of the European Green Deal has signalled its engagement towards becoming a carbon free economy. In this context, EMSA is supporting the maritime stakeholders by providing technologically neutral studies on potential alternative fuels and power solutions for shipping. This report is the last one of a series of studies produced in 2022, 2023 and 2024 covering the Potential use of Biofuels, Potential of Ammonia as fuel and Potential of Hydrogen as fuel, Synthetic fuels and Potential of Wind-Assisted propulsion for shipping.

Some solutions for decarbonisation could involve replacing fuel oil with renewable energy sources such as wind or solar. Other solutions may rely on alternative energy resources that still depend on fossil carbon, such as low carbon gas, or using non-fossil carbon resources, such as biofuels. Zero- or low-carbon '*green*' fuels, such as methanol, ethanol, ammonia and hydrogen, are other options. However, with some of the green fuels, due to their lower energy density, in comparison to traditional marine fuels, it might require that some vessels may need to sacrifice cargo space and have more frequent bunkering operations. This aspect, together with the higher fuel prices of the green fuels and additional cost for the fuel handling systems, could lead to financial setbacks.

The shipping sector is not the only industry whose goal is to reduce greenhouse gas (GHG) emissions; it faces competition from aviation, road transportation and other industries in the race for carbon-neutral energy. To meet its emission-reduction targets, the production of carbon-neutral fuel alternatives must increase significantly, which may bring about supply uncertainties and price fluctuations. As a result, shipowners need to consider every opportunity, such as fuel flexibility, to navigate these uncertain times.

Until now nuclear power has been used for ships mainly for military purposes and for the propulsion of icebreakers in the Arctic. However, at European level, nuclear energy has been identified as a sustainable source of energy able to assist in meeting the zero-emission goal of the EU and therefore is eligible to green sustainable financing.

Nuclear power has zero-emission during operation and low carbon during its lifecycle and research is ongoing. New applications are being studied to explore the feasibility of introducing nuclear reactors in shipping.

Therefore, nuclear power for shipping seems a pathway that could be explored to contribute to the decarbonization of the sector, but it presents a series of challenges that will need first to be addressed in relation to production, safety, security, training and also liability and insurance regime.

Nuclear technology

Key to expanding the use of nuclear reactors for merchant shipping is to have the right technology available in the near future and a collaborative global effort. The Generation IV International Forum (GIF) on nuclear systems is leading the advancement of some groundbreaking reactor concepts. The goal is to develop reactors that are safer, more sustainable, less waste-producing and to use technologies that are resistant to proliferation. Six technologies are in focus:

- Pressurised Water Reactor (PWR)
- Gas-cooled Fast Reactor (GFR)
- Lead-cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)
- Sodium-cooled Fast Reactor (SFR)
- Very High-Temperature Reactor (VHTR) / High-Temperature Gas-cooled Reactors (HTGR)

These '*Generation IV*' reactors, as they are called, offer the potential for efficient operation, as well as compact and reliable power for merchant vessels. Their benefits -- higher energy output, greater fuel longevity and potentially smaller reactor footprints -- could represent a technical solution for maritime power systems. Among these, VHTRs and MSRs are more suitable for marine use, given their high efficiency, load-following capabilities, and waste management advantages. LFRs, while valuable for niche applications or potentially specialised military vessels, may face challenges due to heavy shielding requirements.

Suitability of Reactor Types for Merchant Marine Applications and Availability of Fuel

Most of the nuclear-powered vessels that have been so far in operation are navy ships. When considering alone the type of reactors which are most suitable for merchant vessels, this largely depends on the availability and cost of fissile material. Reactor designs that can operate with a range of fissile materials may offer flexibility in fuel sourcing, helping to mitigate supply chain disruptions. This flexibility is particularly advantageous for countries seeking stable, long-term nuclear fuel options, supporting the resilience of nuclear-powered merchant shipping in a complex global market. Nuclear-powered vessels would also be better equipped to handle any changes in emission regulations and the associated costs, due to their long refuelling periods and almost zero emissions from a Tank-to-Wake perspective. In addition, considering the extended periods without the need for refuelling, nuclear power is especially well-suited for deep sea shipping.

The suitability also depends on factors like cost-effectiveness, operational compatibility, and regulatory acceptance. PWRs, VHTR/HTGR-based SMRs, and MSR-based SMRs rank among the most promising options. PWRs offer a high level of maturity and proven reliability, making them an attractive choice for integration into merchant fleets, though they require adaptation for optimised marine use. MSR and VHTR/HTGR-based SMRs, with their extended refuelling cycles, load-following capabilities passive safety, waste management advantages and compact designs, are ideal for long-haul vessels, such as bulk carriers and tankers, that prioritize low-maintenance, high-efficiency energy sources.

Sustainability

Nuclear propulsion presents a unique advantage in that its use almost produces no well-to-wake (WTW) emissions. The energy generation process in nuclear fission, which does not involve the combustion of fossil fuels, results in zero GHG tank-to-wake emissions during operation. Also, the upstream well-to-tank (WTT) emissions produced during the extraction, processing and transportation of uranium fuel can still be considered rather low, and eventually renewable energy could be used for the extraction, processing and for the transportations. Therefore, nuclear propulsion is a potential pathway to decarbonising the shipping sector, bypassing the production processes associated with green fuels which could be energy intensive.

Furthermore, the zero-CO_2 output during operation of nuclear-powered vessels offers significant environmental benefits, providing an additional incentive for investment. This aspect not only contributes to global efforts to combat climate change, but it could also enhance public readiness and acceptance.

Total Cost of Ownership

It is noted that some uncertainties can occur in any techno-economic analysis of new fuels based on the evolution of research and development and as policies mature. These may be even higher in the case of nuclear-powered vessels given that research is still ongoing and due to the lack of available data. Based on the assumptions made in this study and when considering uranium as fuel, the case studies of container ships, bulk carriers, liquefied gas carriers and oil tankers have demonstrated that the TCO for nuclear-powered and VLSFO-fuelled vessels are similar during the initial years of operation. However, over time, the operating-expense (OPEX) components in the TCO for VLSFO-fuelled vessels can increase in line with rising carbon costs and higher fuel expenses; this is expected to create a divergence in the TCOs of vessels powered by nuclear and very low sulphur fuel oil (VLSFO).

Although nuclear-powered vessels may have higher initial CAPEX, they could achieve lower OPEX over time as oil prices and carbon costs increase. The expected stable fuel costs and long refuelling intervals offered by advanced reactor designs like MSRs align well with the financial demands of merchant shipping over the vessel's operational life.

The maturity and advancement of nuclear technology could reduce the CAPEX of nuclear-powered vessels, making investments in this technology more attractive. Additionally, the importance of reduction in GHG and the introduction of a carbon tax can create more interest among investors.

Regulations

A substantial amount of regulatory work would be required to facilitate the adoption of nuclear power on merchant vessels. It may require the modernisation of regulatory frameworks to promote safety, environmental protection, technology integration and a comprehensive liability regime. While nuclear power could offer key benefits in meeting emission-reduction goals, not every nation is equally accepting this infrastructure. In countries with a low tolerance for nuclear applications, addressing the public perception surrounding nuclear power is expected to be paramount to the technology's trajectory for marine use. In these areas, merchant nuclear-powered vessels might be used if precise regulations and international oversight develop. This would also allow for smooth and co-ordinated efforts by Flag Administrations as a whole.

Creating and updating regulations would need to include an active '*partnership*' of industry and national and international regulatory authorities as well as classification societies in their technical supporting role for the definition of standards by the regulators at International and European level and in conducting risk assessments in the case of novel technologies and arrangements. These partnerships would need to include members with various areas of expertise and across multiple marine applications. Overall, with industry, regional and national involvement in aligning regulations and the assistance of class, first movers and promotional incentives could then have the potential to influence the creation of sustainable solutions for marine applications of nuclear power.

Risk and Safety

There is lack of updated analyses of the risks and adequacy of the existing regulatory framework in relation to nuclear-powered ships. In order to identify these risks and potential gap, this study assesses several potential designs for nuclear-powered vessels from the risk and safety perspectives. Three vessel types have been analysed:

- Cruise Ship with Lead-cooled Fast Reactor (LFR)
- Bulk Carrier with VHTR/HTGR
- Container Ship with VHTR/HTGR

The analyses highlighted a list of major concerns related to: radiation leaks and control; flooding, vessels sinking, capsizing; collision; grounding; manning and training; technology licences; compliance with non-proliferation treaty requirements; external risk (such as piracy, hijacking, terrorist attacks, etc.); shipyard licencing and technical capabilities; marine load variation and impact on nuclear reactor, material issue and regulatory requirements. These issues require further detailed studies to better understand the risks and additional safeguards that will be needed to mitigate the major hazards.

The Hazard Identification (HAZID) studies identified preventive and mitigative safeguards and recommendations for the vessel types that were studied. Not all safeguards and recommendations listed in present HAZID registers will apply to all the vessel types and need to be carefully considered. However, they are all listed and may help to inform safer designs and arrangements and the development of more specific, prescriptive requirements. Importantly, the additional safeguards and recommendations will contribute to further risk reduction.

Based on this study and the risk assessments conducted, several key recommendations have emerged and need to be addressed when designing the needed regulatory framework. All risks must be thoroughly identified and addressed, including qualitative and quantitative risk assessments, minimizing potential human error to the greatest extent possible, developing robust risk management plans, and ensuring safe operations. Additionally, the protection of nuclear reactors against external marine risks -- such as grounding, collision, submergence, capsizing, and cargo fires -- requires further study and appropriate regulation. Comprehensive studies are also essential to evaluate the technical, economic, and environmental impacts of nuclear power on merchant shipping, with a focus on safety, long-term fuel management, and risks associated with both routine operations and emergency scenarios.

By taking concerted action across the different areas and setting an appropriate holistic international legal framework, the maritime industry and regulatory bodies can address both technical and societal challenges, enabling nuclear power to become a viable, sustainable solution in merchant shipping.

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1. Introduction

1.1 Background

The ocean serves as the primary highway for international trade, with about 90% of goods moving by sea. In the past two decades, there has been a significant increase in public recognition of shipping's impact on the global environmental, despite its long-standing reputation as the most energy-efficient mode of freight transport (Hirdaris, et al., 2014). As a result, the industry is facing significant challenges from increasingly stringent environmental regulations. The increase in global temperatures – shipping is responsible for about 3% of the worldwide output of carbon-dioxide (CO_2), a component of the anthropogenic emissions behind global warming – require prompt action if society is to ensure a more sustainable future.

In April 2018, the International Maritime Organisation (IMO), shipping's governing body, agreed to reduce the GHG emissions from shipping and align itself with goals of the UN's Paris Agreement. Its initial strategy to reduce GHGs (Resolution MEPC.304(72)) included an ambition to reduce annual emissions by at least 50% by 2050 (compared to 2008). This strategy was revised in June 2023 (MEPC 80), increasing the levels of ambition to reach net-zero GHG emissions by or around (i.e., close to) 2050, providing the impetus for an international shift towards alternative sources of power. The IMO's mid-term measures (technical and economic) have yet to be decided. However, with the typical marine asset having a lifetime of more than 20 years and decisions pending for the new fleet, the transition needs to begin as soon as possible.

At the same time, the European Union (EU), through initiatives such as the European Green Deal and the 2030 Climate Target Plan, aimed to reduce GHG emissions by at least 55% by 2030 (relative to 1990) and achieve climate neutrality in 2050. All sectors are required to contribute to these targets, including maritime transport. The EU's '*Fit for 55*' package of measures has, for the most part, been adopted, including the extension of the EU Emissions Trading Scheme to maritime transport and the FuelEU Maritime Regulation. These initiatives are expected to incentivise the demand for renewable or zero-carbon fuels and confirm that the regulatory transition is already happening at a regional scale.

In addition to the new emerging regulatory framework, the uncertainties of globalisation, geopolitical shifts, digitalisation and cyber risks are all contributing to a complex operating landscape for shipping stakeholders, who will remain dependent on the effectiveness of new propulsion technologies, fuel strategies and energy solutions to address the global demand for maritime transport.

Decarbonisation strategies include renewable energy sources such as wind and solar (Hirdaris & Cheng., 2012), alternative fossil fuels such as natural gas, and non-fossil fuels such as biofuels. Low-carbon fuel options such as methanol, ethanol, ammonia and hydrogen are viable, but they pose challenges due to their lower energy density, which affects cargo space and the required frequency of refuelling (see the EMSA Study *"Potential of Hydrogen as Fuel for Shipping"* (EMSA, 2023). At the same time, shipping faces competition for carbon-neutral fuels from other industries, leading to potential challenges related to supply and price.

Nuclear power is a potentially feasible alternative to carbon-neutral fuels, offering minimal emissions and stability against fuel price fluctuations; it is promising for powering long voyages without refuelling (ABS, 2024) (World Nuclear Association, 2023). For the time being, there are many innovative modern nuclear power plant designs, but few have been designed, tested or demonstrated for marine applications. There is ongoing research into the feasibility and sustainability of nuclear-powered merchant vessels that consider modern safety standards and environmental concerns.

Many nuclear technologies are under development and the focus is currently on small-scale, modular nuclear fission reactors. Fission is characterised by the splitting of a larger atomic element into smaller elements through a process that releases energy. It is more mature than fusion, which is the process of combining two or more small atomic nuclei to form another substance and is distinct from fission. Fusion occurs naturally in stars and has yet to be developed for useful power generation applications. Another source of nuclear energy is provided by the radioactive decay that occurs naturally, releasing much smaller amounts of energy over long periods of time. These applications are often known as radioisotope batteries, in which the radioactive decay is converted into electricity. This has been applied to pacemakers and used as long-term energy sources for spacecraft equipment. The scope of this report is limited to nuclear energy from fission.

While the management of nuclear materials is highly regulated and controlled, nuclear fission technologies can offer high-energy density, reliable power and no generation of GHGs or other polluting emission other than those coming from production and decommissioning plants.

1.2 Scope and Objectives

The scope and objectives of this study examine the technical issues, regulatory frameworks and state of play for the application of nuclear power from fission. They address the potential for nuclear power to be used as an alternative power for shipping, a part of the EMSA tender EMSA/OP/43/2020 for '*Studies on Alternative Fuels/Power for Shipping*'.

The scope specifically addresses the tasks of the tender by:

- Providing a state of play on the use of alternative fuel/power in the shipping sector. (See Section 2 of this report for the findings under this task.)
- Providing a detailed description of existing safety and environmental standards/regulations/guidelines, as well as onboard handling and disposal radioactive materials (See Section 3 for the findings.)
- Providing a safety assessment of the fuelled/powered cargo and passenger vessels engaged in the short-sea (coastal) or deep-sea trades. In total, three assessments are offered. (See Section 4 for the findings).

1.3 Acronym List

Refer to Appendix I – Symbols, Abbreviations and Acronyms.

2. Use of Nuclear Power in the Shipping Sector

This section provides an overview of the state of play for using nuclear power in the shipping sector. It is divided into the following subsections:

- Fundamentals of Nuclear Power Plants
- Classification of Nuclear Power Plants
- Suitability of Reactor Type for Merchant Marine Applications and Availability of Fuel
- Sustainability
- Cost Developments and Techno-Economic Analysis

2.1 Fundamentals of Nuclear Power Plants

A nuclear power plant exploits the energy from atomic nuclei to generate electricity, a resource indispensable to modern civilisation. Throughout Subsection 2.1, the aim is to understand the operational aspects of nuclear power plants and how nuclear reactions are managed within them.

2.1.1 Nuclear Fuel and Radioactive Material Properties

Nuclear fuels play a key role in generating nuclear power; they are materials that undergo fission reactions within a reactor. The choice of nuclear fuel, its chemical and physical properties and the technologies used to harness nuclear energy are crucial for the efficient, safe and sustainable lifecycle operations of nuclear power plants. Below is a comprehensive overview of these aspects, along with the associated safety hazards and concerns.

2.1.1.1 Radiation

The process of fission, initiated by the absorption of a neutron, results in the division of large atomic particles into other fission products, additional neutrons and other emissions of alpha, beta and gamma radiation, as described in Table 1.

Table 1. Types of primary radiation

Type	Residual Nucleus Change in Neutrons	Residual Nucleus Change in Protons	Residual Nucleus Change in Charge	Form of Radiation	Radiation Charge	Example Shielding
α Alpha	-2	-2	-2	Helium Nucleus	+2	Paper, skin
β Beta	-1	+1	+1	Electron	-1	Plastic, glass, or aluminum
γ Gamma	No Change	No Change	No Change	Electromagnetic	0	Lead
Neutron	-1	No Change	No Change	Neutron	0	Water, cement

Alpha particles, being relatively heavy and positively charged, can be stopped by a sheet of paper or even human skin. However, they are highly dangerous if ingested or inhaled. Due to their high ionising power, alpha particles can cause significant biological damage if they come into direct contact with living tissues. This makes it crucial to prevent any internal exposure to alpha radiation.

Beta particles are lighter and can carry either a negative or positive charge. To a certain extent, these particles can penetrate the skin, but they can be effectively stopped by materials such as plastic or glass. Beta radiation poses external and internal health risks depending on the level of exposure. Protective measures must be taken to minimise contact and prevent ingestion or inhalation of beta-emitting materials.

Gamma rays are high-penetrating electromagnetic waves that require dense materials such as lead or several centimetres of concrete for effective shielding. Unlike alpha and beta particles, gamma radiation can penetrate deep into the body, posing serious health risks, including radiation sickness and an increased risk of cancer. The need for substantial shielding and careful monitoring is critical in environments where gamma radiation is present.

2.1.1.2 Chemical Properties

The most commonly used nuclear fuel is uranium, specifically its isotope U-235, which is fissile and capable of sustaining a nuclear chain reaction. Natural uranium contains about 0.7% U-235, and for most reactors, it needs to be enriched to increase the U-235 content. Uranium oxide (UO_2) is a typical form used in fuel pellets.

Another important fissile material is Plutonium-239 (Pu-239), which is generated from Uranium-238 (U-238) in a reactor's breeding process. Pu-239 is used in mixed oxide (MOX) fuel, which combines plutonium with natural or depleted uranium.

Also, Thorium-232 (Th-232) has potential as a nuclear fuel source. When Th-232 is bred into Uranium-233 (U-233), it becomes a fissile material like U-235, and though it can technically be used for weapons, the practical challenges associated with creating and sustaining a fission reaction in a reactor setting alongside Th-232 and its intermediate products contribute to its non-proliferation advantages. However, Operation Teapot (Military Effects Test) demonstrated the potential weaponisation of U-233 under specific conditions.

It is also important to note that the chemical challenges posed by nuclear waste, which contains fission products and transuranic elements. These byproducts, such as cesium-137 and strontium-90, are often highly radioactive and chemically reactive, necessitating robust containment and long-term storage solutions. Their chemical stability over time is essential to prevent environmental contamination, underscoring the need for advanced waste management strategies alongside fuel utilisation.

TRISO (TRi-structural ISOtropic) Particles

TRISO particles are an advanced type of nuclear fuel engineered to maximise safety, durability, and containment under extreme operational conditions, making them particularly well-suited for applications in the merchant shipping sector. Each TRISO particle contains a small uranium kernel encased within three protective layers: an inner porous carbon buffer, a dense pyrolytic carbon layer, and an outer layer of silicon carbide (SiC). This multi-layer structure not only provides an independent, self-contained barrier for the nuclear fuel but also enables each particle to act as its own containment vessel, offering superior shielding and structural integrity.

The inner porous carbon layer acts as a buffer that absorbs gaseous fission products generated during nuclear reactions, preventing internal pressure build-up that could compromise the particle. Surrounding this is a pyrolytic carbon layer, which reinforces the particle and adds another level of containment. Finally, the outermost silicon carbide layer serves as a robust ceramic shell, effectively preventing radioactive material release, even under extreme temperatures and mechanical stress.

This design gives TRISO particles an exceptional level of fission product retention -- a critical safety feature that makes them virtually meltdown-proof in conditions that could compromise traditional nuclear fuels. In maritime reactors, this resilience is vital, as TRISO particles ensure containment even in the event of accidental damage or extreme environmental conditions, minimizing radioactive release and adhering to strict maritime nuclear safety standards. Additionally, TRISO fuel's extended life cycles can reduce the frequency of refuelling, aligning with the long operational durations typically required in marine applications.

This built-in containment and durability make TRISO particles an ideal choice for advanced marine reactors, ensuring high safety and minimal environmental impact, which are essential for adopting nuclear power in the shipping sector.

2.1.1.3 Physical Properties

The high melting points of nuclear fuels is of significance. Nuclear fuels have high melting points (UO_2 melts at about 2,865°C), which are critical for maintaining structural integrity under the high-temperature conditions within a reactor. The density and thermal conductivity of nuclear fuels determine their efficiency in transferring the heat generated during fission. UO_2, for example, has a relatively low thermal conductivity, which affects the design of fuel rods used to prevent overheating.

2.1.1.4 Properties of Nuclear Fuels Used by Navies

Highly Enriched Uranium (HEU) is the most common fuel for naval nuclear reactors, using uranium enriched to significantly higher levels of the fissile isotope U-235 than in commercial reactors (often exceeding 90%). This fuel type allows for compact core sizes, which are ideal for the space constraints onboard submarines and carriers. Long refuelling intervals support extended missions without major refuelling outages. HEU shares the fundamental radioactive properties of all nuclear fuels.

While, HEU carries a higher proliferation risk and is therefore restricted from commercial use, it is theoretically possible for naval reactors to be modified to operate with Low Enriched Uranium (LEU) below 20% enrichment. Such adaptation would primarily involve adjustments to the fuel arrangement and core design but would retain much of the associated reactor technology, including shielding, cooling, heat conversion, and safety systems. Therefore, experience with naval reactors could offer relevant insights for commercial applications (including marine), although operational and regulatory differences remain.

2.1.1.5 First Chain Reaction

The first sustained nuclear chain reaction was achieved on December 2, 1942, under the leadership of Enrico Fermi, as part of the U.S.'s Manhattan Project. This historic event took place at the University of Chicago in a makeshift laboratory under the university's Stagg Field stands. The experiment was famously known as Chicago Pile-1 (CP-1).

The CP-1 experiment demonstrated that it was possible to initiate and control a nuclear chain reaction. The core mechanism behind this process was nuclear fission, where the nucleus of an atom, such as U-235, is split into smaller atomic units upon absorbing a neutron, as shown in Figure 1. The fission process releases a significant amount of energy, along with two or three more neutrons. The newly released neutrons can then induce fission in other nearby U-235 nuclei, creating a self-sustaining chain reaction.

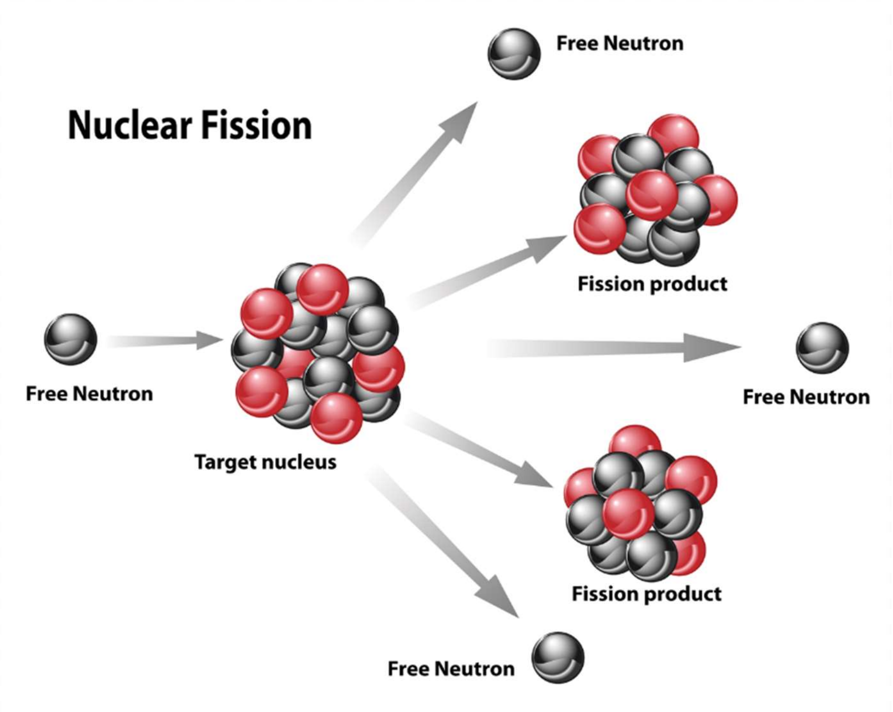

Figure 1. Nuclear fission reaction ©Shutterstock/OSweetNature

The setup for the first chain reaction consisted of a carefully arranged pile of graphite blocks as a neutron moderator to slow down the neutrons; embedded within this graphite lattice were uranium oxide and uranium metal. The design ensured that each fission event would, on average, cause just one more event, achieving a critical state where the reaction could sustain itself without escalating uncontrollably, or fizzling out. This breakthrough not only marked a pivotal moment in the field of nuclear physics, but it also set the stage for the development of nuclear energy and atomic weapons. It showcased the possibility of harnessing the immense energy of the atom for peaceful and military applications.

It is worth mentioning that the basic principle of nuclear fission was initially described by Niels Bohr and John Wheeler in 1939 in the paper "*The Mechanism of Nuclear Fission*" (Bohr & Wheeler, 1939).

2.1.2 Nuclear Criticality

'*Nuclear criticality*' is a condition in which a nuclear reaction sustains itself through a self-perpetuating series of reactions without external intervention. This state is achieved when the rate at which neutrons are produced in the reaction equals the rate at which they are lost, either through absorption or escape from the system. Criticality is a key concept in nuclear engineering and is crucial for the operation of nuclear reactors and the safe handling of fissile materials.

The interaction between neutrons and the nuclei of fuel atoms is central to the reactor's operation. In particular, certain isotopes, such as U-235, are prone to fission upon neutron absorption. This process splits the nucleus into two smaller nuclei, known as fission products, while releasing a significant amount of energy and additional highly energetic neutrons. Besides fission, neutrons can engage in other interactions, such as absorption -- where the neutron is effectively captured by the nucleus, removing it from the chain reaction -- and simple collisions. These collisions can be either elastic, resembling a hard sphere impact, or inelastic, where the neutron imparts energy to the nucleus without causing it to split. A nuclear assembly reaches a critical state when every fission event releases enough neutrons to, on average, cause exactly one more fission event. The multiplication factor denoted as 'k' equals 1 in this state. 'k' < 1 indicates a subcritical state and 'k > 1' indicates a supercritical state. If the reactor becomes supercritical, it can lead to an increase in power output and potentially dangerous conditions. If it becomes subcritical, the reaction will slow down and eventually stop. For a nuclear reactor to operate steadily and safely produce energy, it must maintain a critical state. Control rods, made of materials that absorb neutrons, are adjusted to keep the reactor at criticality. The management of criticality is meticulously orchestrated using control rods, moderators and coolant materials.

2.1.3 Nuclear Reactor Components

Currently, numerous countries are contemplating a greater reliance on nuclear power within their energy strategies, including the European Commission's '*Fit for 55*' package, as discussed in Subsection 3.2. This interest is driven by the need to address global warming, the worldwide surge in energy consumption and the comparative costs of different energy sources. Currently, there are approximately 440 nuclear-power reactors in operation across 33 countries including Taiwan, boasting a total capacity of around 390 GWe. In 2022, these reactors generated 2,545 TWh, accounting for roughly 10% of the global electricity supply. Around 30 countries are considering planning or starting nuclear power programmes. National regulations for nuclear power are discussed in Subsection 3.3, including Canada, Japan, South Korea, the United Kingdom (U.K.) and the United States of America (U.S.).

The challenges of ensuring adequate energy resources, combating climate change, improving air quality and securing energy supplies underscore the significant contribution nuclear power could make to future energy needs.

Although current nuclear power plants, which includes Generation II and III designs, offer a reliable and cost-effective source of electricity in numerous markets, there is still potential for innovation in nuclear technology. Advancements in the design of nuclear-energy systems could expand the scope of nuclear energy use. In pursuit of this potential, the *Generation IV International Forum* (GIF) was established in 2001 to collaboratively pursue international efforts aimed at advancing the research needed to assess the viability and effectiveness of modern nuclear systems, with the goal of making them ready for industrial implementation by 2030.

The GIF brings together 13 countries (Argentina, Australia, Brazil, Canada, China, France, Japan, South Korea, Russia, South Africa, Switzerland, the United Kingdom and the United States), along with Euratom – which represents the 27 European Union members − to collaborate on research and development related to these technologies. Based on a decision made by the EU Commission, Euratom joined GIF by officially signing the "*Charter of the Generation IV Forum*" in July 2003. Subsequently, Euratom became a party to the International "*Framework Agreement*" alongside other members of the Generation IV International Forum. The Joint Research Centre of the European Commission acts as the Implementing Agent for Euratom within GIF. In the U.S. Department of Energy's Office of Nuclear Energy has initiated comprehensive discussions with governments, industry stakeholders and the global academic community on the development of advanced nuclear-energy systems, termed '*Generation IV'*. For more information on the evolution of the design generations refer to Appendix X – Development of Nuclear Technology and An Inventory of Nuclear-Powered Vessels.

Nuclear reactors produce energy through a meticulously orchestrated process known as a controlled fission chain reaction. The fundamental operation of a nuclear power plant revolves around leveraging the heat produced by nuclear fission in the nuclear reactor. This thermal energy is then converted into steam, which propels turbines that produce electricity. This operational principle shares similarities with other power-generation plants that rely on coal and natural gas.

At the heart of all nuclear reactors lies a core set of components essential to their function. These include the fuel assemblies, which contain the nuclear material where fission occurs; control rods for regulating the fission process; and, in many reactors, a moderator to reduce the velocity of neutrons produced during fission. The coolant system plays a critical role in removing heat generated in the core, where the fuel, control rods, and moderator (if present) interact.

The reactor's core is housed within a pressure vessel. This vessel is constructed from heavy-duty steel to withstand the high pressures and temperatures encountered during the operation of the reactor, or during accidents and emergency conditions. Surrounding the pressure vessel and other critical components is the containment structure. Made of robust concrete and reinforced with steel, this barrier serves a dual purpose: it prevents the escape of radioactive materials during an accident; and it provides security against unauthorised access or external threats. Finally, an external cooling facility--such as a cooling tower or seawater system--dissipates excess heat into the environment to maintain safe operating temperatures.

The nature of neutron interactions, particularly their speed, is a defining characteristic that determines the type of nuclear reactor. Thermal reactors (explored in detail in Subsection 2.2.1.2), which are in focus as they are the most widely used and their principles apply broadly to other reactor types, rely on slow-moving neutrons to sustain the chain reaction. They are equipped with a moderator to reduce neutron velocity, enabling the fission process to continue efficiently. In contrast, fast reactors and fast breeder reactors (FBRs), discussed in Subsection 2.2.1.1, operate with high-speed, unmoderated neutrons to drive the fission process. This distinction underscores the diversity in nuclear reactor design, showcasing various strategies to harness atomic power for energy production and other applications. Thermal reactors, particularly small modular reactors (SMRs), are among those identified as having potential for adaptation within the maritime industry.

Thermal-nuclear reactors are designed around a fundamental principle of nuclear physics: U-235, a fissile material, is more susceptible to fission when bombarded with slow (thermal) neutrons compared to fast neutrons. This characteristic underpins the operational efficiency of thermal reactors. The most common moderators, used to slow down the fast neutrons, are light water (H_2O), heavy water (deuterium oxide, D_2O), and graphite (carbon in a solid form). Each moderator has unique properties that make it effective at reducing neutron velocities, thus facilitating more efficient fission reactions with U-235. Different types of moderators used for thermal reactors are discussed in Subsection 2.2.2.

Given U-235's great propensity to undergo fission with slow neutrons, thermal reactors are designed to operate with fuel assemblies consisting of either natural uranium, which contains about 0.7% U-235, or slightly enriched uranium, where the U-235 concentration is increased to around 2-5% (see Subsection 2.1.1 for more details). To control the fission process within the reactor core, control rods made from neutron-absorbing materials -- such as cadmium or boron -- are strategically placed adjacent to or between the fuel assemblies. The precise positioning of these control rods is critical for regulating the intensity of the fission chain reaction, essentially acting as a throttle for the reactor's power output. The role of the coolant in a thermal reactor is twofold. Firstly, it is responsible for transferring the substantial heat generated in the core to a steam generator, where steam is produced to drive the turbines connected to electricity generators. Secondly, in thermal reactors that use H_2O or D_2O as a coolant, the coolant also performs the function of a moderator, contributing to the reduction of neutron speeds. For thermal reactors that use gaseous coolants, such as CO_2 or helium (He), graphite serves as the primary moderator, decoupling the moderation and cooling functions.

Cooling towers, the distinctive, often hyperboloid structures associated with many nuclear power plants (and some coal and natural gas plants), play a vital role in the plant's thermal management system. After steam passes through the turbines, it is condensed back into water in a condenser, and the cooling towers dissipate heat from the condenser's cooling water before recirculating it back into the cooling system. Efficient operation of cooling towers is essential for maintaining the reactor's overall thermal efficiency and helps minimise environmental impact by reducing the amount of heated water discharged into nearby water bodies. Understanding the dual-role elements within a thermal reactor's fuel assembly sheds light on the intricacies of nuclear power generation. In these reactors, while U-235 is the primary fuel undergoing fission to release energy, U-238, a more abundant isotope present in the assembly, plays a pivotal role in the reactor's lifecycle by absorbing neutrons. This absorption process transmutes the U-238 into Pu-239, a fissile material. Remarkably, around one-third of the energy output in a thermal power reactor is attributed to the fission of this plutonium, underscoring its significant contribution to the reactor's overall production of energy (Zohuri & Fathi, 2015).

Nuclear power plants are optimised for maximal energy production and retain their fuel assemblies within the core for extended periods, often for years without refuelling. The extended duration enhances the efficiency of energy production by fully exploiting the fission process of uranium and plutonium within the fuel. Despite the primary focus on the generation of energy, it remains feasible to extract plutonium from the spent fuel assemblies of power reactors. This process, although secondary to the reactor's energy-producing objective, contributes to the versatility of nuclear technology by providing a method to recycle and reuse material from spent fuel, extending the fuel's lifecycle and potentially contributing to a more sustainable nuclear fuel cycle. However, the extraction of plutonium also introduces an increased proliferation risk, as the material could potentially be diverted for weapons production. This dual-use aspect underscores the need for stringent regulatory oversight and secure handling protocols to balance sustainability with non-proliferation objectives.

Nuclear reactors vary widely in design, yet they share core operating principles. What differentiates one design from another is its unique implementation. To help distinguish among the reactor types, several classification systems are in place. These will be concisely explained in Subsection 2.2 under three primary classification categories by: (1) moderator material, (2) coolant material and (3) reaction type. Further on, the common reactor types implementing these classification systems will be outlined. The overview is intended to shed light on the diverse technologies utilised in the generation of nuclear power, providing a clear understanding of how the reactors operate and are categorised. An example of a nuclear reactor is shown in Figure 2, where a conventional, simplified pressurised water reactor (PWR) is showing the flow of coolant through the core, consisting of fuel and control-rod components, as well as the moderator surrounding the core.

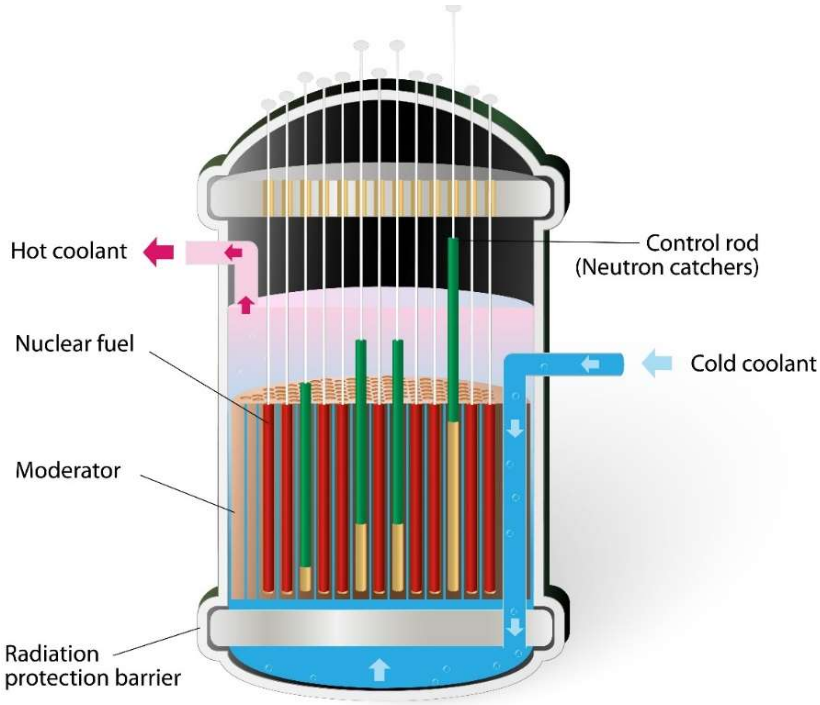

Figure 2. Schematic of nuclear reactor ©Designua/Shutterstock

2.1.4 Nuclear Reactor Capacity

The capability of a nuclear power plant to generate electricity is quantified in terms of its electrical power output, measured in megawatts of electricity (MWe). This measurement, however, represents only a portion of the reactor's thermal energy output, denoted as megawatts of thermal energy (MWt), due to the inefficiencies involved in the conversion of heat to electricity. Typically, the electrical power output constitutes about one-third of the reactor's thermal energy production, highlighting the significant loss of energy during the conversion process. The relationship between electrical and thermal output is a critical aspect of the power plant’s efficiency and design considerations. More information on energy balance is shared in Subsection 2.1.6.

According to annex IV of International Atomic Energy Agency (IAEA) (IAEA, Nuclear Technology Review 2007, 2007), small-sized reactors are defined as having an equivalent electric power of less than 300 MWe. While medium-sized reactors are those with an equivalent electric power ranging from 300-700 MWe. A large reactor has a power output exceeding 700 MWe. In addition, reactors with output power of 1-10 MWe are called '*microreactors*' (National Academies of Sciences Engineering and Medicine, 2023).

Another important metric for evaluating reactor performance is burnup, which measures the amount of energy extracted from nuclear fuel, expressed in gigawatt-days per metric ton of uranium (GWd/MTU). Burnup is defined as the energy produced per unit mass of fuel, calculated based on the total thermal energy output relative to the initial mass of the nuclear fuel. For instance, a burnup rate of 40 GWd/MTU indicates that one metric ton of uranium fuel has produced 40 gigawatt-days of energy. High burnup rates indicate efficient fuel utilisation, reducing both refuelling frequency and the volume of spent fuel generated. Advanced reactors, such as PWRs and some Gen IV designs, can achieve burnup levels of 60 GWd/MTU or more, extending fuel life and lowering fuel cycle costs.

The capacity factor is a critical metric for evaluating reactor performance as it offers insight into the operational efficiency and reliability of a nuclear power plant. The capacity factor is defined as the ratio of the electrical output of a reactor over a specified period to the hypothetical output it would have produced if it was operated at full capacity during the same period. Factors influencing the capacity factor include operational interruptions for maintenance, repair and the periodic removal and replacement of fuel assemblies. Over the years, there has been an improvement in the capacity factors of reactors, though it varies by country.

In France, for example, the capacity factor was increased from 60% in 1990s to 70% in recent years, which is considered low by world standards. This is because France's nuclear reactors comprise 90% of Électricité de France's (EDF) capacity and therefore are used in load-following mode[2] (World Nuclear Association, 2024). In the United States, on the other hand, the average capacity factor has escalated from around 50% in the early 1970s to more than 90% in recent times. This remarkable increase reflects advancements in reactor technology, operational practices and maintenance efficiency; it has contributed to higher productivity from reactors and helped to maintain more affordable electricity prices.

The evolution of reactor efficiency underscores the complex interplay between technological innovation, energy policy and environmental considerations. Burnup and capacity factor together serve as key indicators of how efficiently a reactor utilises its fuel and sustains energy production over time. As reactors have become more efficient and reliable, they have played a pivotal role in meeting energy demands, while also posing challenges and opportunities in terms of nuclear proliferation and environmental sustainability.

2.1.5 Conventional Land-Based Nuclear Power Plants

The landscape of nuclear-power generation is predominantly characterised by the operation of water-moderated, thermal reactors, the most common type of reactors in operation globally. These reactors are primarily divided into two categories based on the type of water they use for moderation and cooling (for more details refer to Subsection 2.2): Light water reactors (LWRs) and heavy water reactors (HWRs). LWRs use ordinary water (H_2O), while HWRs use D_2O, which contains the heavier isotope of hydrogen, deuterium, offering a more effective moderation than H_2O. The choice between light and heavy water as a moderator is significant in that it influences the reactor's design, efficiency, fuel requirements and overall operational strategy.

The more prevalent LWR types are further subcategorised as PWRs and boiling water reactors (BWRs), each with its unique approach to managing the water that cools and moderates the reactor core. In PWRs, the water is kept under high pressure to prevent it from boiling, even when superheated. This superheated water circulates

[2] Load-following mode in nuclear reactors refers to the capability of a nuclear power plant to adjust its power output based on the demand from the electrical grid. Unlike base-load operation, where the plant runs at a constant, maximum power output, load-following allows the plant to increase or decrease its power generation in response to fluctuating electricity demand. This mode is essential for integrating nuclear power into grids with significant shares of variable renewable energy sources (such as wind and solar) which can cause rapid changes in power demand.

through the reactor core, absorbing the heat generated from nuclear fission. It then transfers this heat to a secondary water loop via a heat exchanger, where the secondary water is turned into steam to drive the turbines that generate electricity. Crucially, the water in the primary loop of a PWR does not mix with the water in the secondary loop, ensuring that radioactive material does not leave the containment structure. Refer to Subsection 2.2.3.1 for more details.

Conversely, in BWRs, the water circulating through the reactor core is allowed to boil, creating steam directly within the reactor vessel. The steam then travels directly to the turbines, without a secondary loop, driving them to produce electricity. After its energy is used, the steam is condensed into water and returned to the reactor core. The direct use of steam from the reactor to drive turbines simplifies the BWR design, but it requires stringent controls to ensure the purity and safety of the steam exiting the containment structure. Refer to Subsection 2.2.3.2 for more details.

Both types of LWRs utilise low-enriched uranium fuel, necessitated by the neutron-absorption properties of light water. The enrichment process increases the concentration of U-235 in the fuel, compensating for the neutrons absorbed by the water and ensuring a sufficient rate of nuclear fission within the reactor core (Statista, 2023).

As of July 2024, there were 167 operational nuclear reactors in Europe (Statista, 2023). Of these, 144 are LWRs, including 132 PWRs and 8 BWRs (NEI, 2024). This leaves an additional 4 LWRs, which may include other sub-types, such as water-water energetic reactors (known as WWER or VVER) developed in the Soviet Union. France has the highest number of operational reactors, with 56 units (Statista, 2023). The remaining reactors include two HWRs in Romania, two FBRs in Russia, 11 light-water-cooled graphite-moderated reactors in Russia, and eight gas-cooled reactors in the United Kingdom. Table 2 provides detailed information on active nuclear reactors, including their capacities and locations across Europe.

Table 2. Active nuclear reactors, their capacities, and locations in Europe.

Country	Active Reactors	Capacity (MWe)	Reactors under Construction	Capacity under Construction (MWe)
Belarus	2	2,220	-	-
Belgium	5	3,928	-	-
Bulgaria	2	2,006	-	-
Czech Republic	6	3,934	-	-
Finland	5	4,394	-	-
France	56	61,370	1	1,630
Hungary	4	1,916	-	-
Netherlands	1	482	-	-
Romania	2	1,300	-	-
Russia	36	26,802	4	3,759
Slovakia	5	2,308	1	440
Slovenia	1	688	-	-
Spain	7	7,121	-	-
Sweden	6	6,882	-	-

Country	Active Reactors	Capacity (MWe)	Reactors under Construction	Capacity under Construction (MWe)
Switzerland	4	2,960	-	-
Ukraine	15	13,835	-	-

In the U.S., the dominance of LWR technology is evident; all of its 103 nuclear power plants employ this type of reactor. Among these, 69 are PWRs, while the remaining 34 are BWRs.

Globally, approximately 425 nuclear reactors are operational, with around 11% being HWRs, primarily located in Canada (World Nuclear Association, 2024). The predominance of LWRs highlights the historical evolution and regulatory landscape of the nuclear-power industry, which has traditionally favoured LWR technology due to its established safety, reliability and efficiency. The continued reliance on LWRs emphasises their central role in global energy strategies, significantly contributing to efforts to maintain a stable, low-carbon energy supply amid rising energy demands and environmental challenges.

2.1.6 Energy Balance Equipment

The energy balance of a nuclear power plant reflects the distribution and conversion of energy from nuclear fuel into electrical power and other forms of energy during the plant's operation. It involves several key processes and components, from the initial nuclear reaction to the final delivery of electricity to the grid, with losses and efficiencies along the way. Understanding this balance is crucial for evaluating the efficiency and environmental impact of nuclear power. For conventional nuclear power plants, the equipment used in power conversion includes turbines and generators to produce electricity and transformers to step up voltage and distribute power to the grid, . The energy conversion equipment can be major components that would increase the overall effort to install and maintain.

Not all the heat produced in the reactor is converted to electricity. A significant portion is lost to the environment, primarily through the cooling system, which might use water from a river, lake, or cooling towers to dissipate excess heat. Typically, nuclear power plants have a thermal efficiency of about 30-40%, meaning that 60-70% of the thermal energy produced by fission is not converted into electrical energy. The efficiency rate is similar to that found in fossil-fuelled power plants, but lower than in some modern gas-fired plants.
The waste heat must be effectively removed and dissipated to prevent the plant's systems for overheating. This is usually achieved through large cooling towers or direct water-cooling systems, which can have environmental impacts, such as the thermal pollution of aquatic ecosystems.

The energy balance of nuclear power plants includes the entire process of converting nuclear energy into electrical energy, dealing with inherent inefficiencies and managing the heat and radioactive materials that are produced. Despite the losses, a nuclear power plant offers a low-carbon source of continuous power, contributing significantly to the energy mix. Continuous advancements in reactor technology, such as the development of fast reactors and SMRs, aim to improve the efficiency and safety of nuclear power, potentially altering its energy balance for the better.

The most common types of commercial reactors worldwide, PWRs and BWRs, can operate at thermal efficiencies typically in the range of 30-36%. Their limited efficiency is partly due to the thermodynamic properties of water and the need to keep the reactor pressure vessel at a temperature that water remains liquid (in the case of PWRs) or produces steam at manageable pressures (in BWRs). CANada Deuterium Uranium (CANDU) Reactors, which are a type of HWR, have similar efficiencies to LWRs, generally around 29-34%. The use of D_2O as a moderator allows these reactors to use natural uranium as fuel, but it does not significantly impact the overall thermal efficiency compared to LWRs.

VHTRs/HTGRs[3] can achieve higher thermal efficiencies, around 40-50%, due to their ability to operate at higher temperatures. The gas coolant (usually He) can be heated to around 700°C without reaching high pressures, making it possible to use more efficient thermodynamic cycles, such as the Brayton cycle, to generate power. FBRs are designed to breed fuel (create more fissile material than they consume) and, theoretically, can achieve higher efficiencies (around 40-45%) because they operate at higher temperatures than traditional reactors. However, practical efficiency values can vary based on specific reactor designs and operational parameters[4].

Advanced Reactors and Generation IV Concepts aim for even higher thermal efficiencies, potentially reaching 45-50% or more. These reactors are designed to operate at very high temperatures, allowing for more efficient conversion of heat to electricity. For instance, Molten Salt Reactors (MSRs) can operate at high temperatures without high pressures. The efficiency of MSRs can vary widely depending on which reactor technology is used. Some designs are based on traditional PWR technology and may have similar efficiency to larger PWRs, while others incorporate advanced materials and cooling systems aiming for higher efficiencies.

The cooling cycle itself is a key element of the plant's energy balance. As heat is produced in the reactor, it must be dissipated to ensure the plant operates within safe thermal limits. The cooling system often uses water from natural sources such as rivers or lakes, or through dedicated cooling towers, to transfer excess heat away from the plant. This process can result in thermal pollution, as warmer water is returned to the environment, potentially affecting local ecosystems. The efficiency of the cooling cycle is therefore not just a technical concern but also an environmental one. A more efficient cooling system not only enhances the plant's overall energy balance but also minimises its ecological footprint.

Thermal cooling cycles are central to improving this efficiency. Traditional nuclear reactors use the Rankine Cycle, where steam is generated to drive turbines, but the maximum efficiency of this process is limited by the operating temperatures and pressures. For instance, the steam produced in PWRs typically reaches temperatures of 300-350°C. The cooling cycle in these reactors ensures that the steam condenses back into water after passing through the turbines, allowing the cycle to repeat. However, the process of condensation and reheating introduces losses that contribute to the relatively low efficiency.

To address these limitations, advanced nuclear reactors and cooling cycles are being developed. Next-generation designs, such as VHTRs/HTGRs and MSRs, can operate at much higher temperatures. By raising the operating temperature of the reactor core, these reactors can employ more efficient thermodynamic cycles, such as the Brayton Cycle and supercritical CO_2 (sCO_2) cycles, which enable more direct and efficient energy conversion. In these cycles, gases like He or CO_2 are used as coolants, which can be heated to much higher temperatures without reaching high pressures. This allows for the use of more efficient heat-to-electricity conversion processes, raising thermal efficiencies to 40-50%, compared to the 30-36% range seen in conventional reactors.

In the Brayton Cycle, for example, the reactor heats a gas (like He or CO_2), which expands and directly drives a turbine. This bypasses the need for steam generation and condensation, reducing the inefficiencies found in the Rankine Cycle. sCO_2 cycles take this concept further by using CO_2 in a supercritical state, where it behaves as both a gas and a liquid, allowing for extremely efficient heat transfer and power generation. These advanced cooling cycles not only improve the overall thermal efficiency but also reduce the amount of waste heat that must be dissipated, thereby improving the plant's energy balance and reducing environmental impacts.

Furthermore, the integration of combined cycles into nuclear plants represents another promising approach to improving energy balance. In combined cycle systems, the heat from the primary thermodynamic cycle (like the Brayton Cycle) is used to generate steam for a secondary Rankine Cycle. This two-stage process allows the plant to extract more useful energy from the heat produced, significantly boosting overall efficiency. In some cases, these combined cycles can push thermal efficiencies beyond 50%, making nuclear power more competitive with advanced gas-fired power plants.

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[3] It is noted that the terms HTGR and VHTR are used interchangeably in this study. Both refer to gas-cooled reactors utilizing TRISO fuel, with operating temperatures (above 700°C). VHTRs are often associated with higher operating temperatures (above 850°C), while HTGRs cover a broader range of high-temperature operations.

[4] The thermal efficiency of a nuclear reactor power plant and its thermodynamic cycle describes the ability to generate useful electric energy from thermal energy produced by the nuclear reactor during the fission process. Fuel efficiency, which refers to the consumption of nuclear fuel or fissile materials over time, is a separate measure.

2.1.7 Nuclear Safety and Protection from Radiation

Nuclear fuel undergoes fission, a process where the nucleus of an atom splits into two or more smaller nuclei, releasing a tremendous amount of energy. The energy is primarily harnessed to generate electricity in nuclear power plants. The process of fission not only produces the desired energy output, but it also generates byproducts that are highly radioactive and must be addressed by the plants' designs and arrangements. These byproducts pose significant challenges due to the radiation they emit, such as alpha particles, beta particles, gamma rays and neutrons. Each type of radiation possesses unique properties and penetration levels, necessitating specific handling and protection measures to ensure safety. Refer to Subsection 2.1.1.1 for more information on the physics of radiation.

The neutrons, neutral particles released during fission, are highly penetrating and can make other materials radioactive through a process called neutron activation. Shielding against neutrons typically involves using materials rich in hydrogen, such as water or polyethylene, which effectively slow and capture the neutrons. Proper neutron shielding is essential to prevent secondary radiation hazards and to ensure the safety of personnel and the environment. It involves the use of thick, dense materials around the reactor core and storage facilities to absorb and block the radiation. The design and implementation of these shielding measures are crucial to minimising exposure to radiation. In addition to physical shielding, strict handling protocols are essential to ensure the safety of workers and the public. Controlled environments are maintained by using containment structures designed to prevent the release of radioactive materials. These structures are engineered to withstand accidents and natural disasters. Protective equipment plays a vital role in safeguarding workers from radiation exposure. Specialised clothing and equipment are given to personnel to shield them from radiation. The equipment includes lead-lined garments, respirators and gloves, all designed to offer maximum protection in high-radiation areas.

Monitoring and detection systems are implemented to continuously assess radiation levels. These systems allow for the early detection of leaks or exposure incidents, enabling prompt response and mitigation measures. Regular monitoring is implemented to check that any deviations from safe radiation levels are quickly identified and addressed.

Training and procedures are fundamental components of radiation safety. All personnel working with, or around nuclear materials must undergo rigorous training in radiation safety and emergency-response procedures. This training gives them the knowledge and skills to handle radioactive materials safely and to respond effectively to any incidents. By adhering to these measures, the risks associated with the handling and use of nuclear fuel can be effectively managed. Ensuring the safety of individuals and the protection of the environment requires a comprehensive approach that integrates shielding, handling protocols, monitoring and training. Through these efforts, the benefits of nuclear energy can be harnessed while minimising the hazards associated with radiation.

2.2 Classification of Nuclear Power Plants

Nuclear power plants have evolved significantly over time, with the current 'generation' of reactors, known as '*Generation IV*' or '*Gen IV*', focusing on innovative features of conventional PWRs and additional efforts to develop other types of reactors:

- Gas-cooled Fast Reactor (GFR)
- Lead-cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)
- Sodium-cooled Fast Reactor (SFR)
- Very High-Temperature Reactor (VHTR) / High-Temperature Gas-cooled Reactors (HTGR)

While the previous generation of PWRs has provided compact, reliable power, Gen IV reactors offer the potential for even more efficient operation. Higher energy outputs, greater fuel longevity and potentially smaller reactor footprints could revolutionise power systems. In this report, PWRs and the five types of reactors listed above are considered for marine application in Subsection 2.3. First, to describe the differences between all types of reactors, this section discusses the principle properties and characteristics of reactors that differentiate nuclear power plants.

SMRs are defined as reactors with less than 300 MWe of installed power per unit. They represent an evolution in nuclear power technology, characterised by their smaller size, modularity and the ability to be fabricated at a central facility before being transported to a site for installation. This approach offers several benefits, including lower initial capital investment, increased safety features and the flexibility to match power generation to demand. The scaled-down power output and size may allow for additional operational deployments for remote locations, small towns, specific industrial facilities, or other specific applications such as offshore installations or power for merchant shipping.

As known from the shipbuilding industry, the modular design of SMRs could support the mass production of reactor units at centralised facilities, allowing for efficient transportation and installation at operating sites. With these considerations in mind, SMRs may be able to access the market for merchant shipping and floating nuclear power-plant applications. The term SMR is specific to the size, however, they can vary widely depending on the reactor technology that is used. Some SMR designs are based on traditional PWR technology and may have efficiencies similar to larger PWRs, while others incorporate advanced materials and cooling systems that aim for higher efficiencies. Integral Pressurised Water Reactors (iPWRs) are the most common type of SMRs currently under development; they resemble traditional PWRs, but on a smaller scale. They also integrate the primary system components, such as the steam generator and pressuriser, into a single container for the reactor. Similarly, as explained earlier, microreactors are smaller than SMRs (less than 10 MWe of installed power per unit).

Nuclear reactors come in various designs, each with its unique approach to achieving the same fundamental goal: safely and efficiently converting nuclear energy into electrical energy. In general, all nuclear reactors extract energy from the fission process originating from the fuel and incorporate materials that affect the fission process or contribute to radiation safety. Despite the diversity of designs, reactors can be broadly categorised according to the energy spectrum of the reaction (thermal or fast reactors), the moderator material used in thermal reactors and the coolant material that is used. Each characteristic highlights different aspects of reactor technology. Here, the common reactor types are outlined based on three primary classification criteria:

Reaction Type

This classification is based on the speed of the neutrons that sustain the reaction in the fission chain and, by extension, the design philosophy of the reactor.

- Fast Neutron Reactor (FNR): Operates with unmoderated (fast) neutrons, typically requiring fuel that is more highly enriched in fissile material.
- Thermal Neutron Reactor (TNR): Uses moderated (slowed down) neutrons to sustain the fission process, compatible with a wider range of fuel types, including low-enriched uranium.

Moderator Material

This classification defines the type of material used to slow down neutrons in thermal reactors to facilitate the fission process.

- Light Water Reactor (LWR): Uses ordinary water (H_2O) as a coolant and a neutron moderator. This includes PWRs and BWRs.
- Graphite Moderated Reactor (GMR): Employs graphite, a form of carbon, to moderate neutrons without significantly absorbing them. These can be arranged with graphite acting as the primary moderator and water or gas circulating as the coolant.

- Heavy Water Reactor (HWR): Uses D_2O, which contains the deuterium isotope of hydrogen, as a moderator, allowing for the use of natural-uranium fuel, reducing fuel enrichment costs while maintaining high neutron economy (NEA, 1994) (IAEA, 2002).

Coolant Material

This categorisation focuses on the substance used to extract heat from the reactor core, a critical component in converting nuclear energy to electrical energy. Different reactor designs use specific coolants to optimise performance:

- Pressurised Water Reactor (PWR): Uses water under high pressure to prevent boiling, transferring heat to a secondary loop for steam generation. This design ensures that radioactive water from the core remains isolated from the turbine system, improving safety.

- Boiling Water Reactor (BWR): Allows water to boil within the reactor vessel, producing steam directly for turbine operation. Its simpler design eliminates the need for a separate steam generator but requires stringent controls to manage radioactive steam.

- Gas Cooled Reactor (GCR): Employs inert gases, such as CO_2 or He, as coolants, enabling higher temperatures and increased efficiency. The use of gas as a coolant allows for lower corrosion risks compared to liquid coolants; however, gas generally has lower thermal conductivity than liquids like water or molten metals. This difference in thermal conductivity impacts the reactor's heat transfer efficiency, requiring design adaptations to maintain effective cooling.

- Liquid Metal Cooled Reactor (LMCR): Utilises molten metals, like sodium, lead, or lead-bismuth, allowing for operation at high temperatures with near-atmospheric pressure. These coolants have excellent heat-transfer capabilities but require careful management due to their chemical reactivity.

- Supercritical CO_2 Reactor (sCO_2): Uses supercritical CO_2 as a coolant, which operates at high temperatures and pressures, significantly improving thermal efficiency and reducing system complexity. The use of supercritical fluids enables more efficient energy conversion cycles, like the Brayton cycle.

- Supercritical Water Reactor (SCWR): Operates at supercritical pressures and temperatures, where water acts both as a coolant and a working fluid in the turbine cycle. SCWRs offer enhanced thermal efficiency and reduced infrastructure complexity by eliminating the need for phase change from liquid to steam.

- Molten Salt Reactor (MSR): Uses molten fluoride or chloride salts, such as lithium fluoride, as a coolant and, in some designs, as the medium in which the nuclear fuel is dissolved. MSRs can operate at very high temperatures, improving thermal efficiency while also offering inherent safety features, such as passive heat dissipation.

- Heavy Water Reactor (HWR): Uses D_2O as both a coolant and a neutron moderator.

Each classification sheds light on the nuanced approaches to nuclear-reactor design, reflecting the different strategies engineers and scientists employ to harness nuclear energy safely and efficiently. Understanding these classifications gives insight into the technological diversity and innovation underpinning the nuclear power industry. More details can be found in the following subsections.

2.2.1 Classified by Reaction Type

2.2.1.1 Fast Neutron Reactors (FNR)

FNRs, also referred to as Fast Breeder Reactors (FBRs) if it is specifically designed to breed more fissile material than it consumes, represent a revolutionary approach in nuclear technology in that they leverage the potential of depleted nuclear waste as a valuable energy resource. Unlike conventional reactors that primarily use U-235

(0.7% of natural uranium), FNRs are designed to make efficient use of the more abundant U-238 (99.3% of natural uranium), converting it into isotopes such as Pu-239 and Pu-241, which can continue a fission reaction. This process not only expands the fuel resource base, but it also enhances the overall efficiency of nuclear power generation.

Different types of reactors that fall under this category -- and certain reactors traditionally not classified as fast reactors -- can be configured to operate within the fast-neutron spectrum. The FNR category can cover various reactor types, including the GFR, LFR, and SFR. Furthermore, VHTRs/HTGRs and MSRs can be designed to operate within the fast-neutron spectrum, further expanding the versatility and potential applications of this advanced nuclear technology.

VHTRs and HTGRs while not always strictly classified as FNRs, can be configured to operate within the fast-neutron spectrum. These advanced reactors utilise helium gas as a coolant and achieve extremely high core outlet temperatures, with VHTRs sometimes exceeding 1000°C, while HTGRs typically operate at temperatures around 800–850°C. Such high temperatures make them particularly promising for applications beyond electricity generation, including hydrogen production and industrial heat processes. The designs of VHTRs/HTGRs emphasise passive safety features and exceptional thermal efficiency, which contribute to their versatility and suitability for a broad range of uses. VHTRs/HTGRs demonstrate flexibility by being capable of functioning in both thermal and fast neutron spectrums. This adaptability enhances their appeal for diverse industrial and energy applications.

A significant advantage of FNRs is their operational efficiency, which is estimated to be 60% greater than traditional nuclear reactors. The increased efficiency is partly due to the use of liquid-metal coolants -- such as sodium or a bismuth eutectic -- in some FNR designs; these offer superior thermal properties than water. These coolants facilitate the extraction of heat more effectively, allowing the reactor to operate at higher temperatures and thereby improving its thermal efficiency. Additionally, the metallic nature of the fuel used in FNRs contributes to a more stable operation of the reactor, enabling better control of the fission process.

However, FNR technology also comes with its challenges. The high reactivity and the presence of liquid metal coolants introduce complexities in the design and operation of the reactor. The potential for more dynamic behaviour and the need to manage the heat more effectively to prevent overheating are notable concerns. Moreover, the use of exotic coolants such as liquid sodium poses additional safety and engineering challenges, given their chemical reactivity and the need for specialised handling and containment systems.

Globally, research and development efforts are underway to refine and improve FNR technology, particularly focusing on enhancing safety features, operational stability and fuel efficiency. These advanced reactors may have the ability to significantly extend the fuel supply by using U-238, which comprises most natural uranium, and by efficiently recycling spent nuclear fuel.

FNRs have the potential to transform the nuclear energy sector by offering a sustainable and efficient method to generate power. By optimising the use of available nuclear materials and minimising waste, FNRs could play a crucial role in addressing some of the most pressing concerns associated with nuclear power: the risk of proliferation, the management of long-lived radioactive waste and the sustainability of nuclear fuel resources. The integration of advanced recycling technologies, such as pyrometallurgical processing, with FNRs could further revolutionise this sector. This combination would not only significantly reduce the volume and toxicity of nuclear waste, but it would also shorten the time required for the radioactivity of the waste to decline to safe levels, potentially mitigating the need for long-term storage solutions.

FNRs offer a forward-looking approach to nuclear energy, advertising enhanced efficiency, reduced waste, and a more sustainable use of nuclear materials. As these technologies evolve and mature, they could mark a new era in nuclear power, aligning it more closely with global energy, environmental and safety goals, and making nuclear energy a more viable and sustainable option for the future.

2.2.1.2 Thermal Neutron Reactor (TNR)

TNRs operate on a principle distinct from that of FNRs, specifically in the methodology of neutron moderation and its implications for the fission process, including plutonium production. Unlike FNRs, where fission is driven by high-energy (fast) neutrons, thermal reactors employ a neutron moderator to decelerate neutrons until they reach thermal energies, aligning with the average kinetic energy of particles in their surroundings. This moderation process transforms the neutrons to a low-velocity state, significantly enhancing their ability to induce fission in U-235.

The effectiveness of a neutron in causing fission is quantified by its fission cross-section, a measure of neutron's likelihood to interact with a fissile nucleus. For U-235, the fission cross-section is significantly higher for slow (thermal) neutrons -- approximately 1,000 times more than that for fast neutrons. This difference underscores the critical role of neutron speed in determining the efficiency of the fission process. Neutrons are moderated from their initial high energy state -- typically around 2 million electron volts (MeV) when they are produced in fission events -- to thermal equilibrium energies around 0.025 electron volts (eV), a process that reduces their kinetic energy by nine or more orders of magnitude. Due to their lower kinetic energy, these slow neutrons, or thermal neutrons, have a higher probability of interacting with and splitting the nucleus of fissile atoms, making them more effective in sustaining the chain reaction essential in producing energy. Thermal equilibrium is reached when the speed of the neutrons matches the thermal motion of the atoms within the reactor's environment, making these neutrons '*thermal neutrons*'.

The phenomenon where the fission cross-section increases with decreasing neutron energy has profound implications for reactor design. In thermal reactors, the lower requirement for fissile material to achieve criticality is a direct consequence of the high interaction probability of thermal neutrons. The use of thermal neutrons for fission significantly enhances the reactor's fuel efficiency, as the high probability of neutron interaction at low energies reduces the amount of fissile material necessary to sustain a chain reaction. This efficiency is achieved by optimising the moderation process to ensure a consistent supply of thermal neutrons, which maximises the likelihood of fission events in U-235. By carefully selecting and controlling the materials used for moderation, such as water or graphite, the reactor design can sustain a high neutron economy. This allows for a more efficient use of fuel, reducing the need for enriched fissile material and extending the fuel's operational life. Additionally, thermal reactors can be designed to minimise neutron leakage and parasitic absorption, further improving the overall efficiency and energy output of the reactor.

The widespread adoption of thermal reactors globally can be attributed to their fuel efficiency and the practicality of their design. Moderators such as water, heavy water, or graphite are commonly used to slow down the neutrons to thermal energies, with the moderator chose affecting the reactor's design and operational characteristics. Thermal reactors can achieve criticality with relatively small quantities of fuel, thereby reducing the cost of nuclear fuel and making nuclear power an economically more viable energy source.

Thermal reactors represent a highly efficient and widely used class of nuclear reactors, predicated on the effective moderation of neutrons to low-energy states. This approach not only enhances the probability of interaction between neutrons and fissile nuclei but also optimises fuel utilisation. Thermal reactors can achieve burnup levels -- measuring fuel efficiency -- up to 40-60 GWd/MTU, compared to the 20-30 GWd/MTU range in some traditional fast reactors, effectively doubling fuel utilisation. This fuel efficiency reduces the frequency of refuelling, which is especially advantageous for marine applications where reactor refuelling is complex and costly. These efficiency gains contribute significantly to the economic and operational appeal of thermal reactors in the global energy landscape.

2.2.2 Classified by Moderator Material

2.2.2.1 Light Water Reactor (LWR)

LWRs represents a prominent category within the thermal-reactor family, distinguished by its use of ordinary water -- referred to as '*light water*' -- as a neutron moderator and coolant. Among the thermal reactor designs, LWRs are the most prevalent in nuclear power plants. They have been historically favoured over other types, allowing the designs to mature during many years of experience with power-plant engineering. They are known for their reliability, efficiency, and the abundance of their primary moderator and coolant.

Central to the operation of a conventional LWR power plant is its containment within a robust, pressurised steel structure known as the reactor vessel. The vessel is engineered to withstand the extreme conditions of nuclear fission occurring within the reactor's core, where the nuclear fuel undergoes a chain reaction, releasing a significant amount of heat. The nuclear fuel, organised into assemblies roughly 3.65 m in length and slender like a pencil, is composed of fuel rods, which are tightly packed with cylindrical pellets made from an oxidised uranium compound, Uranium Triuranium Octaoxide. The arrangement and composition of these fuel assemblies are meticulously designed to sustain a controlled and steady process of nuclear fission.

In an LWR, the cooling system plays a pivotal role in the reactor's safety and efficiency. H_2O is circulated through the reactor core, where it absorbs the heat generated by nuclear fission. This thermal-energy transfer process is critical for maintaining the reactor core at safe operational temperatures, preventing overheating, and enabling the reactor to efficiently produce electricity. After collecting heat from the reactor core, the water is directed away from the core to exchange energy with a secondary loop, which produces steam.

The BWR variant of LWRs circulates water through the reactor core, which is directly boiled by the heat of fission, producing steam within the reactor vessel itself. The steam is then channelled directly to turbines, driving them to generate electricity without the secondary cooling circuit. After its energy is extracted, the steam is condensed back into water and returned to the reactor core, completing the cycle.

This efficient use of light water for moderation and cooling, coupled with the highly pressurised containment provided by the reactor vessel, underscores the LWR's design philosophy. It aims to achieve a balance between maximising the production of energy, while ensuring operational safety and environmental sustainability. The widespread adoption of LWRs across the globe is a testament to their effectiveness in meeting the demands of modern electricity generation, making them a cornerstone of the nuclear power industry.

2.2.2.2 Graphite Moderated Reactor (GMR)

GMRs stands out in the realm of nuclear reactor design, utilising graphite as its neutron moderator. This unique choice of moderator material allows for the slowing down of neutrons without significant absorption, facilitating the nuclear-fission process. The historical significance of GMRs is marked by their role in pioneering moments of nuclear-energy development; notably, the first sustained nuclear chain reaction of the CP-1 experiment (see Subsection 2.1.1.5). Furthermore, the GMR design also was involved in one of the most infamous incidents in nuclear history, the Chernobyl accident (Zohuri & Fathi, 2015).

One of the distinct advantages of GMRs is their ability to operate using natural, un-enriched uranium. This aligns them with HWRs and distinguishes them from many other reactor types that require uranium fuel to be enriched, thereby reducing initial fuel-processing costs and complexities. Another noteworthy feature of GMRs is their low power density. This attribute implies that, in the event of a sudden power outage, the heat the reactor produces from residual decay is relatively low compared to reactors with higher power densities, a fact that potentially reduces the risk of fuel damage and allows for more manageable emergency-response scenarios.

However, despite these advantages, GMRs are not without shortcomings. One notable limitation is the design’s constrained capacity for suppressing steam. In most nuclear reactors, mechanisms for steam suppression are crucial for managing the pressure and temperature within the reactor vessel, especially during accidents. These related design limitations can pose challenges related to ensuring the containment of radioactive materials.

Additionally, the inherent safety features of GMRs have been a subject of concern. The historical design and operational practices of some GMRs have demonstrated limitations in the safety precautions available to mitigate the consequences of severe accidents. The Chernobyl disaster serves as a stark reminder of the potential risks associated with insufficient safety measures in the operation of GMRs.

2.2.2.3 Heavy Water Reactor (HWR)

HWRs represent a sophisticated category within nuclear fission reactors in that they use D_2O as a neutron moderator. This type of reactor leverages the unique properties of heavy water to slow down neutrons effectively, facilitating the nuclear-fission process that is essential to produce energy. Using heavy water allows neutrons to be moderated with less absorption compared to ordinary water, enabling HWRs to operate using natural or only slightly enriched uranium fuel. This fuel flexibility is one of the main advantages of HWRs, significantly reducing the initial fuel-processing requirements and associated costs and making them an attractive option for countries with limited access to uranium-enrichment facilities. This capability distinguishes HWRs from LWRs, which require enriched uranium due to the higher neutron absorption rate of regular water.

HWRs can also use MOX fuel, or even thorium-based fuels. This characteristic provides further flexibility with operational and economic advantages, as HWRs can be adapted to different fuel cycles depending on resource availability or geopolitical considerations. Moreover, the ability to use recycled or reprocessed fuel further enhances the sustainability of the reactor, reducing reliance on fresh uranium resources and minimizing nuclear waste. This capability distinguishes HWRs from LWRs, which require enriched uranium due to the higher neutron absorption rate of regular water.

The Pressurised Heavy Water Reactor (PHWR) is best represented by the CANDU reactor. It exemplifies the application of heavy water in moderation and cooling within nuclear reactors. While the CANDU reactor design is widely recognised for its use of heavy water as a coolant and moderator, there are exceptions within the HWR category, such as the Lucens reactor in Switzerland, which was cooled by gas rather than liquid. CANDU reactors have seen widespread use, particularly in Canada, India, and South Korea, and they continue to be a reliable and efficient option for countries seeking to diversify their nuclear energy portfolios with a proven and adaptable technology.

Another key feature of HWRs is their online refuelling capability. Unlike many other reactor designs, which must be shut down periodically for refuelling, HWRs can be refuelled while still in operation. This allows for more continuous energy generation and improves the overall capacity factor of the reactor. The online refuelling system also enables better fuel utilisation, as operators can optimise the reactor's fuel composition throughout its operation, extracting more energy from the fuel.

However, the advantages do not come without its controversies. Critics of heavy-water reactors point out potential risks associated with nuclear proliferation. Specifically, two characteristics of HWRs raise concerns:

- The ability to use unenriched uranium as fuel, bypassing the oversight of international institutions dedicated to monitoring uranium-enrichment activities.
- The production of greater quantities of plutonium and tritium -- radioactive substances that can be repurposed for nuclear weapons, including advanced designs such as fission, boosted fission and neutron bombs, as well as components of thermonuclear weapons.

The case of India's "*Operation Smiling Buddha*", where plutonium extracted from the spent fuel of the Canada India Research Utility Services' heavy-water research reactor was used for its first nuclear test, underscores the necessity for stringent safeguards to prevent the misuse of HWR technology for weapons proliferation.

Despite the proliferation concerns, the operational advantages of HWRs are significant. The use of heavy water as a moderator and coolant, although an expensive liquid, offers unmatched efficiency in neutron moderation. This efficiency allows HWRs to use fuel ranging from natural uranium to slightly enriched uranium (1-2%), without requiring the uranium to be highly enriched. Additionally, the design ensures that heavy water does not boil under operational conditions by maintaining high pressure within the primary circuit, similar to the pressure levels in PWRs. This contributes to the overall safety and stability of HWRs, reinforcing their role in the diverse landscape of technology used to generate nuclear power.

2.2.3 Classified by Coolant Material

The different coolant materials highlight the variety of approaches taken in nuclear reactor design, each offering distinct advantages and challenges based on the specific operational goals, whether it be high efficiency, passive safety, or the ability to use alternative fuel cycles. Each classification sheds light on the nuanced approaches to nuclear-reactor design, reflecting the different strategies engineers and scientists employ to harness nuclear energy safely and efficiently.

2.2.3.1 Pressurised Water Reactor (PWR)

The PWR represents a significant innovation in nuclear reactor design and is extensively used to generate civilian energy. Over the years, companies such as Framatome-ANP and Westinghouse have become the primary manufacturers of PWR technology for contemporary nuclear power plants, demonstrating the technology's widespread acceptance and reliability.

PWRs distinguish themselves by their operational mechanisms, particularly in how they manage the flow of coolant and the generation of steam. Unlike BWR designs where water directly cools the reactor core and then flows to the turbine to generate electricity, the PWR adopts a more indirect approach. In this system, water is circulated through the reactor core under high pressure to prevent it from boiling, despite reaching temperatures significantly above its normal boiling point. This pressurised water acts as a coolant and a neutron moderator within the primary loop of the reactor.

One of the critical innovations in the PWR design is the incorporation of a secondary loop. Here, the heat transferred from the reactor core to the pressurised water in the primary loop is then used to heat water in a separate secondary loop through a heat exchanger. It is in this secondary loop that water turns into steam without coming into direct contact with the reactor core. This method of generating steam effectively isolates the radioactive materials from the steam used to drive the turbines, significantly reducing the risk of radioactive contamination in the turbine or the surrounding environment.

One of the most notable advantages of the PWR is the complete containment of fuel and radioactive materials, preventing leaks into the turbine system or the environment. Additionally, the ability of the PWR to operate at higher pressures and temperatures not only enhances the safety margins but it also improves the Carnot efficiency[5] of the power-generation process, leading to a more efficient way to produce electricity. Furthermore, the separation of the primary and secondary loops adds a layer of safety by minimising the risk of radioactive contamination in the steam-turbine system.

However, the sophistication and safety of the PWR design do come with challenges. The complexity of the reactor design, which includes additional components such as the pressuriser and heat exchanger, results in higher initial costs and more maintenance requirements than simpler reactor types. Moreover, the engineering and material demands for handling high pressures and temperatures require rigorous standards and quality-control measures, adding to the overall operational costs.

Despite these challenges, the PWR remains one of the most widely adopted reactor types, especially in the United States, where it comprises most nuclear reactors. This prevalence is a testament to the PWR's successful balance between operational efficiency, safety and environmental protection. Many modern PWR designs incorporate inherent safety features, which, when coupled with its high efficiency, make them a cornerstone of modern nuclear power generation, contributing significantly to the global energy mix.

In Europe, PWRs are extensively used, particularly in countries such as France and Germany. France is a leading example, with a significant portion of its electricity generated from nuclear power, predominantly using PWRs. The French energy company, EDF, operates numerous PWRs; they are central to the country's energy policy aimed at reducing carbon emissions and ensuring energy security. Germany, despite its recent move towards phasing out nuclear power, has historically relied on PWRs for a substantial part of its electricity supply.

In Asia, countries such as China, Japan and South Korea have embraced PWR technology as a cornerstone of their nuclear-energy programmes. China, in particular, has rapidly expanded its nuclear capacity; numerous PWRs have been built and are planned as part of its strategy to meet growing energy demands and reduce air pollution from coal-fired power plants. Japan, although having faced significant challenges after the Fukushima Daiichi disaster, continues to rely on PWRs for a portion of its energy needs as it seeks to balance energy security with safety concerns.

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[5] The Carnot cycle represents the theoretical limit for the efficiency of any heat engine that operating between two temperature reservoirs and shows that by increasing the temperature of the hot reservoir (or reducing the temperature of the cold reservoir) improves efficiency.

South Korea also operates a significant number of PWRs and has developed advanced PWR designs, such as the APR-1400, which are being exported to other countries, including the United Arab Emirates.

2.2.3.2 Boiling Water Reactor (BWR)

The BWR, a brainchild of General Electric from the 1950s, represents a pivotal advancement in nuclear-reactor technology. This innovation set a new direction in how nuclear reactors could be designed, focusing on a straightforward approach to steam generation with a simplified arrangement. The hallmark of the BWR lies in its direct use of the reactor's core to boil water, thus serving as a coolant mechanism and as a direct source of steam for powering turbines. The process eliminates the need for a separate steam generator, distinguishing it from other reactor types such as the PWR.

In a BWR, water is circulated through the reactor core, where it absorbs the heat generated by nuclear fission, directly converting it into steam within the same circuit. The steam is then channelled to turbines located directly above the reactor, where it drives them to produce electricity. After its energy has been harnessed, the steam is condensed back into water and recirculated into the reactor core, completing the cycle.

The BWR design brings several notable advantages to the table. Its simplicity stands out in that it eliminates the need for a separate steam-generation system and streamlines the overall reactor design. This leads to a smaller footprint for reactor system and, consequently, lower construction and operational costs. The cost-efficiencies, combined with the straightforward design and operation principles, have propelled BWRs to global recognition and adoption.

However, the BWR design is not without its challenges. One significant concern is the potential for increased radioactivity in the turbines, as the steam that drives the turbines is in direct contact with the nuclear fuel. The direct cycle increases the risk of radioactive contamination in comparison to reactor designs where the steam generation occurs in a separate system; this is especially hazardous during maintenance and decommissioning. Additionally, the reliance on direct boiling raises the possibility of exposing the fuel rods and 'burnout', if the water level drops too quickly and leaves the fuel rods without sufficient coolant. This scenario underscores the critical importance of maintaining optimal water levels and reactor conditions to ensure safety and prevent fuel damage.

Despite these disadvantages, the BWR's economical and straightforward design has led to its widespread adoption. Its ability to combine efficiency with cost-effectiveness makes it an attractive option for many nations seeking to expand their nuclear power capabilities.

2.2.3.3 Gas Cooled Reactor (GCR)

The GCR, also known in some iterations as the gas-graphite reactor, is distinctive within the broad spectrum of nuclear-reactor technologies. This category of reactors is characterised by using graphite as a neutron moderator and a gas -- predominantly CO_2 in earlier models, and He in more recent designs -- as the coolant. This dual graphite-gas configuration is one of the pioneering approaches in the design of nuclear reactors, marking an important milestone in the evolution of nuclear-power generation.

One of the first and most notable examples of this reactor type was inaugurated with the Calder Hall power plant reactor, which began operation in 1955, in England. The facility not only demonstrated the viability of GCRs it also marked a significant leap forward in nuclear engineering and energy production. The reactor was part of a series known as '*MAGNOX*', named after the magnesium alloy used in the fuel cladding. The alloy was chosen for its low neutron absorption and high melting point, qualities that significantly enhance reactor safety and efficiency.

MAGNOX reactors, and by extension GCRs, are distinct for their use of natural uranium as fuel. This fuel choice, in combination with the graphite moderator and gas coolant, exemplifies the engineering ingenuity of the era, which sought to achieve efficient nuclear fission without enriched uranium. That not only simplified the fuel cycle it reduced the overall operational costs associated with fuel-enrichment processes.

Despite these innovations, GCRs, including MAGNOX reactors, account for a relatively small fraction -- approximately 1.1% -- of the global nuclear-power plant capacity. The modest share reflects the transition within the nuclear-energy sector towards more advanced and efficient reactor designs. New construction of GCRs has ceased because the nuclear industry has evolved to embrace other reactor technologies that offer improved safety features, greater efficiency and reduced environmental impact (Zohuri & Fathi, 2015).

2.2.3.4 Liquid Metal Cooled Reactor (LMCR)

Liquid metal-cooled reactors are a unique class of nuclear reactors that use liquid metals as the primary coolant to transfer heat from the reactor core to the power-generating systems. They have been developed primarily for their ability to operate at higher temperatures, offering potential improvements in efficiency and safety compared to traditional water-cooled reactors.

The idea of using liquid metals as coolants can be traced back to the mid-20th century, during the early development of nuclear technology. FBRs, which were designed to produce more fissile material than they consumed, were some of the earliest types of reactors to employ liquid metal coolants. The U.S. and the Soviet Union led the initial research, with significant projects such as the U.S.'s Experimental Breeder Reactor I (EBR-I), which in 1951 became the first reactor to generate electricity using nuclear power.

Several types of liquid metals have been used or proposed as coolants in these reactors, each offering distinct properties and advantages. Sodium is the most common liquid-metal coolant. Although a corrosive material, sodium (Na) has excellent heat-transfer capabilities, a low melting point, and it does not slow down neutrons, making it ideal for use in fast reactors. Notable sodium-cooled reactors include the Sodium-cooled Fast Reactor (SFR) and the historic EBR-I and EBR-II reactors.

Lead and lead-bismuth eutectic (LBE) are also popular choices due to their high boiling points, which allow these reactors to operate at elevated temperatures without pressurisation. The coolants provide good radiation-shielding properties as well. However, lead and LBE present challenges, such as higher melting points than sodium, and corrosiveness, which complicates the design and maintenance of the reactor.

The Soviet Union successfully developed and operated lead-bismuth-cooled reactors in their '*Alfa Class*' submarines, demonstrating the potential of these coolants. Potassium has also been explored as a coolant due to its lower melting point compared to sodium, but its higher chemical reactivity, especially with water, has limited its widespread adoption. A eutectic mixture of sodium and potassium, known as NaK, is liquid at room temperature and has been used in some experimental reactors and space reactors. NaK combines the low melting point of potassium with the favourable thermal properties of sodium, although it retains a high reactivity with water.

The use of liquid-metal coolants in nuclear reactors offers several significant advantages over water-based systems, among the most notable is their higher thermal conductivity, which allows liquid metals to transfer heat more efficiently. This capability enables reactors to operate at higher temperatures, potentially improving their thermal efficiency. Additionally, due to the high boiling points of liquid metals, these reactors can operate at lower pressures, which reduces the risk of explosive accidents and simplifies reactor design.

In fast reactors, liquid metal coolants such as sodium do not slow down neutrons, preserving the fast neutron spectrum that is essential for breeding new fuel. However, the advantages come with challenges. Sodium and potassium, for instance, are highly reactive with water and air, requiring stringent safety protocols to prevent leaks and fires. Lead and LBE can be highly corrosive to reactor materials, necessitating the use of specially selected materials and protective coatings. Furthermore, the design and maintenance of LMCRs are more complex due to the unique properties of their coolants, which may lead to higher costs and technical challenges.

In recent years, there has been renewed interest in LMCRs, particularly within the framework of Gen IV reactors, which aim to improve safety, efficiency and sustainability in nuclear power. The Sodium-cooled Fast Reactor (SFR) is one of the six Gen IV reactor designs that are actively being developed, with significant progress being made in countries such as Russia, China and India.

LFRs are also under development, with projects such as the Russian BREST-OD-300 and the European ALFRED reactor leading the way. Despite the challenges, the potential for high efficiency and safety continues to drive research and development in the field of LMCRs, making them a promising technology for the future of nuclear energy.

2.2.3.5 Molten Salt Reactor (MSR)

MSRs are an advanced and innovative class of nuclear reactors that use molten fluoride or chloride salts, such as lithium fluoride or sodium fluoride, as both a coolant and, in some designs, as the fuel carrier. In these designs, nuclear fuel is dissolved directly in the molten salt, allowing the reactor to operate at temperatures as high as 900°C, significantly enhancing thermal efficiency. This high-temperature operation facilitates more efficient power generation, often using advanced thermodynamic cycles like the Brayton cycle, and can enable the production of industrial heat for processes such as hydrogen production.

One of the most attractive features of MSRs is their inherent safety. Unlike traditional reactors that use water as a coolant, molten salts are chemically stable and do not react explosively with air or water, greatly reducing the risk of catastrophic failure. In the event of overheating, MSRs can incorporate a passive safety mechanism such as a freeze plug -- a solid block of salt that melts if the reactor gets too hot, allowing the molten salt to drain into a safe containment area where the nuclear reaction is naturally halted. This passive safety design eliminates the need for complex, active emergency cooling systems.

Also, MSRs have fuel flexibility. They can use various fuel types, including low-enriched uranium, plutonium, or thorium, making them versatile and capable of efficiently breeding fuel. Thorium-based MSRs, in particular, hold promise for long-term energy sustainability due to the abundance of thorium compared to uranium. MSRs also generate less long-lived radioactive waste, as the fuel is continuously reprocessed and recycled during operation, further improving their environmental footprint and reducing the need for long-term waste storage solutions.

2.2.3.6 Supercritical Water Reactor (SCWR)

The SCWR is an advanced nuclear reactor design that builds on the principles of PWRs but takes them further by operating with water at supercritical pressures -- above 22.1 MPa -- and temperatures over 374°C. Under these conditions, water behaves as both a liquid and a gas, eliminating the need for a phase change from liquid to steam, which is required in conventional reactors for steam production. This supercritical state allows the reactor to operate with higher thermal efficiency, potentially reaching 45% or more, compared to the 30-36% efficiency of typical PWRs and BWRs.

SCWRs can be designed with either thermal or fast neutron spectrums, allowing them to be flexible in terms of fuel usage and neutron economy. By operating at higher temperatures and pressures, SCWRs can also use more compact turbine systems and require less infrastructure for heat exchange, leading to simpler designs and lower operational costs.

The supercritical water used in SCWRs has the advantage of higher thermal conductivity and lower heat transfer resistance, making the overall heat extraction from the core more efficient. However, these advantages also present significant engineering challenges, particularly in terms of material science, as the reactor components must withstand extremely high temperatures and pressures for prolonged periods. Research is ongoing to develop materials that can endure these harsh conditions without degradation, ensuring the long-term reliability and safety of SCWRs.

SCWRs are part of the Gen IV reactors being researched globally and are seen as a promising solution for the future of nuclear power, offering both improved efficiency and the potential for enhanced fuel utilisation, particularly when integrated with closed fuel cycles or breeder configurations.

2.2.3.7 Supercritical CO_2 Reactor (sCO_2)

The Supercritical CO_2 Reactor (sCO_2) is an advanced nuclear reactor design that uses supercritical CO_2 as the coolant. Operating at conditions above CO_2's critical point (31°C and 7.38 MPa), where the gas exhibits properties of both a liquid and a gas, sCO_2 reactors leverage the thermodynamic benefits of this phase to achieve high thermal efficiency. Supercritical CO_2 can transfer heat more effectively than water or other conventional coolants, making it a promising choice for next-generation nuclear reactors.

One of the key advantages of the sCO_2 reactor is its ability to operate at much higher temperatures (up to 550°C or more) without the need for excessive pressure or complex cooling systems. The higher operating temperatures also enable the use of more efficient energy conversion cycles, such as the Brayton cycle, which further improves the reactor's overall efficiency. This efficiency boost can reduce the size of the reactor system, making it more compact and easier to integrate into smaller, modular reactor designs.

The supercritical CO_2 fluid behaves in a way that allows the reactor to achieve thermal efficiencies of around 40-50%, surpassing traditional water-cooled reactors (typically in the 30-36% range). Additionally, the use of supercritical CO_2 enables the elimination of complex steam-generation systems, which simplifies the overall design and reduces costs related to system complexity.

Regarding safety, sCO_2 reactor offers several advantages. Supercritical CO_2 is chemically inert, meaning it does not react violently with water or air, which reduces the risk of catastrophic failures in the event of a coolant leak. Its excellent heat-transfer capabilities allow for rapid removal of heat from the reactor core, enhancing passive safety mechanisms and minimizing the risk of overheating.

While the sCO_2 reactor holds great potential, it also faces significant technical challenges. The materials used in the reactor system must withstand high temperatures and pressures while resisting corrosion and radiation damage. Research and development efforts are currently focused on identifying suitable materials and improving the long-term durability of reactor components.

2.2.3.8 Heavy Water Reactor (HWR)

HWRs use D_2O as both a neutron moderator and a coolant and are designed with robust safety features. The lower operating pressure of the coolant system compared to light water reactors reduces the risk of coolant loss or catastrophic failure. Additionally, the heavy water used in the reactor does not need to be highly pressurised to remain in liquid form at the operating temperatures, contributing to the reactor’s overall safety and operational stability. More details can be found in Subsection 2.2.2.3.

2.3 Suitability of Reactor Types for Merchant Marine Applications and Fuel Availability

Historically, the development of nuclear-powered submarines and aircraft carriers marked significant advancements in naval capabilities. Although less common, there have been merchant nuclear-powered vessels, such as the Russian icebreaker fleet starting with Lenin in 1959, which pioneered nuclear power for Arctic icebreaking duties.

Nations with nuclear navies -- the U.S., Russia, the United Kingdom, France, China, and India -- continue to develop advanced nuclear submarines and aircraft carriers. An inventory of both military and merchant nuclear marine applications can be found in Appendix X – Development of Nuclear Technology and An Inventory of Nuclear-Powered Vessels. However, merchant nuclear -powered vessels remain rare due to high capital costs, safety challenges, and limited public acceptance.

Only two reactor designs have been fully implemented for vessel propulsion: PWR technology (the most widely adopted) and heavy liquid metal-cooled reactors, including Lead-Bismuth Fast Reactors (LBFRs), which were used in Soviet-era nuclear submarines. While LFRs have historically been used in military submarines, their specific requirements for heavy shielding and weight make them a more challenging option for merchant vessels that prioritise compactness and fuel efficiency. Other candidate reactors remain conceptual and preliminary. Therefore, while some general insights can be shared, detailed conclusions about their marine suitability await further design and development.

As explained earlier, the Gen IV International Forum has provided a strong focus on developing six different advanced reactor types for a variety of applications. While vessel propulsion has not been a primary driver in the Gen IV activities, the technology options under consideration can reasonably be drawn on for applicable insights.

Table 3 summarises the key properties of these reactors. In the short term, it is more likely that the VHTR/HTGR will be used than the more conventional PWR, due to higher burnup, continuous refuelling capabilities, and the ability to operate at higher temperatures. VHTR/HTGR also offers significant safety and non-proliferation benefits as a Gen IV reactor. Over the long term, MSR reactors may offer a compelling alternative, with improved burnup, continuous refuelling capabilities, and higher operational temperatures. MSRs inherit many VHTR/HTGR advantages and can potentially operate on thorium in the future and theoretically better load-following capabilities. LFRs are safer in terms of coolant reactivity due to their use of lead-bismuth but require extensive shielding and are heavy due to the coolant's density, making them difficult under some circumstances to integrate into compact, weight-sensitive merchant vessels (Houtkoop, Visser, Sietsma, & de Vries, 2022).

SFRs and GFRs offer advanced features and efficiencies in land-based applications but may face significant challenges for marine use. SFRs use liquid sodium as a coolant, which reacts dangerously with water, making them unsuitable for marine settings. GFRs rely on high-pressure containment systems for inert gas cooling, adding further complexity. Consequently, while these reactors show promise for land applications, the specific operational and safety demands of marine environments make them comparatively less suitable for shipping applications.

Table 3. Properties of reactor types with possible applicability for the marine application (Houtkoop, Visser, Sietsma, & de Vries, 2022).

Reactor type	PWR	VHTR/HTGR, Pebble bed	VHTR/HTGR, Prismatic	SFR	LFR	GFR	MSR
Neutron spectrum	Thermal	Thermal	Thermal	Fast	Fast	Fast	Thermal/ fast
Fuel cycle	Open/ closed	Open	Open	Open/ closed	Open/ closed	Open/ closed	Open/ closed
Burnup (GWd/tHM)	45-75	90-200+	90-200+	130+	130+	130+	90+
Fuel type	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th	U/Pu/Th
Uranium enrichment	LEU < 5% HEU in special application	LEU (3-20%)	LEU (3-20%)	LEU (5-20%)	LEU (5-20%)	LEU (5-20%)	LEU (5-20%)
Refuelling cycle (low end)	1.5 – 2y	1.5 – 2y	1.5 – 2y	1.5 – 2y	1.5 – 2y	1.5 – 2y	1.5 – 2y
Refuelling cycle (high end)	7 – 8 y	1.5 – 2y	1.5 – 2 y	Lifetime (20+ y)	Lifetime (20+ y)	Lifetime (20+ y)	Lifetime/ Continuous
Passive safety	-	+	+	+	+	O	+
Active safety	+	+	+	+	+	+	+
Operating temperature	< 330 °C	< 700°C	700 -1,000 °C	500-550 °C	< 600 °C	< 850 °C	< 800 °C

Reactor type	PWR	VHTR/HTGR, Pebble bed	VHTR/HTGR, Prismatic	SFR	LFR	GFR	MSR
Technology readiness level	8-9	7-8 (V) 6-7	7-8 (V) 6-7	6-7	4-5	4-5	4-6

LEU: Low Enriched Uranium; HEU: High Enriched Uranium; U: Uranium; Pu: Plutonium; Th: Thorium and GWd/tHM: GW-days/metric ton of heavy metal
Refuelling Cycles: The high-end values indicate potential lifetime or continuous operation without traditional refuelling for certain advanced reactors.
Passive and Active Safety: "+" denotes the presence of safety features, "O" indicates some passive safety features may be present but are limited.
Operating Temperature: Ranges given reflect the typical operating conditions based on reactor design.
TRL: Values in parentheses (V) indicate variable readiness levels depending on design maturity.

To ensure safe operation, nuclear reactors incorporate active and passive safety systems. Active systems rely on pumps, valves, motors, and controls that require external power and are backed by redundancies like Emergency Core Cooling Systems (ECCS). However, reliance on active safety poses challenges for vessels, where external power may be disrupted.

Conversely, passive safety systems work autonomously, relying on natural processes like gravity or convection. These systems reduce risks tied to mechanical or human error. For instance, gravity-driven cooling can ensure core cooling even without pumps. In marine applications, however, passive safety designs must consider orientation shifts in emergencies, such as listing or capsizing, emphasizing the need for adaptable passive safety mechanisms alongside active systems.

Different reactor types use passive safety in unique ways. For example, LWRs (including PWRs and BWRs) use gravity-driven and natural convection systems. SMRs integrate passive heat dissipation to allow extended operator-free functionality. Gen IV reactors, like MSRs and VHTR/HTGR, further emphasise passive safety. MSRs employ freeze plugs that halt reactions by draining fuel, while VHTRs/HTGRs use TRISO fuel to contain fission products at high temperatures, ideal for marine operations.

In merchant shipping, where downtime incurs costs, TRISO-powered reactors can operate continuously for long periods, reducing maintenance. TRISO's resilience supports longer refuelling cycles and reduced complexity, ideal for the shipping sector's needs. Aligning refuelling cycles with dry-dock schedules (around five years) minimises disruptions. Recent designs show some reactors can achieve extended cycles at full power (IAEA, 2024c), enhancing reliability for extended marine use.

2.3.1 Maritime Industry Challenges

At present, a key challenge that the nuclear-powered vessels would face is the lack of uniform global regulations. Since these vessels operate internationally, inconsistencies among countries, Flag Administrations and port States may pose operational challenges. This is particularly important in tramp shipping, where vessels do not follow fixed routes and must adapt to different ports' regulations. Non-uniform safety standards and potential port restrictions could hinder access and create delays, impacting the efficiency and viability of nuclear-powered vessels in international shipping. However, it is noted that nuclear-powered vessels would be better equipped to handle future changes in emission regulations and the associated costs.

While the navies have significant requirements for manoeuvring in a combat situation, merchant vessels do not face the same urgency for rapid power adjustments and usually use low speed diesel engines designed for gradual power increases rather than rapid manoeuvres. This operational difference is critical. However, the operation of these vessels still requires variable load. This is a main difference to land-based applications which require constant power with relatively little variability output, allowing for most efficient operation. This demand for variable propulsion power, e.g., for manoeuvring near the shore or in traffic separation zones, including docking and shutdown or near-shutdown conditions, creates the need for robust load following.

There are two ways to achieve the capability for load-following: (1) to rely on the intrinsic characteristics of the reactor system itself; and (2) introduction of an appropriately sized energy-storage system (which could be electrical, thermal or mechanical) to act as a buffer between the reactor system and the load (propulsion demand, as well as the supply to other vessel systems). Load-following using control-rod manipulation is clearly important in matching output to demand, but with energy storage as a buffer, more flexibility can be achieved while avoiding short-term fluctuations in the output of reactor power.

A related approach which has been in use for at least 100 years in some vessels and being implemented in nuclear-powered military vessels is the use of electric (or turbo-electric) drives. According to the World Nuclear Association, the Russian, U.S. and British navies rely primarily on steam-turbine propulsion, while the French and Chinese use the turbine to generate electricity for propulsion (World Nuclear Association, 2023). Russian nuclear-powered ice breakers also utilise turbo-electric propulsion, and the same document indicates that certain U.S. submarines (‘*Columbia Class*’) under construction will use turbo-electric propulsion. The U.S. Congressional Research Service has reports on the option of Electric-Drive Propulsion for U.S. Navy vessels.

Current plans to implement advanced nuclear reactors for merchant vessel propulsion are very conceptual in nature and do not provide details to indicate whether steam drive or turbo-electric drive would be selected (or some hybrid form), so it is not possible to fully answer the question about whether adjusting reactor output by control-rod manipulation would be the primary method of matching output to demand. This adjustment could involve control rods or removing excess heat via a steam dump system to match power output. For SMR designs with a modular approach, direct electric drive might be feasible, while other SMRs could necessitate more conventional steam-driven systems. The integration would likely involve a traditional steam plant, where excess steam might be managed through a steam dump system. Also, depending on the reactor technology chosen and the vessel’s load-following requirements, it is likely that the turbo-electric drive approach may provide greater flexibility in achieving improved load-following while maintaining fuel-use efficiency. The need for turbo components is, therefore, design-specific.

Another essential consideration for nuclear-powered vessels is the management of radioactive waste generated during operations. This waste includes high-level waste (e.g., spent fuel) and low- to intermediate-level operational waste, such as contaminated tools, clothing, and reactor components. Managing these wastes follows strict regulations to ensure safe containment, transportation, and disposal, often mirroring protocols used in land-based nuclear facilities. For merchant vessels, the storage and transfer of spent fuel pose specific challenges, as international regulations may restrict refuelling and waste transfer to ports within the vessel’s flag State or designated locations with adequate infrastructure. Additionally, due to the vessel's mobile nature, onboard waste storage solutions must meet stringent safety and security standards to prevent accidental release during maritime operations.

Advanced reactor designs, such as MSRs and VHTRs/HTGRs, offer potential advantages by generating less long-lived radioactive waste and, in some cases, reducing the need for frequent fuel changes. However, all nuclear-powered vessels will still produce fission products and activated materials that require careful management throughout the vessel's operational life and at decommissioning. International collaboration and regulation will be crucial in establishing standardised waste management protocols for nuclear-powered vessels, ensuring these technologies meet the safety and environmental standards required to protect marine ecosystems and comply with global non-proliferation agreements.

The appeal of MSRs and VHTR/HTGRs as potential solutions for marine applications stems from a combination of factors beyond just refuelling efficiency. These technologies offer distinct advantages that align well with the demands of merchant shipping. On safety aspect, as explained earlier, both MSRs and VHTRs/HTGRs are equipped with inherent safety features. MSRs incorporate passive safety mechanisms like freeze plugs, which allow the reactor to safely shut down in an emergency by draining the molten fuel. VHTRs/HTGRs, on the other hand, have high thermal stability and utilise TRISO fuel, a type of fuel that retains fission products even at elevated temperatures, reducing the risk of release. On the operational flexibility area: MSRs, with their liquid fuel composition, theoretically enable continuous refuelling or ‘*continuous makeup*’ by allowing for periodic fuel conditioning and topping up. VHTRs/HTGRs, due to their high fuel efficiency, can achieve extended burnup, which may align their refuelling needs with standard marine dry-dock intervals, simplifying maintenance cycles. On the load-following capabilities: VHTRs/HTGRs offer robust load-following capabilities thanks to their thermal stability, making them well-suited for variable power output. Similarly, MSRs can adapt to power fluctuations due to the flexibility of their fluid fuel, offering adaptability for the load variability needed in marine propulsion. Both MSR and VHTRs/HTGRs designs are relatively compact, which is essential for marine applications where space is limited. This compactness makes them more feasible for integration into vessel designs compared to larger, more shielding-intensive reactors like traditional PWRs or fast reactors. MSRs and VHTRs/HTGRs produce less long-lived radioactive waste compared to other reactor types. This characteristic aligns with the environmental and regulatory priorities in the shipping sector, which favours sustainable and lower-impact technologies.

The suitability of various reactor types for merchant shipping depends also on the availability and cost of fissile material. Just as oil and gas supplies are tightly linked to global and national security and stability, so is nuclear fuel. Reactor designs, such as MSRs, that can operate with a range of fissile materials may offer flexibility in fuel sourcing, helping to mitigate supply chain disruptions.

Refuelling needs is another important aspect. PWRs generally require a refuelling cycle that may vary from about 18-24 months. This cycle length reflects land-based applications, where reactors typically operate continuously at high power output. For marine applications, reduced and variable operational loads can enable extended refuelling cycles. For example, the Russian icebreaker PWR design achieves up to 10 years between refuelling, as its high enrichment and variable operating profile allow for longer intervals between maintenance. However, fuel enrichment is a key factor, and in commercial applications, including stationary power reactors, only LEU can be used to comply with international regulations and non-proliferation agreements.

The shorter refuelling intervals of land-based nuclear power plants stem from their continuous operation at full or near-full power, as refuelling requirements are based on effective full-power years. For these plants, effective full-power years closely match operational time due to their steady power output. In contrast, for vessel propulsion, where full power operation is not continuous, refuelling intervals can be extended. The actual refuelling interval will vary depending on the vessel type and its specific operational profile. For instance, a container ships may typically operate at around 50% of their full power output, with full power reserved mainly for maintaining tight port schedules. Practical deployment for these vessels may vary between 40-70% at sea, allowing for potentially extended refuelling intervals. In comparison, LNG carriers generally operate with a higher average load, leading to shorter refuelling intervals. For context, the NS Savannah required refuelling approximately every 3.5 years, whereas the Russian PWR-operated icebreaker could achieve a 10-year refuelling cycle due to its relatively high (20%) fuel enrichment and seasonal, intermittent operation.

Switching from PWRs to other advanced reactor systems, one might consider two candidate technologies in terms of refuelling interval/costs: the MSR and the LFR. These are two very different options (refer to Table 3).

The MSR is a reactor concept which has gained considerable attention in recent years and is currently being promoted for use on vessels by a private-sector company in the U.K. There are many MSR concepts, offering a broad range of technology options. In general, they feature a molten salt-fuel material that circulates through an active zone in which a critical condition is maintained. When the fuel material exits this active zone, it is in a subcritical condition, and it carries the heat generated by fission in the active zone to a secondary system where steam is produced. The steam is then used to produce direct vessel propulsion, or it is used indirectly through the production of electric energy. A key feature is the ability to continuously condition the molten salt fuel by adding additional fuel components and removing reaction products to maintain the conditions that can sustain reactor criticality. In so doing, the requirement for periodic refuelling, as commonly required for solid-fuelled systems, is overcome. In a sense, this approach could be considered '*continuous refuelling*'.

Reaction products refer to the fission byproducts created as the reactor fuel undergoes nuclear fission. In an MSR, these byproducts, which are in the form of fission fragments and other reactive components, must be managed within the reactor's liquid fuel system to maintain safe and efficient operation. On a ship, there would need to be dedicated systems in place for the safe containment, removal, and potentially temporary storage of these fission byproducts. Since some byproducts are highly radioactive, they must be handled and processed carefully to prevent leaks, contamination, or exposure to the crew and environment. Therefore, integrating an MSR on a vessel would require additional systems and protocols for managing, storing, and safely disposing of radioactive byproducts. This would add complexity to the design and operation of nuclear-powered vessels. Overall, much remains to be done in terms of technology maturity as MSRs have a very limited history of operation.

On the other hand, LFR is a solid-fuelled reactor cooled by heavy liquid metal (either the alloy mixture of lead and bismuth, or Lead-Bismuth Eutectic, referred to as LBE) is the only alternative to the PWR that has been fully implemented (it was used by the Soviet Union and, subsequently, Russia in its relatively small fleet of '*Alfa Class*' submarines from 1970 to the early 1990s). This experience led many countries to explore and progress plans to implement updated LFR designs for various applications (central station power, small reactor applications, and marine propulsion). These systems, which operate in the fast-neutron spectrum, can achieve very long reactor core life without refuelling (in some cases 20-30 years or more of effective full power years).

With these two reactor types (the MSR and the LFR), the option exists to match the life of the reactor core to the design life of the ship, thereby avoiding refuelling for the operational life of the ship. This could be one of the trade-off goals in selecting a reactor technology for the propulsion of merchant vessels. Overall, the limited refuelling needs make nuclear power especially well-suited for deep sea shipping. However, as explained earlier, LFRs require significant shielding and weight, a feature which can make it challenging to integrate into vessel designs.

While it is not possible to provide a quantitative comparison (PWR vs. MSR, LFR, or VHTRs/HTGR) due to significant uncertainties on both sides of the equation, a key element in the unfavourable economics of the experience with NS Savannah was related to refuelling infrastructure. This infrastructure had to be set up for a single ship, which limited cost-efficiency. Had there been a fleet of vessels using this type of fuel, the refuelling infrastructure costs could have been spread across multiple vessels, as is typically the case for nuclear-powered military fleets. VHTRs/HTGRs, like MSRs and LFRs, would similarly benefit from economies of scale, potentially lowering infrastructure expenses for merchant applications and increasing viability.

Modular construction, a cornerstone of the shipbuilding industry, enables the assembly of vessels in sections or modules at centralised facilities before transporting them to the final assembly site. This method not only enhances efficiency and reduces construction time but also lowers costs and improves quality control, as inspections occur in a controlled manufacturing environment. The development of SMRs for marine applications could leverage these same principles, potentially revolutionizing nuclear power use in merchant vessels by offering safer, more flexible alternatives to traditional large reactors.

Applying modular production to SMRs could bring substantial benefits. SMRs could be mass-produced in factory settings, allowing for standardised units to be manufactured, rigorously inspected, and transported directly to installation sites. This approach would drive down costs through economies of scale, reduce construction time, and expedite deployment, as pre-fabricated SMR modules can be quickly assembled compared to reactors constructed entirely on-site. Moreover, this flexibility makes SMRs adaptable for deployment in remote locations or aboard vessels, where modular units could be transported and integrated in much the same way as traditional vessel sections.

By adopting modular production methods, the deployment of SMRs in the maritime industry could be accelerated, making them particularly suitable for marine power and remote applications. Future projects aimed at meeting GHG reduction targets (see Subsections 3.1.2 and 3.2) could benefit from international collaboration to address the safety, regulatory, and environmental standards necessary for advancing nuclear-powered merchant shipping.

Regarding the applicability to specific vessel types, a comprehensive review of literature performed by Houtkoop (Houtkoop K. C., 2022) suggested that large vessels such as bulk carriers, tankers and containers are suitable for installing nuclear-propulsion systems, even at a relatively low installed power. For other vessel types, which are designed to maximise cargo and passenger capacity (such as ferries, cruise and ro-ro vessels), the implementation of nuclear-propulsion systems may present challenges related to the additional weight and volume required to house and shield a nuclear reactor; especially if it is retrofitted with a larger and heavier reactor system than the original power arrangement. The need for robust containment structures, safety systems and fuel storage would reduce the available space for passengers and cargo, and it may also impact the vessel's overall efficiency and commercial viability. The regulatory, safety and public-perception concerns associated with nuclear power being used in the shipping sector further complicate its adoption for these types of vessels. For vessels serving the offshore industry, general cargo and car carriers, the application of nuclear systems may be more feasible at relatively large installed powers. In addition, it is noted that nuclear-powered vessels could potentially supply emission-free power to onshore during port stays.

To put this into perspective, a 50 MWt nuclear reactor onboard a vessel, operating at 30% efficiency, can produce approximately 15 MWe of electrical power. Accounting for the vessel's own power demands while at berth, typically estimated at around 2 MWe depending on the vessel's purpose and size, the reactor could supply approximately 13 MWe to external facilities or communities. For context, a small village of 1,000 inhabitants typically consumes about 1 MW of electricity. This means that the reactor could supply power to approximately 13 such villages simultaneously. By framing this capability in terms of energy demand equivalence, the utility of nuclear-powered vessels in providing emission-free power to onshore facilities during port stays becomes more apparent, further demonstrating their potential contribution to decarbonisation goals.

2.3.2 Assessing Readiness for Nuclear-Powered Vessels

Technology readiness level (TRL), shown in Table 3, is a critical factor in assessing the feasibility of deploying nuclear-powered merchant vessels. While nuclear-reactor technology has reached a rather high TRL -- indicating that it is mature and has been proven in operational environments -- the lower readiness levels in investment and community acceptance present significant barriers. These lower levels reflect the challenges in securing the financial backing and overcoming public concerns related to safety, environmental impact and regulatory compliance. As the economic viability of any new technology is often the decisive factor in its adoption, the high TRL of nuclear reactors must be complemented by advancements in these other areas.

The introduction of measures such as GHG-reduction incentives and carbon taxes may help to shift the economic balance in favour of nuclear-powered solutions, encouraging greater investment and fostering broader acceptance within the maritime industry. However, for these solutions to be adopted, a change in the public perception would be a key.

Table 4 shows the readiness level across different dimensions of readiness and feasibility. In this Table, levels 1 and 9 are the lowest and highest readiness levels, respectively. The table compares a range of reactor technologies.

Table 4. The readiness level of various technologies across various dimensions.

	PWR	MSR	LMCR	VHTR/HTGR	FBR	LFR
Investment Readiness	8	4	5	4	5	4
Community Readiness	7	2	4	2	4	2
Technical Maturity	Developed	Emerging	Mature	Emerging	Mature	Developing
Investment Attractiveness	High	Moderate	Moderate	Low	Moderate	Low
Community Support Level	Medium	Low	Medium	Low	Medium	Low
Ship Integration	4	1	4	2	3	3
Bunkering & Port Readiness	4	2	2	4	3	2
Propulsion Compatibility	2	1	1	1	2	1
Fuel Handling Readiness	5	5	5	5	4	4
Energy Conversion Efficiency	2	2	2	2	3	3
Risk Level (Community)	2	2	2	2	3	2

	PWR	MSR	LMCR	VHTR/HTGR	FBR	LFR
Long-Term Scalability	High	Moderate	High	Moderate	Moderate	Low
Environmental Impact	Low	Moderate	Moderate	Low	Moderate	Low

Sources: (Carmack, Braase, Wigeland, & Todosow, 2017)*,* (Shepherd, Rossiter, Palmer, Marsh, & Fountain, 2015) (Lloyd's Register, 2024)

The high level of readiness for nuclear reactor technology, particularly for PWR, underscores that while public acceptance and community readiness remain significant challenges, there are also critical technical and infrastructural barriers to address. These include ship integration, propulsion compatibility, and port readiness for handling nuclear fuel. Together, these barriers illustrate the multifaceted approach required to advance nuclear-powered merchant vessels toward widespread adoption.

In fact, the determination of whether new technology will be adopted or not heavily relies on its economic feasibility, as evidenced by the Investment Readiness and Attractiveness scores. The importance of reduction in GHG emissions and the potential introduction of a carbon tax can create more interest among investors by enhancing the economic appeal of nuclear technologies. Technologies like PWR also score favourably in terms of Long-Term Scalability and Environmental Impact, positioning them as attractive candidates for decarbonizing the maritime industry.

It can be observed that while PWRs have been used widely in navies, the score in ship integration and propulsion compatibility is still low. Transitioning PWR technology to merchant shipping presents unique challenges that impact its integration and performance in this sector. Navies are specifically designed to accommodate the size, weight, and operational characteristics of PWRs. In contrast, merchant vessels vary widely in design and purpose, often prioritizing cargo capacity and fuel efficiency. Integrating a PWR into a merchant vessel may require significant modifications to the vessel's structure and layout, potentially reducing cargo space and altering stability. Also, PWRs are optimised for the operational profiles of navies, which differ from those of merchant vessels. This discrepancy can lead to inefficiencies in propulsion and maneuverability when applied to merchant vessels.

The LFR and MSR both demonstrate strong potential for vessel propulsion, particularly for their ability to operate with extended refuelling intervals and their inherent safety features, which are highly advantageous for long-distance, deep-sea applications. However, compared to PWRs, both LFRs and MSRs encounter challenges related to Investment Readiness and Community Readiness due to their lower commercial maturity and heightened public uncertainty around their handling and operation. Addressing these issues will require focused development efforts to make these reactors both economically viable and socially accepted for merchant shipping. Overcoming these barriers will be essential to achieving broader adoption and investment in LFR and MSR technologies within the maritime industry.

The VHTR/HTGR is also highlighted as a promising technology due to its high thermal efficiency and robust safety profile, particularly with the use of TRISO fuel, which enhances safety by containing fission products. VHTR/HTGRs also offer advantages in environmental impact, with low waste generation and strong load-following capabilities that align well with the variable power requirements of marine propulsion. However, similar to LFRs and MSRs, VHTRs/HTGRs need advancements in Investment Attractiveness and Community Support to address public acceptance and financial backing challenges. While PWRs currently lead in readiness, LFRs, MSRs, and VHTRs/HTGRs each hold significant potential that, with strategic investments and increased community engagement, could establish them as viable options for the maritime industry's decarbonisation and modernisation efforts.

Readiness levels are calculated based on specific technical advancements, regulatory hurdles, community acceptance, and demonstrated applications, especially for low-carbon, high-efficiency energy solutions in maritime industries. These frameworks collectively offer a comprehensive view of nuclear technology’s feasibility to be implemented in other industries, such as shipping. However, challenges remain with Ship Integration and Propulsion Compatibility, where most reactor technologies still face significant hurdles. This underlines the need for further innovation and adaptation to align these technologies with maritime infrastructure.

This analysis underscores the need for a multidisciplinary approach to advance nuclear reactor technologies for maritime applications. Key areas include technological innovation, regulatory alignment, public engagement, and strategic investments. Addressing these factors cohesively will help overcome integration and compatibility challenges, enhance economic viability, and foster public acceptance. With these efforts, nuclear reactor technologies like PWRs, LFRs, MSRs, and VHTRs/HTGRs can play a pivotal role in the maritime industry's transition to decarbonisation and modernisation.

2.3.3 Suitability Conclusions

In the coming decades, nuclear power may prove advantageous for deep-sea shipping, enabling vessels to operate for extended periods without refuelling. This consistent and reliable energy source is critical for demanding, fuel-intensive routes and will reduce the logistical complexities and costs associated with frequent refuelling stops, while facilitating compliance with stringent emission regulations.

The suitability of nuclear reactors for merchant marine applications requires careful evaluation across operational, safety, and regulatory dimensions. Historically, nuclear reactors have been effective in military and specialised merchant applications, such as in navies and Russian icebreakers. However, adapting these technologies for mainstream merchant shipping presents significant challenges, particularly with respect to cost, infrastructure, public perception, and operational compatibility across different vessel types.

Among the available technologies, PWR, VHTR/HTGR, MSR, and LFR have been identified as the most promising for merchant shipping. Each type has unique benefits and limitations and should be considered based on the specific marine operational profile. PWRs, with their proven reliability and high technology readiness, lead in technical maturity and investment attractiveness, though further adaptation is needed for seamless integration into merchant vessels. Advanced reactors like MSRs and LFRs offer extended refuelling intervals and inherent safety features, making them strong candidates for deep-sea applications. MSRs also provide the greatest flexibility with continuous fuel makeup. The VHTR/HTGR, known for its high thermal efficiency and TRISO fuel-based safety, also holds potential for marine use but requires further investment and public acceptance to become viable.

All these types, reactors can be developed as SMRs or microreactors to accommodate the diverse power needs of merchant vessels. SMRs are well-suited for merchant shipping and deep-sea operations, providing flexibility across different vessel types. Their modularity allows for deployment in various vessel configurations, including bulk carriers, tankers, and container ships.

Ultimately, widespread adoption of nuclear power in merchant shipping will hinge on overcoming regulatory, infrastructural, and community barriers. The development of modular SMRs presents a practical path forward, leveraging production efficiencies and adaptability for ship integration. As the maritime industry increasingly seeks low-emission solutions, nuclear technology -- supported by targeted investments and public engagement -- could emerge as a viable alternative to conventional fuels, contributing to the sector’s decarbonisation.

2.4 Sustainability

Compared to coal and natural gas plants, nuclear reactors are much cleaner in terms of air pollution and GHG emissions. Coal-fired plants emit large amounts of CO_2, sulphur dioxide (SO_X), Nitrous oxides (NO_X) and particulate matter (PM), all of which contribute to climate change and poor air quality. Even natural gas, often considered a cleaner fossil fuel, still emits significant quantities of CO_2 and methane during extraction and combustion. In contrast, nuclear energy’s primary environmental concern lies in radioactive waste management and the potential for accidents.

2.4.1 Emissions

Fission-based nuclear reactors are recognised for their low-emission footprint and play a key role in reducing global GHG emissions. In nuclear fission, the nucleus of a uranium atom splits, releasing substantial energy without the combustion process typical of fossil fuel-based power plants. As a result, nuclear reactors emit virtually no CO_2 during operation, as fission does not involve burning fuel. This characteristic makes nuclear energy a lower GHG-emitting source compared to coal and natural gas plants.

Additionally, some indirect emissions, such as CO_2, may occur from auxiliary systems like diesel generators used during emergencies or for routine maintenance. Small amounts of NO_x may also be emitted from fuel combustion in backup systems on board. However, these emissions are minor when compared to those from conventional fossil fuel-based systems.

During operation, nuclear reactors release small amounts of radioactive gases, such as xenon and krypton, as byproducts of the fission process. Under normal operating conditions, the amount of these radioactive gases released to the atmosphere is negligible and safely managed. These gases are typically captured and managed within containment systems designed to prevent environmental release. Nuclear plants employ rigorous filtration and containment protocols to ensure that any emissions are well within strict regulatory limits. Occasionally, very small, controlled releases may occur, but these are tightly monitored and regulated, to remain within regulatory limits, posing minimal environmental risk under normal conditions.

Emissions associated with the broader lifecycle of nuclear power, including activities such as uranium mining, processing, construction, maintenance, and waste management, are separate from operational emissions. While these lifecycle processes may emit small amounts of methane (CH_4) and other GHGs, they remain minimal relative to emissions from coal or natural gas plants. Over the full lifecycle, nuclear power generates significantly lower emissions than fossil fuels, making it a promising pathway for reducing GHG emissions in various sectors, including marine propulsion.

Uranium mining and processing are energy-intensive activities that can release CO_2 and other pollutants. The fuel used in most reactors must be enriched, and this process requires significant electricity, potentially leading to emissions depending on the power source. A study by NREL found that these stages contribute approximately 1.8 gCO_2e/kWh, a fraction of the total lifecycle emissions (NREL, n.d.).

In addition, building and decommissioning nuclear reactors require large quantities of materials like concrete and steel, which contribute to the overall carbon footprint of nuclear energy.

However, the indirect NO_X emissions from nuclear power are more challenging to quantify and are often not the central focus of environmental assessments. Indirect emissions of NO_X can occur due to the use of fossil fuels in machinery and the transport activities associated with the construction and decommissioning of the nuclear power plant, as well as in the fuel-production cycle. NO_X emissions are primarily associated with the combustion of fossil fuels, a process not involved in nuclear fission. Therefore, the operational phase of nuclear power generation is not a significant source of NO_X emissions.

It is also noted that conventional nuclear power plants may be characterised by large cooling towers that, when in operation, may appear to be emitting gaseous clouds. However, the cooling towers do not convey emissions into the atmosphere other than the transfer of heat through the steam cycle to provide a heat sink (see also Subsection 2.4.3). That is, only water vapour is emitted through the towers.

To conclude, to accurately assess the lifecycle GHG emissions of nuclear power, it's essential to consider both upstream (Well-to-Tank, WTT) and operational emissions. As explained, nuclear energy generation does not involve the combustion of fossil fuels, it results in zero GHG emissions during operation. Additionally, the upstream Well-to-Tank (WTT) emissions are considered comparably low. As an example, it is noted that the Intergovernmental Panel on Climate Change (IPCC) report indicate a median lifecycle GHG emissions for nuclear energy at 12 grams of CO_2 equivalent per kilowatt-hour (gCO_2e/kWh), compared to 11 gCO_2e/kWh for wind and 45 gCO_2e/kWh for solar photovoltaic systems. In contrast, coal-fired power generation emits approximately 820 gCO_2e/kWh, and natural gas combined cycle plants emit about 490 gCO_2e/kWh (IPCC, n.d.).

To further quantify nuclear power's lifecycle emissions, developing a calculation formula tailored to nuclear fuel production and processing would support more precise, localised, assessments and strengthen data-backed comparisons. Also, the use of renewable energy can be considered to minimise the resulting emissions from activities such as uranium extraction, fuel processing and decommissioning.

Based on the above, nuclear propulsion emerges as a potential pathway toward decarbonizing the shipping sector, bypassing the carbon-intensive production processes associated with green fuels. However, its adoption must consider challenges such as safety, regulatory frameworks, and public acceptance.

2.4.2 Nuclear Waste Handling

While nuclear energy's carbon footprint is comparable to renewables, managing long-lived radioactive waste and ensuring plant safety are ongoing challenges. In general, the handling of nuclear waste is a critical part of ensuring both environmental protection and public safety for the nuclear-power industry. Nuclear waste, generated from the fission process in reactors, comprises various radioactive materials with differing levels of radioactivity and half-lives. Effective management of this waste involves several stages, including classification, treatment, storage and disposal.

For the protection of ionising radiation, environmental laws require monitoring, accounting and limiting of gaseous, liquid and solid radiological materials. Any gaseous, liquid or solid radiological materials emitted to the environment must meet the established environmental standards and exhibit radioactivity properties below the allowable limits that are subject to regulatory control. For legal and regulatory purposes, the IAEA defines radioactive waste as *"material for which no further use is foreseen that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels as established by the regulatory body"* (IAEA, 2022).

Nuclear waste with radioactive properties above the allowable limit is categorised into different classes based on its radioactivity level and potential hazards. Low-level waste (LLW) includes items like contaminated clothing, tools and filters, which have relatively low radioactivity and short half-lives. Intermediate-level waste (ILW) contains higher levels of radioactivity and includes reactor components, resins and chemical sludges. High-level waste (HLW), primarily spent nuclear fuel and reprocessing waste, is highly radioactive and generates significant heat. Proper classification of the wastes is essential to determine the appropriate handling and disposal methods for each type.

For nuclear-powered vessels, the types of waste products commonly generated can be classified as follows: Low-level waste (LLW) includes items such as contaminated clothing, cleaning materials, tools, and low-activity maintenance waste. Intermediate-level waste (ILW) includes more contaminated reactor components, chemical sludges, and resins, which may require shielding for safe storage. High-level waste (HLW), mostly spent nuclear fuel, contains highly radioactive fission products that generate significant heat, requiring both shielding and cooling. HLW is generally removed from vessels for storage or disposal in dedicated facilities due to its long-term storage needs.

The treatment of nuclear waste involves processes to reduce volume and mitigate hazards. For LLW and ILW, methods such as compaction, incineration and encapsulation in concrete or bitumen are commonly used. These processes minimise the volume of waste and stabilise it for safe storage and disposal. HLW, particularly spent fuel, undergoes cooling in spent fuel pools to dissipate the heat before being transferred to dry-cask storage. In some cases, HLW may be reprocessed to extract usable materials, reducing the volume of waste that requires long-term management.

The safe storage of nuclear waste is paramount to protect human health and the environment. LLW and ILW are typically stored in shielded containers at designated facilities, which are designed to prevent the release of radioactivity. HLW requires more stringent storage solutions due to its high radioactivity and heat generation. Spent fuel pools provide an initial cooling period for spent fuel rods, followed by transfer to dry-cask storage, where the fuel is encased in robust, air-cooled containers. These storage solutions are designed to isolate the waste from the environment and ensure long-term containment.

The ultimate disposal of nuclear waste aims to provide a permanent solution for isolating radioactive materials from the biosphere. Geological disposal is widely regarded as the most viable method for HLW and long-lived

ILW. This involves burying the waste in repositories that are deep underground, located in stable geological formations that provide natural barriers against the release of radioactivity. For LLW, near-surface disposal in engineered facilities -- where waste is buried at shallow depths and contained within protective barriers -- is commonly used.

Countries, such as Finland and Sweden, have developed projects based on a comprehensive approach to nuclear waste management, integrating technical solutions with financial planning to ensure long-term safety and sustainability. They provide valuable insights into the costs and strategies involved in developing and maintaining repositories that meet public and regulatory expectations. Incorporating these considerations into investment analyses can lead to more informed decisions for new investors, balancing the benefits of nuclear energy with the responsibilities of waste management.

Stringent regulatory frameworks and safety measures govern the handling of nuclear waste. International guidelines, such as those provided by the IAEA, ensure that countries adopt best practices in nuclear-waste management. National regulatory bodies oversee compliance with these standards, conducting regular inspections and assessments. Robust safety protocols, including monitoring and emergency preparedness, are integral to managing the risks associated with nuclear waste (Zohuri & Fathi, 2015).

In a nutshell, the principle nuclear residues in any reactor system are the fission and activation products generated within the fuel and the reactor vessel, where activation can take place due to the presence of neutrons. Much smaller amounts of residues also can accumulate outside the reactor itself; this was an issue for *NS Savanna*h which accumulated low-level radioactive wastewater that greatly exceeded its storage capacity, primarily from valve leaks in the circulating reactor's coolant system. This required disposal at sea of very low-level contaminated water.

Modern reactor system designs are unlikely to face significant challenges with low-level radioactive waste management. However, some onboard6 collection and storage of such waste will still be required. The frequency of waste removal and transport to a waste facility depends on factors such as the waste generation rate, onboard storage capacity, reactor operational schedules, and regulatory requirements.

The much larger sources of highly radioactive residues would accumulate in the fuel material itself. For refuelling, these residues would be removed along with the spent fuel and either processed or disposed of in a similar manner to other land-based reactor plants. All non-irradiated (not used) and used nuclear fuel and fissile products must be constantly managed for security and safeguard purposes. This may be achieved by the creation of a single government authority – through which nuclear fuel is sourced, processed, used and discharged or permanently stored -- when all the related activity occurs within that nation. However, if nuclear fuel and fissile products are brought to a new nation, arrangements must be made by government agencies, often for export/import purposes, to ensure that governance is always provided for the accountancy of nuclear material.

In the case where a nuclear-powered vessel needs to discharge either radioactive material or used fuels, it is unlikely that third-party nations would accept the material unless it originated there or could be further processed and reused. This may limit the availability of discharge ports for nuclear-powered vessels, and it may also depend on the ownership, licencing and registration of the vessel. It is expected that the fuel provider will handle the responsibility for waste disposal, as it will be very challenging to train the crew. Also, this is in accordance with the Non-Proliferation Treaty Act (see Subsection 3.1.1), which mandates strict controls on nuclear materials and consequently, the management of nuclear waste should be entirely excluded from the vessel's operations.

In the case of a solid-fuelled reactor (e.g., an LFR) whose refuelling interval matches or exceeds the design life of the ship, reactor dismantlement and handling of the spent fuel would be conducted in concert with the dispositioning of the vessel which had reached the end of its service life.

[6] In this context, 'onboard' refers to the storage capacity available within the vessel itself to temporarily contain low-level radioactive waste generated by its reactor system. The term emphasises that the storage of radioactive waste is happening within the confined space of the ship, rather than in external facilities.

The other exception is the MSR concept in which continuous refuelling (or fuel reconditioning) is part of the concept. This may require the accumulation and storage/disposal of fission and activation products that accumulate in the circulating molten salt fuel over time. It is possible that this accumulated residue would present a more difficult set of issues for on-board waste management.

It is noted that the timeline for refuelling or maintenance periods at dry-dock depends on the operational concepts and designs of the different reactors and are not yet well understood to be speculated.

2.4.3 Other Environmental Issues

Nuclear reactors require substantial amounts of cooling. Thus, heat sinks are important features in the safety of operational nuclear reactors. Cooling water or circulated air are abundantly available and often provide this essential service. Although not considered emissions, the heat transfer into the cooling medium may impact the environment at the point of release. For example, sending high temperature cooling water back into a body of water can create a local rise in temperature. If warm water is discharged into nearby rivers, lakes, or oceans this may lead to thermal pollution. If not managed properly, this increase in temperature can disrupt local aquatic ecosystems. Local environmental regulations may limit the allowable differential of cooling circuits. These site impacts are carefully considered in the design of nuclear power plants to reduce the overall impact on the environment. Additionally, because of the continuous cooling need, nuclear plants can strain local water resources, particularly in regions where water scarcity is an issue.

It is noted that nuclear reactors generally have lower thermal-to-mechanical efficiency compared to other propulsion systems, with a Carnot efficiency range of 35% to 50%. This means that a nuclear reactor could dissipate the same amount or up to 50% more heat into the sea than conventional systems, due to lower conversion efficiency. For merchant vessels, which typically use a two-loop cooling system, this system allows them to manage and discharge heat at a temperature that is more environmentally acceptable for marine ecosystems. The two-loop system thus helps to mitigate the effects of thermal pollution by cooling the water to a level that complies with regulatory standards for sea discharge, potentially reducing the environmental impact of heat released by nuclear-powered vessels. Incorporating this consideration into reactor and cooling system design can further enhance environmental compatibility, aligning with maritime regulatory standards to protect aquatic ecosystems. Overall, the efficiency of nuclear systems and their interaction with the environment are integral to sustainable power generation, as detailed in the assessment of nuclear power cycles and their potential in supporting low-carbon grids (Fathi, McDaniel, Forsberg, & de Oliveira, 2018).

Moreover, in the process of fissile decay, other elements are formed in the reactors, but they are typically larger atomic elements or substances other than those from conventional power sources. When produced, the structures and layers of protection that surround reactors for radiological safety capture and handle any emitted fission products.

Finally, uranium mining does have environmental and health implications, particularly related to radioactive contamination. Mining and processing of uranium ore into "yellowcake" can lead to the spread of radioactive particles, along with other environmental impacts from chemical byproducts. When comparing the environmental impact of uranium mining to that of oil, gas, and other mineral extraction, several parallels and distinctions emerge. Both uranium and fossil fuel mining are associated with significant environmental risks, though the nature of their impacts varies.

2.5 Cost Developments and Techno-Economic Analysis

This subsection describes the cost developments for nuclear-powered vessels. The total cost of ownership (TCO) is calculated over the first 25 years of vessels' operations[7] and highlighted for the years 2030 and 2050[8]. The TCO is a sum of the capital expenditures (CAPEX), fuel cost and annual operational expenditures (OPEX) for selected vessel types and size categories defined in the *Fourth IMO Greenhouse Gas Study 2020* (IMO, 2020). The specifications of these cost elements are outlined in the forthcoming subsections.

Subsections 2.5.1 and 2.5.2 offer the methods and definitions for the capital and operational costs, which serve as input for the calculating the TCO model for newly built nuclear-powered vessels. After the outline of all cost aspects, the method of the TCO calculation is presented (Subsection 2.5.3). Subsection 2.5.4 provides cost estimations for newly built nuclear-powered vessels and Subsection 2.5.5 discusses the vessel retrofit. The cost figures are presented in EUR using the year average exchange rate in 2023 (1 EUR = 1.0813 [9]) based on Eurostat (Eurostat, 2023).

2.5.1 CAPEX

The CAPEX represents fixed costs (long term investments on assets) for a newly built vessel and does not depend on the frequency and intensity of the use of the vessel. For a nuclear-powered vessel, this includes the nuclear-propulsion system encompassing the reactor system, power conversion and process heat system, and the electrical distribution system. For the VLSFO-fuelled vessel which serves as a reference case in this report, the CAPEX consists of the cost of the engine, after-treatment, onboard storage, fuel tank, piping, gensets and steam system. The analysis focuses solely on unique fixed-cost items related to each case; other costs such as the cost of the vessel's hull structure are excluded due to an assumption of similarity.

Nuclear propulsion system cost

In the naval industry, CAPEX for nuclear propulsion systems is a significant investment that entails the acquisition, development and maintenance of advanced nuclear-powered vessels. These expenditures are crucial for enhancing the operational capabilities, strategic reach and the overall effectiveness of navies. Nuclear-propulsion systems, which provide vessels with unparalleled range, speed and endurance, require substantial initial outlays for the construction of nuclear-powered submarines and aircraft carriers, as well as the associated infrastructure for fuel handling and storage.

The development of nuclear-propulsion systems involves sophisticated technology and stringent safety measures, necessitating significant capital investment in research and development, as well as some initial specialised training for personnel. Financially, these investments are recorded on the balance sheet as assets, with their costs depreciated over the long operational lives of the vessels. While the upfront CAPEX for nuclear propulsion systems is considerable, the benefits include reduced operational costs over time due to the efficiency and longevity of nuclear power, as well as strategic advantages in terms of sustained operations without the need for frequent refuelling[10]. Note that ongoing training costs for personnel are generally part of OPEX, covering regular safety and operations training throughout the vessel's service life.

Funding for these CAPEX can come from governmental budgets, given the strategic importance of naval power, or through partnerships with private defence contractors. Proper management of CAPEX in this area is vital,

[7] This is normal reference given cost of merchant vessels today (also used in the previous studies) and is a trade-off between vessel value, maintenance cost and alternative of new building. Longer lifetime could be considered if the business case could substantiate it, which could be the case of the nuclear-powered vessel.

[8] While some cost components may in practice be passed on to the charterer (e.g. fuel cost, carbon cost), the aim here is to present a complete overview of the cost components for the acquisition and operation of nuclear-powered vessels.

[9] While the conversion factor is based on an average exchange range for 2023, the sources used might be from previous years and most of the data were found in USD.

[10] While it is possible to purchase all nuclear fuel upfront (like a CAPEX), it's continued maintenance, handling, and potential refuelling arrangements may still be necessary. Therefore, any possible refuelling operations should be considered as an OPEX.

ensuring that investments align with the long-term strategic goals of the naval forces and contribute to their sustainable growth and operational effectiveness.

As of today, since the use of nuclear-powered propulsion for merchant vessels is scarce, it is common to estimate CAPEX from land-based nuclear power plants. The details of several land-based nuclear power plants extracted from the 2020 edition of the Projected Costs of Generating Electricity by Organisation for Economic Co-operation and Development (OECD) International Energy Agency and OECD Nuclear Energy Agency (OECD International Energy Agency and OECD Nuclear Energy Agency, 2020) are summarised in Table 5. As can be seen, the capacity, cost and technology vary significantly. The overnight capital cost[11] ranges from 1995 EUR/kW (2,157 USD/kW) in South Korea to 6,400 EUR/kW (6,920 USD/kW) in the Slovak Republic.

Table 5. Nuclear generating technologies (OECD International Energy Agency and OECD Nuclear Energy Agency, 2020).

Country	Technology	Net capacity (MWe)	Overnight capital costs (USD/kW)	Overnight capital costs (EUR/kW)
France	European Pressurised Reactor (PWR)	1,650	4,013	3,711
Japan	Advanced Light Water Reactor (LWR)	1,152	3,963	3,665
South Korea	Advanced Light Water Reactor (LWR)	1,377	2,157	1,994
Russia	Vodo-Vodyanoi Energetichesky Reaktor (PWR)	1,122	2,271	2,100
Slovak Republic	Other nuclear	1,004	6,920	6,400
United States	LWR	1,100	4,250	3,930
China	LWR	950	2,500	2,312
India	LWR	950	2,778	2,570

The thorough literature survey conducted by Idaho National Laboratory (INL) (Abou-Jaoude, et al., 2023) for land-based nuclear reactors revealed that there is a significant overlap between the various reactor types (see Figure 3). Although minimum values vary, the average costs for each reactor type are within about 30% of each other, indicating that reactor type does not heavily impact costs. This suggests that, in nuclear techno-economic analysis, CAPEX is not highly sensitive to reactor type. However, in terms of applicability for marine applications and technology readiness, substantial differences exist among reactor types, as shown in Table 3 and Table 4. For example, while the technology readiness level for PWRs is higher compared to MSRs, the latter provides benefits such as improved burnup, continuous refuelling, and higher operational temperatures.

[11] Overnight capital cost refers to the hypothetical cost of constructing a power plant (or another large asset like a nuclear-powered vessel) as if it was built "overnight", i.e., without any delays, interest, or escalation in prices over time. It represents the total cost to bring a project to operational status, including all direct and indirect costs associated with the project (like materials, labour, equipment, and site preparation), but excluding financing costs such as interest on loans and inflation adjustments that would accrue over the actual construction period. It provides a "snapshot" estimate of the full capital required to complete the project, offering a baseline for comparing projects without the complexities of time-related financial factors.

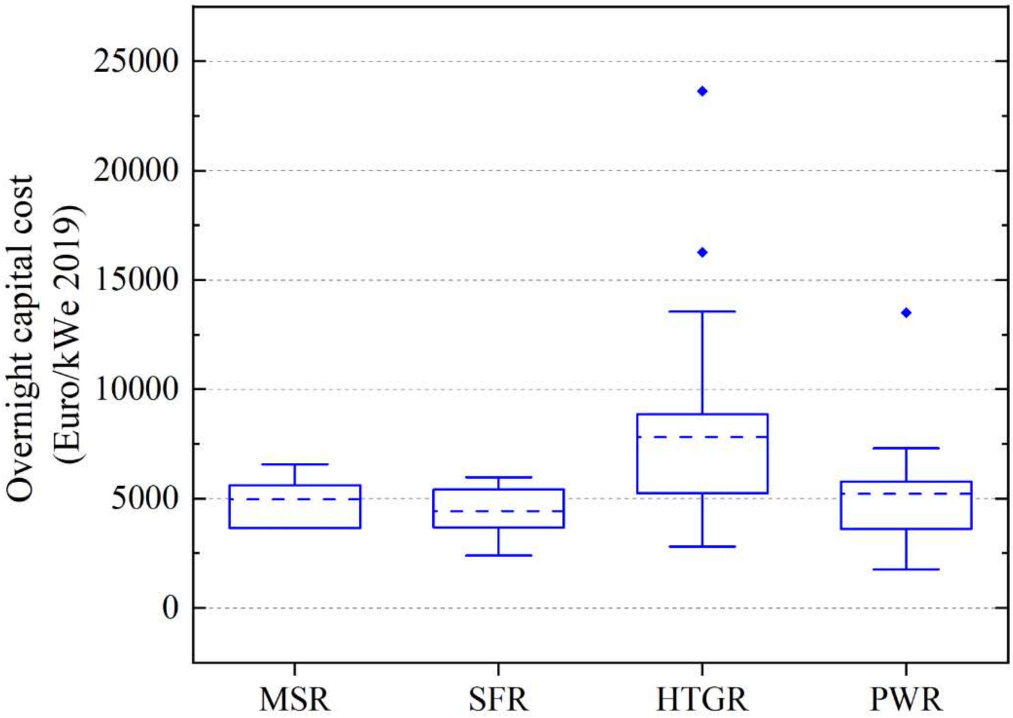


Figure 3. Whisker plot with associated standard deviations CAPEX (Abou-Jaoude, et al., 2023)

The construction of a nuclear power plant has different items, including design, procurement, construction and commission and fuel loading. The breakdown of the budget for these items is provided in Table 6. A portion of the budget is allocated for site development and tasks that are not essential for a vessel. However, the required power for merchant marine vessels is considerably lower than that of land-based nuclear power plants. As a result, the cost per kW of the marine nuclear energy system is higher. For example, as per the U.S. Energy Information Administration, the capital cost for a 2,156 MW large nuclear power plant is more than 7% higher than that of a 600 MW small power plant (U.S. Energy Information Administration, 2023). For merchant marine vessels, the required power is typically below 100 MW and often below 50 MW. Therefore, the extra 20% of the site development for land-based nuclear power plants should be reallocated to cover the extra cost per kW for marine applications.

Table 6. Breakdown of nuclear power plant construction costs, reproduced from (World Nuclear Association, September 2023).

Items	Percentage of cost
Design, architecture, engineering and licencing	5%
Project engineering, procurement and construction management	7%
Construction and installation works:	
Nuclear island	28%
Conventional island	15%
Balance of plant	18%

Items	Percentage of cost
Site development and civil works	20%
Transportation	2%
Commissioning and first fuel loading	5%
Total	**100%**

The cost of the nuclear reactor for marine applications may decrease over time due to learning factors. The learning rate represents a gradual improvement in productivity that can be attained by gaining experience and by mastering the process and tools to produce a product. It is the decrease in costs observed with each doubling of production. The expected learning rate of the SMR industry (which is suitable for marine applications) ranges between 5-10% (Mignacca & Locatelli, 2020). Typically, the learning curve tends to plateau after 5-7 units have been completed (Locatelli & & Mancini, 2010).

The cost per kW of nuclear reactors is not universal. Here, two price estimates are considered: 1) 3,497 EUR/kW (3,782 USD/kW) based on the study by Energy Options Network and SMR Start (Energy Options Network, 2017; SMR Start, 2021); and 2) 7,019 EUR/kW (7,590 USD/kW) from a recent report by the U.S. Energy Information Administration (estimated for an SMR of 600MWe that will be first available in 2028) (U.S. Energy Information Administration, 2023). In a 2023 report, the low scenario for nuclear-powered vessels has been considered 3,699 EUR/kW (4,000 USD/kW) and the high 5,549 EUR/kW (6,000 USD/kW) (DNV, 2023). The corresponding figures in the recent report by INL are 3,699 EUR/kW (4,000 USD/kW) and 6,474 EUR/kW (7,000 USD/kW) (Dowling, Mukhi, Jaoude, & Morin, 2023). Therefore, 7,019 EUR/kW (7,590 USD/kW) has been considered to be the worst-case scenario used for the purpose of this analysis, while 3,497 EUR/kW (3,782 USD/kW) may be achieved assuming the cost reduction due to the maturity of the technology and mass production.

It is noted that in future studies a model could be built to account for economy of scale that is expected to reduce the unit price.

Internal Combustion Engine and genset costs

Conventional propulsion includes internal combustion engines (ICE), the CAPEX of which is assumed at 250 EUR/kW (285 USD/kW) (EMSA, 2022) and 370 EUR/kW (400 USD/kW) (Houtkoop K. C., 2022). In this report, the cost for ICE is considered as 323 EUR/kW (350 USD/kW) as an average cost. Also, the cost of genset is considered as 60% of the engine cost (Ahn, You, Ryu, & Chang, 2017).

After-treatment system cost

Another consideration for conventional fuel is the cost of the after-treatment system[12]. After-treatment costs are those borne by the system and the treatment of harmful substances or elements that cannot be released into the environment due to regulation. A commonly used technique is a selective catalytic reduction system (SCR) to treat the exhaust after the fuels are combusted in the engine to bring NO_X emissions in line with the regulatory limits. According to Hansson, et al. (Hansson, Brynolf, Fridell, & Lehtveer, 2020), the cost of a SCR is proportional to the installed main engine power of the vessel. The SCR cost is 123 EUR (133 USD) per kW in 2050 for all vessel types and sizes. Also, based on budget cost proposals from Asian shipyards, the SCR values at 46.2 EUR/kW (50 USD/kW) of installed power for a 2-stroke diesel engine. Here, the value of 83 EUR/kW (90 USD/kW) was used to calculate the SCR cost. This cost is not applicable to nuclear-powered vessels.

[12] In this study, a comparison is done between a CO_2 emitting solution (VLSFO) with a zero-carbon solution (nuclear power). A more equal comparison could include a Carbon Capture System (CCS) on the conventional vessel. However, for consistency with the previous studies, CCS has not been considered.

Onboard storage, fuel tank and piping

For the supply and storage of the fuels, dedicated onboard tanks and piping systems are necessary. The cost of these components is assumed to be proportional to the power of the vessel's engine. The costs for storage tanks and the fuel-supply system (FSS) are additional to those for the engine. These costs are presented in Table 7. They are scaled to the per-kW cost by calculating the total storage and FSS cost per vessel category and dividing them by the installed power of the ship. This cost does not apply to nuclear-powered vessels as the fuel is inside the reactor and there is no additional storage or FSS.

Table 7. Overview of storage tank and FSS cost (Hansson, Brynolf, Fridell, & Lehtveer, 2020).

Vessel category	Vessel size	Average size storage tank (GJ)	Average installed power (kW)	Storage and FSS Cost per GJ (USD)	Storage and FSS Cost per GJ (EUR)
Deep-sea vessels	All vessel types* with size above 2,500 deadweight tonnage (DWT)	71,300	11,000	35	30
Container ships	All container ships	74,600	23,000	35	30

** Excluding container ships*

Decommissioning cost

In addition to the initial expenses associated with the nuclear-power system, it is important to consider the decommissioning process that will be required at the end of its operational lifespan. Based on the survey published by the OECD Nuclear Energy Agency in 2016 (OECD Nuclear Energy Agency, 2016), for land-based nuclear power plants the decommissioning costs ranged from 0.425-0.675 million EUR/MWe (0.46-0.73 million USD per MWe) for units over 1,100 MWe and costs ranged from 0.989-1.128m EUR/MWe (1.07-1.22m USD per MWe) (World Nuclear Association, May 2022) for units of less than 1,100 MWe.

The decommissioning cost for nuclear-powered merchant vessels is not well established due to the limited available data, however, the estimate was available for *NS Savannah* at 71.21 m EUR (77 m USD) (Sayres and Associates Corporation, 2008). In this report, an average cost of 1.849 m EUR/MWe (2 m USD/MWe) is assumed as a reference value for nuclear-powered vessels, derived as a midpoint between the lower decommissioning costs for land-based plants and higher costs observed for navies (Houtkoop K. C., 2022). While decommissioning costs are not factored into the TCO of nuclear-powered vessels in this analysis, this represents an additional potential expense that shipowners should consider.

Also, nuclear-powered vessels generally have minimal to no residual value at the end of their operational lifespan due to the high costs and regulatory challenges of decommissioning. The removal and disposal of radioactive materials, along with the limited reusability of contaminated components, contribute to this lack of residual value. In contrast, oil-fuelled vessels often retain some residual value through materials like steel, which can be recovered during scrapping. However, this residual value was not quantified in this study either. Therefore, the analysis may lean favourably toward nuclear options, and this should be kept in mind when interpreting the results.

2.5.2 OPEX

In the maritime industry, OPEX, or operating expenditure, refers to the ongoing costs required for the day-to-day functioning and maintenance of vessels and maritime operations. These expenses are essential for ensuring the continuous and efficient operation of vessels, including expenses related to crew wages, fuel, port fees, repairs, maintenance, insurance and supplies.

Fuel costs constitute a significant portion of OPEX in the maritime industry, where vessels consume large amounts of fuel during voyages. Crew wages and benefits are also substantial, given the need for skilled personnel to operate and maintain the vessels. Maintenance and repair expenses are necessary to keep vessels in a good working condition and ensure compliance with safety and environmental regulations. Port fees and tariffs are incurred whenever a vessel docks, while insurance costs protect against potential risks and liabilities.

As items that directly impact the profitability of shipping companies, OPEX is typically recorded on the income statement as expenses incurred during the operational period. Effective management of OPEX is crucial for maintaining the cost-efficiency of maritime operations. Strategies to optimise OPEX might include adopting fuel-efficient technologies, implementing preventive maintenance programmes and streamlining operations to reduce turnaround times at ports.

While CAPEX represents long-term investments in assets, OPEX covers the recurring costs that keep these assets operational and productive. Properly balancing CAPEX and OPEX is essential for the financial health and competitiveness of companies in the maritime industry, ensuring they can sustain operations while investing in future growth.

In a nutshell, OPEX are variable costs, depending on the use of the vessel and can comprise the costs of fuel, maintenance and repair, and crew training[13]. For oil-fuelled vessels, OPEX also includes carbon costs and bunkering.

Fuel costs

The cost of nuclear fuel can be estimated by assessing the price of raw materials, the quantity of fuel needed, and the expenses related to converting the raw materials into nuclear fuel.

The price of 5% enriched uranium has been estimated at 2,368 EUR/kg (2,560 USD/kg) based on a 120 EUR/kg (130 USD/kg) cost for mined uranium (Trading economics, 2024), a conversion cost of 15 EUR/kg (16 USD/kg) for mined uranium (World Nuclear Association, September 2023), an enrichment cost of 92 EUR/SWU (100 USD/SWU) (via a separative work unit) (U.S. Energy Information Administration, 2021) and a fuel-fabrication cost of 277 EUR/kg (300 USD/kg) for the end product (World Nuclear Association, September 2023).

To determine the useful power (mechanical or subsequent electrical power) of nuclear fuel, the amount of fuel burnup and the conversion efficiency of the drivetrain must be considered. The fuel burnup varies based on the nuclear reactor type. For example, PWRs achieve a burnup of 45-75 GWd/tHM (GW-days per metric tonne of heavy metal), while MSRs and VHTRs/HTGRs reach burnups of 90+ GWd/tHM and 90-200+ GWd/tHM, respectively Burning 90 GWd/tHM produces 2,160 MWh of thermal energy from 1 kg of nuclear fuel. Considering 33% efficiency for converting thermal to electrical energy, 1 kg of nuclear fuel generates approximately 712 MWh of electricity. By comparison, the average energy produced per kilogram for marine engines powered by diesel is only 0.005 MWh (Houtkoop K. C., 2022).

It is important to note that nuclear fuel cost has been steadily decreasing due to increasing efficiency. For instance, in the USA, fuel costs declined by 41.4% between 2012 and 2022 according to the Nuclear Energy Institute (Nuclear Energy Institute, December 2023). Recently, however, due to the disruption in some supplier nations and growing geopolitical tensions, uranium prices have started to increase which can affect the cost of nuclear fuel. In this analysis, potential geopolitical issues, such as the lack of Uranium, have not been considered. Nonetheless, the sensitivity analysis showed that even if the nuclear fuel cost increases by 35%, the TCO of nuclear-fuelled vessels will increase by only 1%.

[13] Due to the complex arrangement of ownership, liability and security / safeguards oversight, long-term/permanent nuclear waste management is not likely to be paid by the shipowner. Nuclear waste disposal is to be in accordance with the non-proliferation treaty, while further research is to be done regarding the financial responsibility to manage nuclear waste disposal (may be regional) depending on the regulators. Potential additional insurance costs are still unknown and have not been considered.

It is also noted that since the nuclear fuel is available nuclear-powered vessels could potentially supply emission free power to onshore during port stays. This may lead to additional income for nuclear-powered vessels.

Fuel-oil costs can experience substantial fluctuations which in turn have substantial effects on the TCO of VLSFO-fuelled vessels. In June 2022, for example, VLSFO was traded at 1,036 EUR/tonne (1,120 USD/tonne) while the minimum price in 2024 was 486 EUR/tonne (526 USD/tonne) (Ship & Bunker, 2024). In this report, the minimum and maximum prices for VLSFO (Ship & Bunker, 2024) and the projected fuel prices for 2030 and 2050 (EMSA, 2022) are shown in the Table 8.

Table 8. Fuel cost.

Fuel	2024 Min	2024 Max	2030 Min	2030 Max	2050 Min	2050 Max
VLSFO (EUR/tonne)	486	730	480	1,112	784	1,464
Nuclear (EUR/tonnes*1000)	2368	2368	2368	2368	2368	2368

It is noted that, given the operational profile for nuclear-powered vessels, high-assay low-enriched uranium (HALEU) with enrichment up to 20%, may provide a more appropriate reference than standard low-enriched uranium (LEU). The increased energy density in HALEU supports extended operational periods without refuelling, which aligns well with marine vessel needs.

In addition, the use of TRISO fuel -- whether LEU or HALEU -- introduces higher fuel costs due to complex manufacturing processes but brings significant safety and proliferation resistance benefits. Including a price estimate for TRISO-based HALEU fuel in the cost evaluation would reflect these important considerations.

While TRISO fuel production involves a more complex and costly manufacturing process than traditional nuclear fuels, its unique properties can offer significant economic and operational benefits. The advanced layered design of each particle requires intricate fabrication techniques, resulting in a higher initial cost. However, these costs are offset by TRISO's longer operational lifespan and reduced maintenance and refuelling needs.

Future analyses might consider prices for other fuel types as a benchmark.

Bunkering cost

In this study, bunkering expenses include the expenses associated with the process of supplying the bunker fuel, including expenses related to the port services that provide the fuel, such as the logistics of loading and storage. These costs are estimated in proportion to the annual energy consumption and are based on research conducted by the Dutch technical research institute TNO (TNO, 2020). The bunkering costs do not encompass the cost of the fuel. It is noted that the time needed for bunkering has not been considered in this analysis and this may lead to significant time loss (leading to loss of revenue) over the lifetime of the VLSFO-fuelled vessel. Since nuclear-powered vessels can sail for an extended period of time without refuelling, this approach can be considered conservative, underestimating the cost of the VLSFO-fuelled vessel.

Carbon costs

The European Union Emissions Trading System (EU ETS) includes the maritime industry. Starting in 2024, shipping companies must submit allowances for the CO_2 emissions their vessels produced during journeys to, from and within ports in the European Economic Area (EEA). Carbon costs arise when fossil fuels are burned onboard vessels within the geographical scope of the EU ETS. For more details refer to Subsection 3.2.

To calculate the carbon costs as part of the TCO analysis, carbon costs of €46 per tonne of CO_2 in 2030 (Pons, et al., 2021) and €150 per tonne of CO_2 in 2050 (European Commission, 2021) were considered. The carbon cost between 2030 and 2050 was calculated using an interpolation. For 2026 to 2029, the carbon cost was considered as €20[14] per tonne of CO_2. This number was divided by two because, for the voyages between EEA and non-EEA ports, only 50% of the emissions allowances will need to be submitted[15]. Also, if vessels do not call at EEA ports, the baseline costs for VLSFO also will be lower until global measures are in place. If only intra-EU voyages are considered, then the baseline costs for VLSFO will be higher. The carbon-emission calculation for oil fuel is 3,114kg of CO_2 per tonne of fuel (IMO, 2020). Nuclear-fuelled vessels have no tank-to-wake (TTW) carbon emissions and are not subject to carbon cost at this point of time.

In future studies, it may be considered comparing the TCO of a nuclear-powered vessel with a oil-fuelled vessel equipped with a Carbon Capture and Storage system, making comparison between zero-CO_2 emitting vessels

Maintenance and operation costs

Maintenance and operation (M&O) costs occur yearly.

For nuclear-powered vessels, this includes refuelling operations, waste management and storage, crew training as well as any potential safety clearances. The report by INL considers this cost as 23 EUR/MWh (25 USD/MWh) (Dowling, Mukhi, Jaoude, & Morin, 2023). (Houtkoop K. C., 2022), on the other hand, estimated these costs using the fixed and variable (M&O) costs provided in the report by the United States Energy Information Administration (USEIA). The USEIA's 2023 report (U.S. Energy Information Administration, 2023) estimated the fixed cost and variable M&O costs for land-based SMRs as 98.88 EUR/Kw (106.92 USD/kW) per year and 3.13 EUR/MWh (3.38 USD/MWh).

The M&O costs used in this report were calculated using both methods and based on the assumption that vessels sail at full loads only 40% of the year, with partial loads required 60% of the time (i.e., a 40% load). The results from the two approaches were within 20% of each other. The average of the two numbers was used for the TCO estimation in this report. Also, this approach provides more conservative costs (higher cost) compared to the cost reported for 15,000 TEU (twenty-foot equivalent units) container ships in a report previously published (DNV, 2023) .

The maintenance and repair (M&R) costs for vessels with internal combustion engines are assumed to be 1.5% of the CAPEX (EMSA, 2022). Therefore, this assumption was made for the reference case with VLSFO.

Training cost

The use of alternative fuels involves different risks. Nuclear waste is radioactive, which requires the crew to follow specific safety guidelines. Specialised training is required for new and established crews. Following precedent set by Texas A&M Maritime Academy and Texas A&M University, this cost is already considered in the fixed and variable M&O costs presented above.

2.5.3 Method

Using all cost components as outlined earlier in this subsection, it was possible to calculate indicative TCO figures for vessels powered by nuclear and oil fuel as a reference.

The engine costs were estimated by multiplying the average installed power (kW) of the main engine of a vessel type with the engine cost per kW. The total CAPEX was calculated for discounted scenarios. Yearly costs using an annuity of 25 years and the weighted average cost of capital (WACC) of 7% were calculated[16]. It is worth

[14] Currently, this cost is now around €70 euros. However, for consistency with the previous studies, €20 has been kept here.

[15] In previous studies (EMSA, 2022), (EMSA, 2023), only intra-EU voyages have been considered. However, nuclear power may be considered a reasonable option for bigger vessels with long sailing distances (i.e. mainly extra- EU voyages). Also, given the uncertainties related to the cost of nuclear-powered vessel, this has been selected as more conservative approach.

[16] The reported ranges of the WACC by several maritime freight operators (Faber, Kleijn, Király, & Geun, 2021).

mentioning that although the vessel lifetime may reach 50 years (even exceed 50 years), it is common to calculate the discounted yearly cost for 25 years.

Using all cost components as outlined earlier in this subsection, it was possible to calculate indicative TCO figures for vessels powered by nuclear and oil fuel as a reference. First, the fuel costs per year were calculated using the total yearly fuel consumption (main engine, auxiliary and boiler engines) for each vessel type and size class based on assumed fuel consumption for VLSFO (IMO, 2020). The nuclear fuel consumption was calculated based on the assumption of 90 GWd/tHM burnup and the energy conversion of 33%. To estimate the carbon costs, the amount of CO_2 emission was calculated by multiplying the amount of VLSFO consumption in tonnes by 3,114 kg as mentioned earlier.

To calculate the bunkering costs, the yearly average fuel consumption of VLSFO in GJ is used. The fuel consumption is multiplied by the bunkering cost per GJ to obtain the yearly bunkering cost.

To obtain the yearly maintenance and repair cost, the total CAPEX was multiplied by the M&R factor (1.5%). The yearly TCO is the sum of the yearly fuel cost, bunkering cost, yearly CAPEX and M&R cost. For the nuclear-powered vessels, the costs of maintenance and operation, which included crew training, were considered.

2.5.4 TCO Newbuild Estimation

Here, a detailed TCO comparison is made for four common vessel types: container ships, bulk carriers, liquified gas tankers and oil tankers. The figures for the TCO present four different scenarios. Two price scenarios were considered for the nuclear-powered vessels, namely, Nuclear_Low and Nuclear_High which represent the cost estimation for the low (3497 EUR/kW) and high (7019 EUR/kW) CAPEX, respectively, as explained in the section of nuclear propulsion system cost. For the VLSFO vessels also two case studies were examined: VLSFO_Low and VLSFO_High which denote the low and high fuel cost scenarios as shown in Table 8, respectively.

The results are presented for annual and cumulative TCOs. Also, the cost differences of the nuclear system with respect to the reference case of the same vessel on fuel oil (VLSFO) are highlighted for the years 2030 and 2050. It is noted that the price of fuel oil is increasing over time.

The OPEX costs include those for fuel, carbon emission, bunkering, maintenance and repair, and training for VLSO vessels. For the nuclear-powered vessels, the OPEX costs consist of fuel, maintenance and operation (including training). The fuel costs represent the highest contribution to the OPEX for the VLSFO vessels. Therefore, they are presented separately from the non-fuel OPEX.

2.4.2As explained in 2.4.2, the timeline for refuelling or maintenance periods at dry-dock depends on the operational concepts and designs of different reactors and remains uncertain for precise speculation. These costs, while not itemised separately, have been generally included within the M&O costs.

Container ships

The annual and cumulative TCOs for nuclear-powered as well as VLSFO-fuelled container ships in the 12,000-14,499-TEU range with an average power of 61,231 kW are indicated in Figure 4 (a) and Figure 4 (b), respectively.

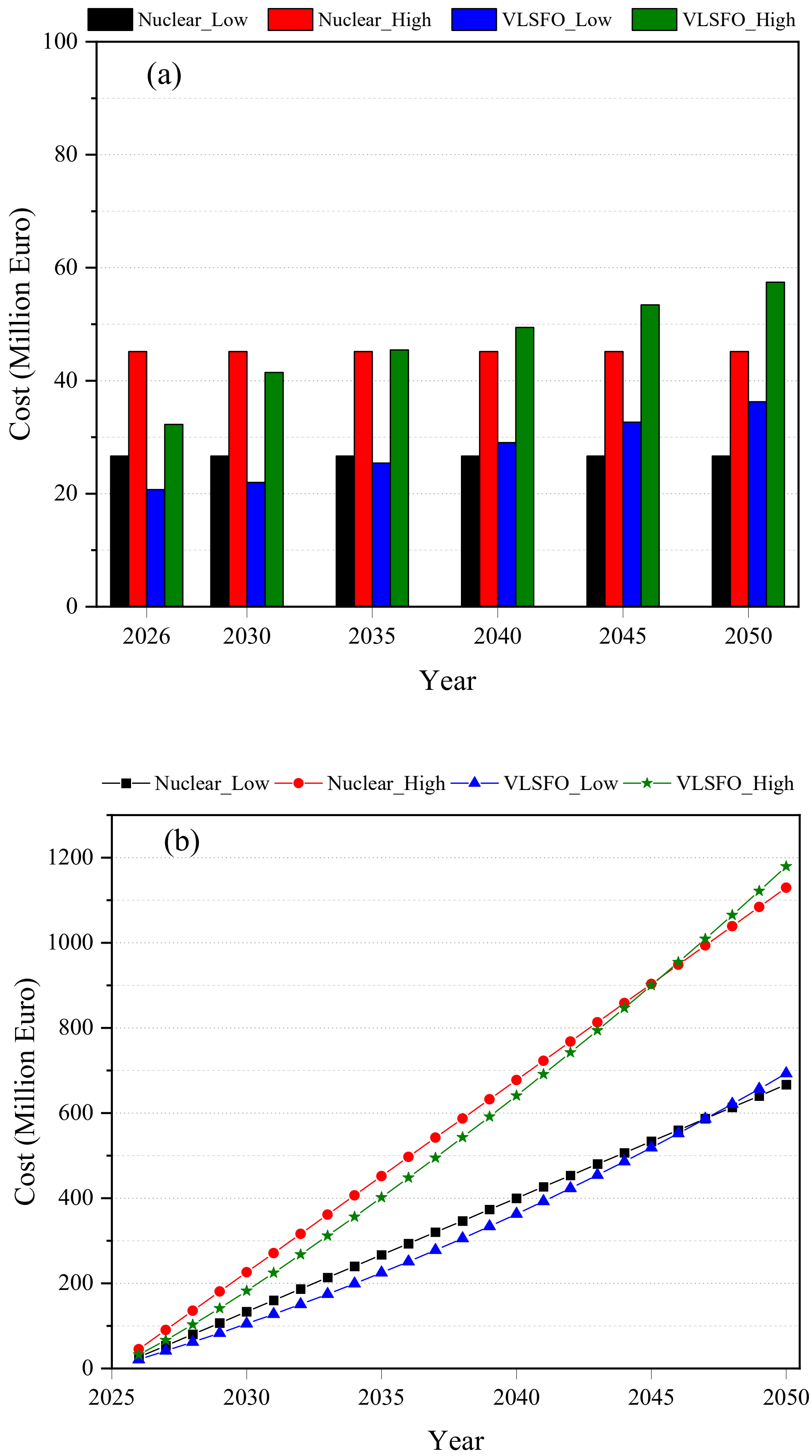


Figure 4. (a) Annual and (b) cumulative TCO over the first 25 years of container ship operation

It can be seen that the TCO for Nuclear_Low are similar to those of the VLSFO_Low and the costs for Nuclear_High are similar to those of the VLSFO_High (Figure 4 (b). A closer look reveals that although the TCO for the nuclear-powered vessel is initially slightly higher than that of its VLSFO-fuelled counterpart, the cost gap reduces (even the TCO of the VLSFO exceeds) as years pass by. This is because of the considerably higher fuel cost of the VSLFO vessels as can be seen from Figure 5. This suggests that for the high fuel price range, the nuclear-powered vessels are economically justified even if the high CAPEX range happens. Of course, the lower CAPEX provides a more attractive investment opportunity.

As shown in Figure 5, the CAPEX difference for the Nuclear_Low scenario is 395%, while in the high scenario it is 894%. On the other hand, the VLSFO fuel cost is 13-30 times higher than the nuclear fuel cost for 2030. In 2050, the respective ratios reach 21-40 times higher due to the projected increase in the price of VLSFO. Therefore, the extra cost accrued from the high CAPEX of the nuclear propulsion system is compensated for by the high fuel cost for container ships powered by VLSFO.

In 2050, for example, for the high price range of VLSFO fuel, the TCO of the VLSFO-fuelled containers is 21%–53% higher than that of the nuclear-powered container ships. Also, although the non-fuel OPEX of the nuclear-powered container ship is higher in 2030, due to the carbon costs the additional non-fuel OPEX becomes negative in 2050, which are zero for the nuclear-powered container ship. This model estimation has been compared with figures from literature (DNV, 2023), which estimated the annual cost for a 15,000 TEU container ship with 42 MW power ranged from 16–22.8m EUR (17.3–24.7m USD), which is comparable to the present estimation when the power difference is considered.

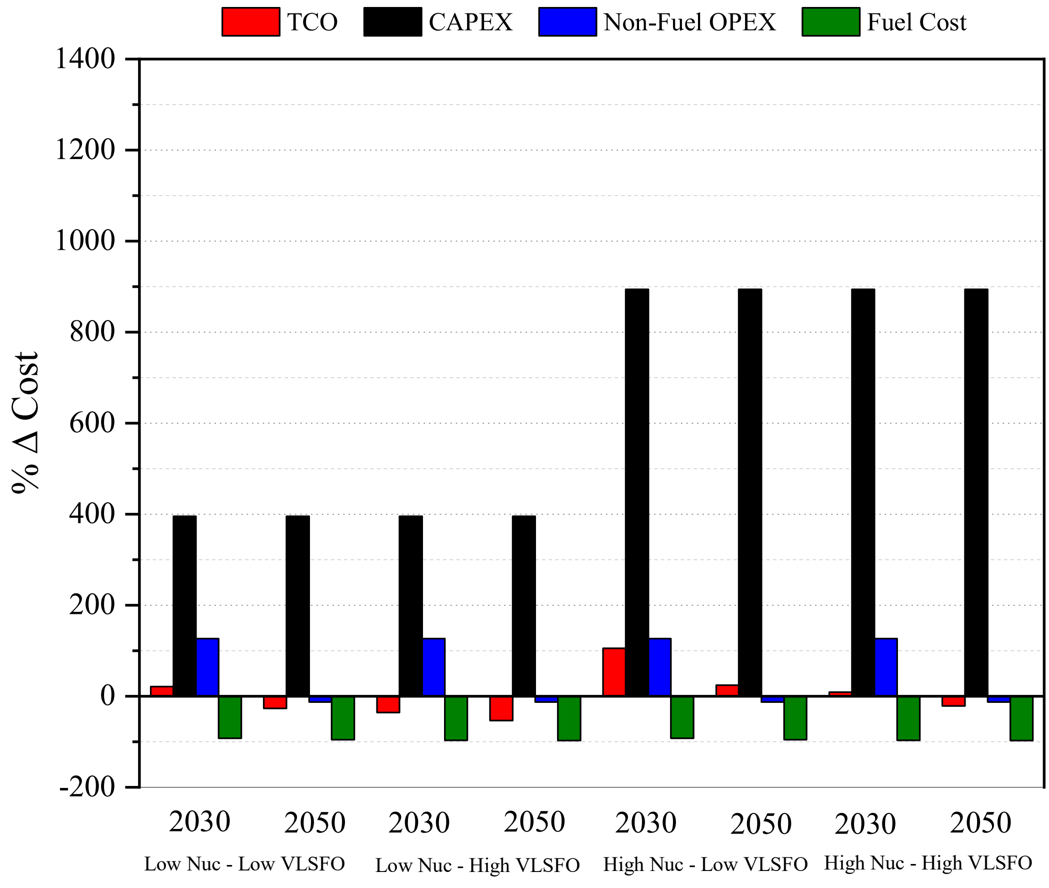


Figure 5. Additional yearly TCO for nuclear-powered container ships in 2030 and 2050 (compared to VLSFO-fuelled)

Bulk carriers, liquefied gas tankers and oil tankers

The TCO estimations for a bulk carrier in the 200,000-+ DWT range with an average power of 20,094 kW, a liquefied gas tanker in the 100,000-199,999 cbm (cubic metre) range with an average power of 30,996 kW and an oil tanker in the 120,000-199,999 DWT range with the average power of 17,446 kW are presented in Figure 6 to Figure 11.

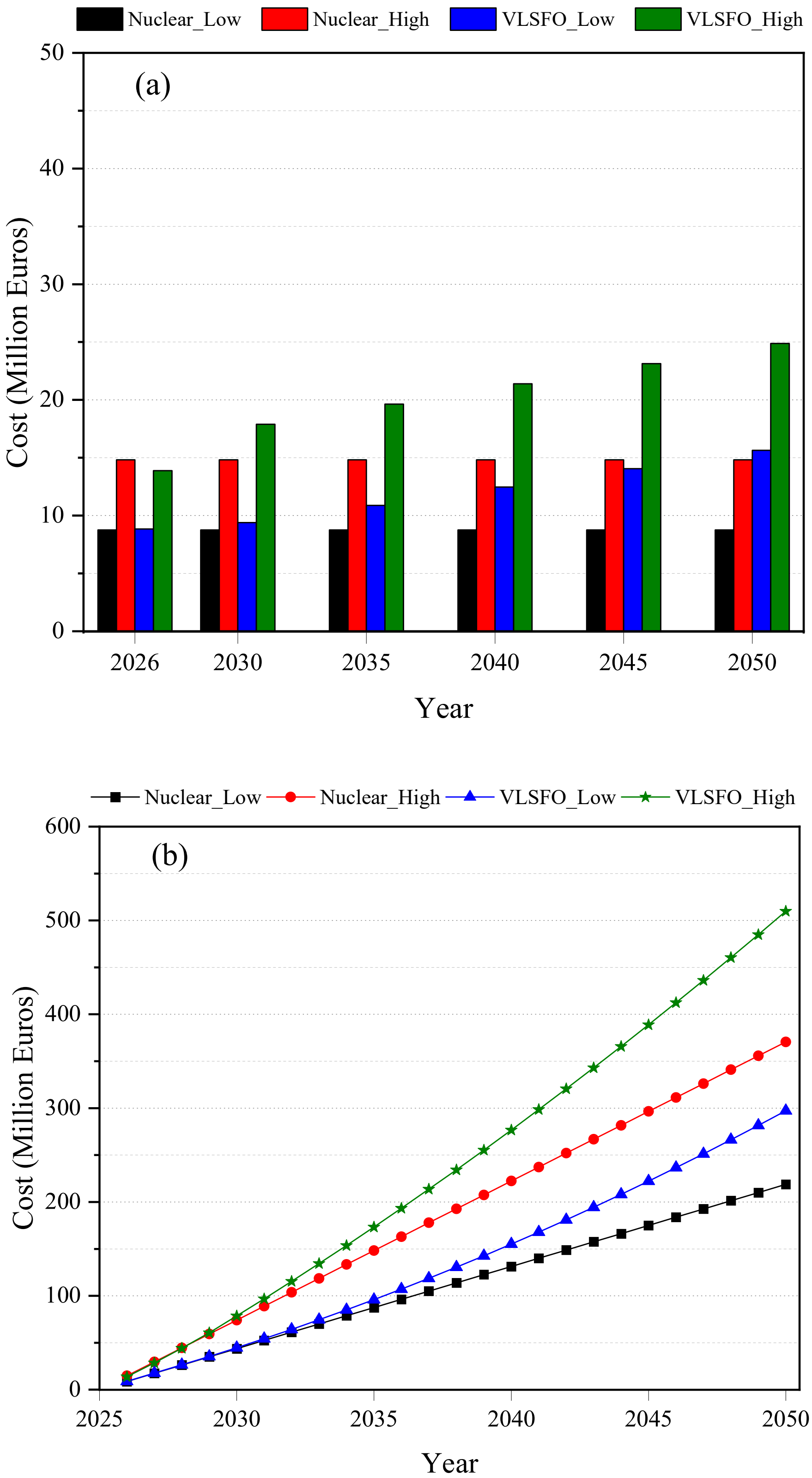


Figure 6. (a) Annual and (b) cumulative TCO over the first 25 years of bulk carrier operation

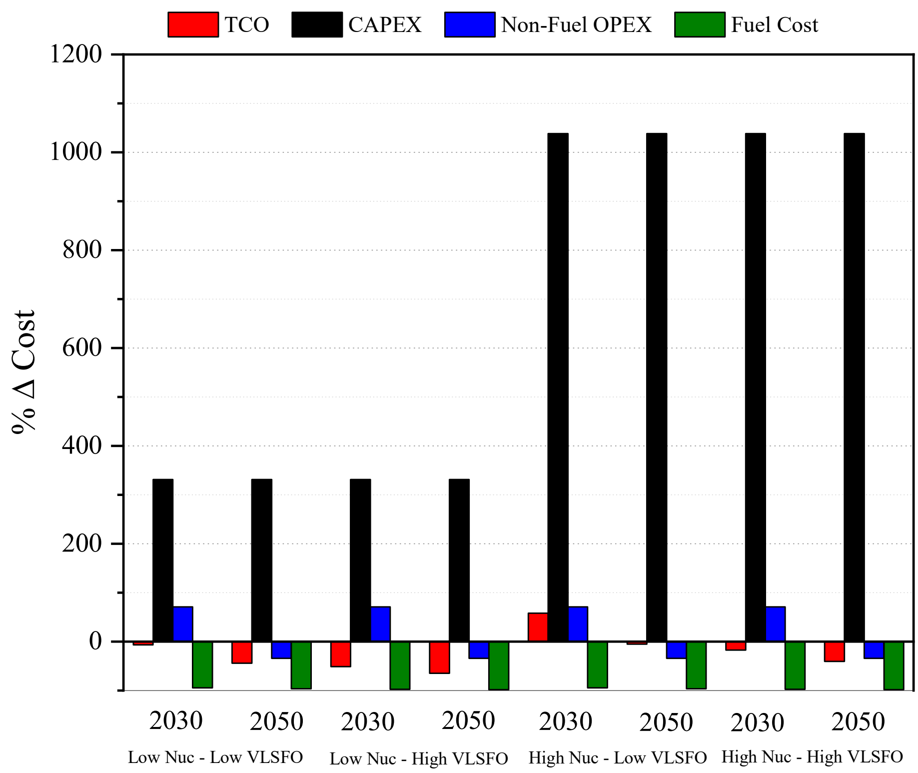


Figure 7. Additional yearly TCO for nuclear-powered bulk carrier in 2030 and 2050 (compared to VLSFO-fuelled)

The annual costs for the nuclear-powered vessels and their VLSFO-fuelled counterparts seem to be similar in the early years of their operation (refer Figure 6 (a), Figure 8 (a) and Figure 10 (a)). A closer examination, however, shows that, even around 2028, just two years after the commencement of ship's operation, the TCO of Nuclear_Low is 21% lower than for the VLSFO_Low for the liquified gas tanker (Figure 8 (a)). The respective value for the oil tanker is 10% (Figure 10 (a)). For the bulk carrier, the TCO of Nuclear_Low is 1% lower than that of the VLSFO_Low (Figure 6 (a)).

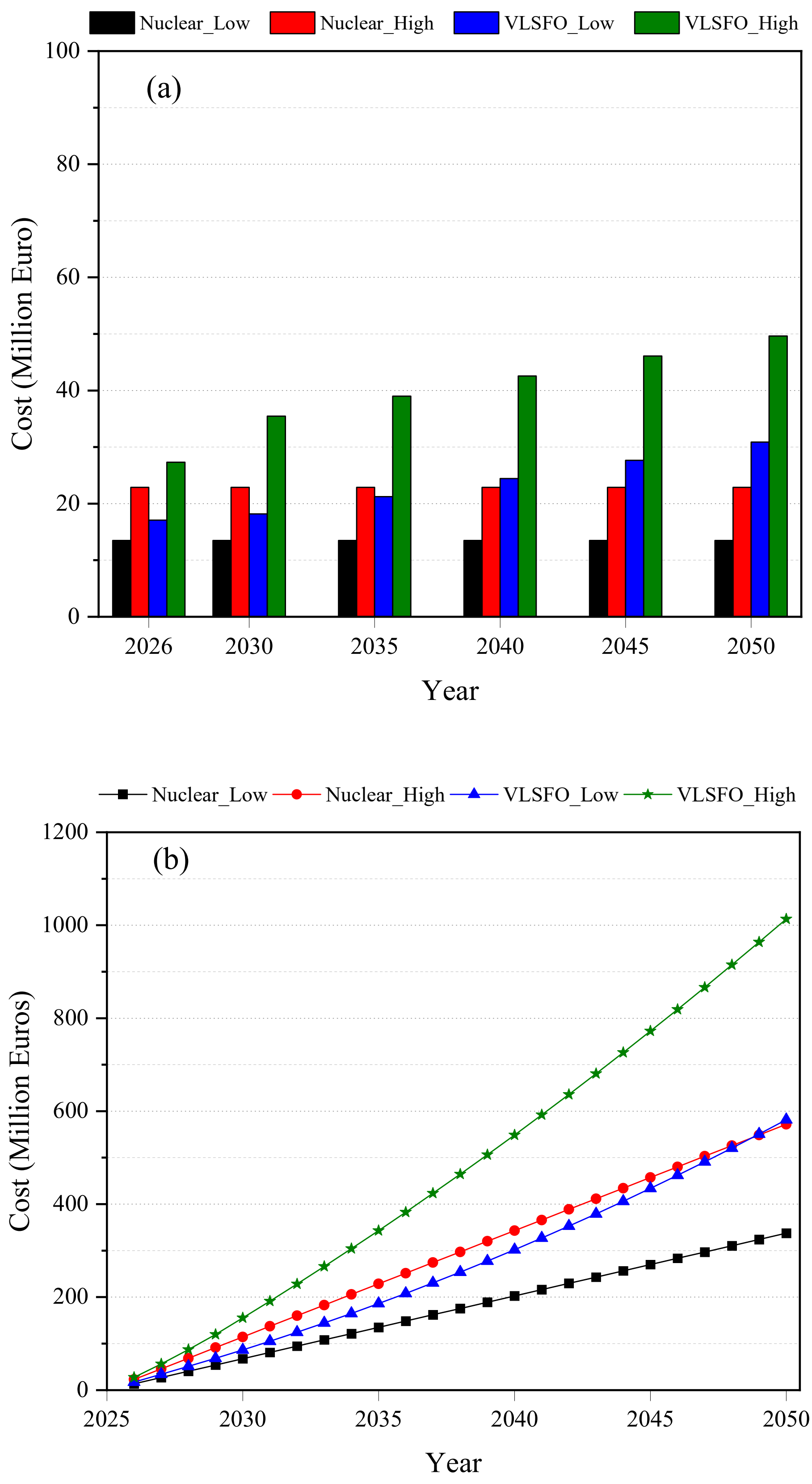


Figure 8. (a) Annual and (b) cumulative TCO over the first 25 years of liquified gas tanker operation

The annual and in turn cumulative costs for the VLSFO vessels increase significantly over time due to the elevated carbon costs as well as higher fuel costs. This provides substantial cost-saving opportunities in favour of nuclear-powered vessels, especially when the high fuel price scenario takes place. Even for the low fuel price scenario and the high nuclear CAPEX (VLSFO_Low – Nuclear_High), the cumulative TCO of the nuclear-powered bulk carriers and oil tankers is only 19% and 11% higher than that of their VLSFO-fuelled counterparts in 2050 (refer to Figure 6 (b) and Figure 10 (b)). For the liquified gas tanker, on the other hand, for the same case (VLSFO_Low – Nuclear_High), the cumulative TCO of the nuclear is 2% lower than that of VLSFO-fuelled power systems (see year 2050 in Figure 8 (b)). These findings suggest that nuclear-powered bulk carriers and tankers are economically viable. It is worth mentioning that as explained, the TCO of Nuclear_High reflects the worst-case scenario (highest CAPEX) for nuclear propulsion system costs.

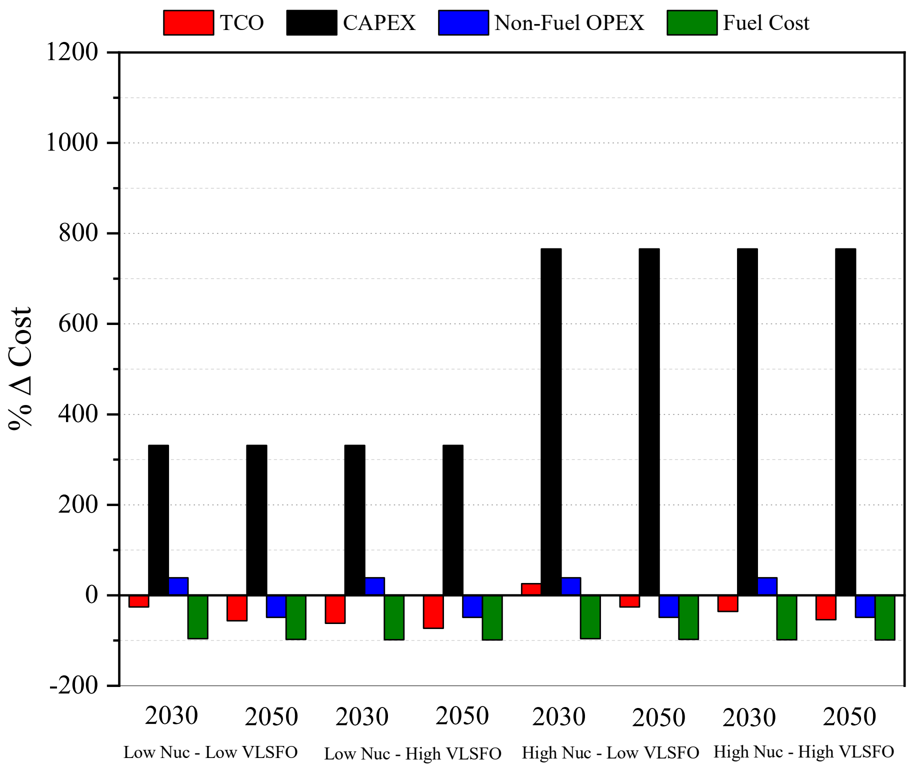


Figure 9. Additional yearly TCO for nuclear-powered liquefied gas tanker in 2030 and 2050 (compared to VLSFO-fuelled)

Similar to container ships, the CAPEX is the dominant cost for nuclear-powered bulk carriers and tankers. While the fuel cost is the highest cost for their VLSFO counterparts (Figure 7, Figure 9 and Figure 11). In contrast to containers, the annual TCOs of nuclear-powered bulk carriers and tankers for VLSFO_Low – Nuclear_Low and VLSFO_High – Nuclear_High scenarios are always lower than those of their respective VLFSO-fuelled vessels (only in the first 2 years, for VLSFO_High – Nuclear_High, the annual TCO of the nuclear-fuelled bulk carriers are slightly more than the TCO of VLSFO-fuelled bulk carriers). This is because of the relatively lower CAPEX of these vessels as the required power for them is lower and therefore cheaper reactors are needed. In 2030, the TCO of the nuclear-powered vessels is higher than that of the reference case only if the fuel price is minimum and the CAPEX of the nuclear is maximum. Even in this case, the TCOs of the nuclear-powered bulk carriers, liquified gas and oil tankers are only 36%, 20% and 30% higher than their respective VLSFO-fuelled vessels. In 2050, regardless of the fuel price and nuclear capital cost, nuclear-powered bulk carriers and tankers cost less than their VLSFO-fuelled counterparts.

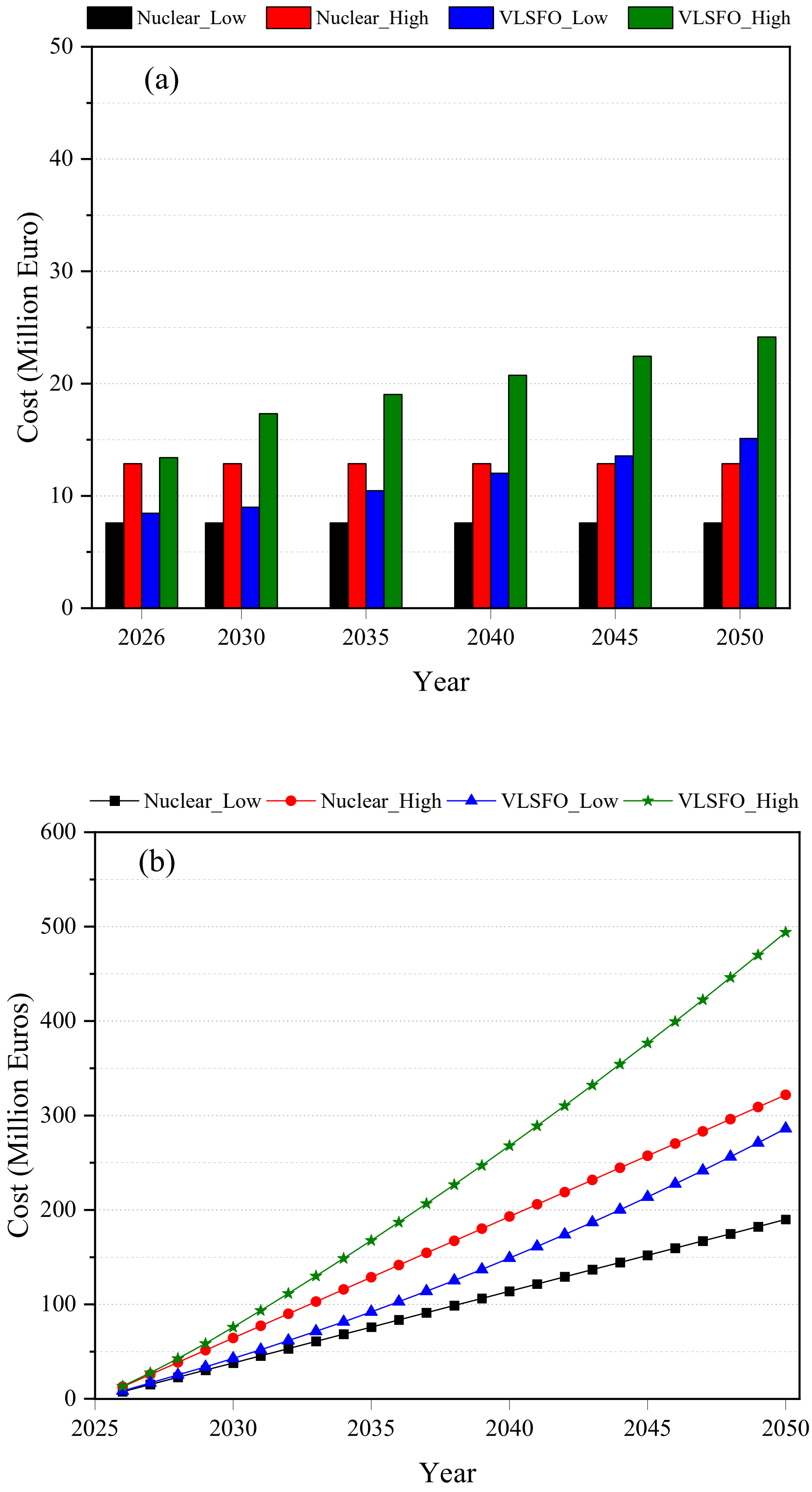


Figure 10. (a) Annual and (b) cumulative TCO over the first 25 years of oil tanker operation

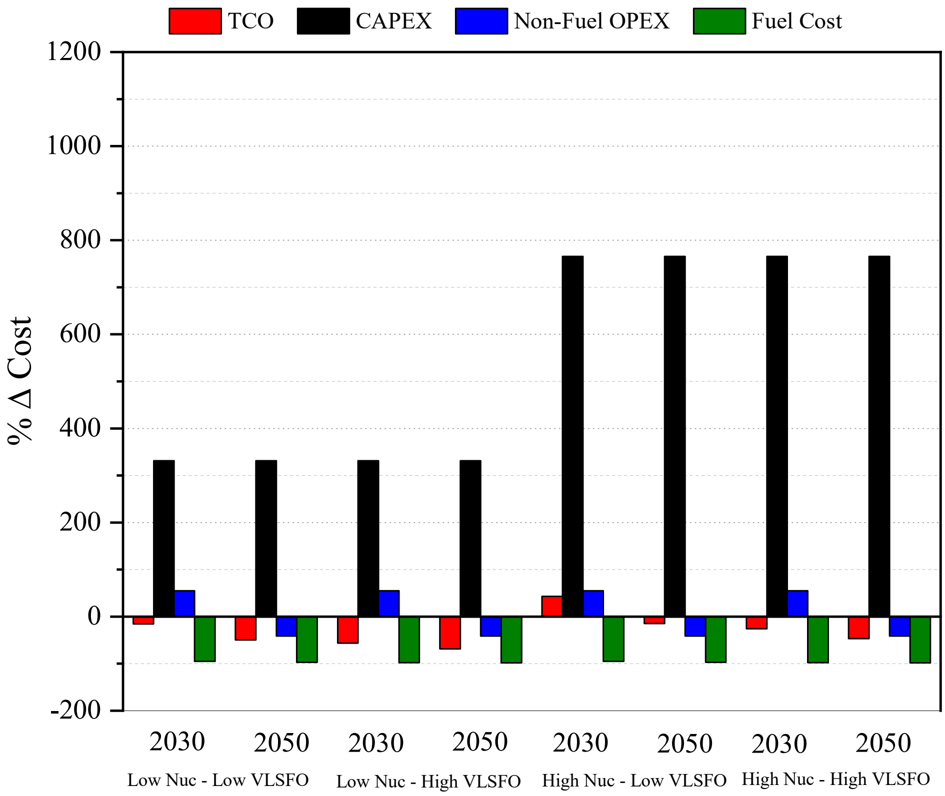


Figure 11. Additional yearly TCO for nuclear-powered oil tanker in 2030 and 2050 (compared to VLSFO-fuelled)

2.5.5 Vessel Retrofit

A vessel retrofit involves updating and modernising an existing vessel to improve its performance, compliance and efficiency. This process can encompass a range of modifications, from upgrading propulsion systems and installing new technology to enhancing safety features and environmental compliance measures.

Common retrofit projects include the installation of more fuel-efficient engines or scrubbers to reduce emissions, which helps vessels to comply with international environmental regulations such as the IMO 2020 sulphur cap. Updating navigation and communication systems is also a key aspect of retrofitting, improving the safety and efficiency of maritime operations. Additionally, retrofitting ballast water treatment systems ensures vessels meet global standards aimed at preventing the spread of invasive aquatic species. The financial implications of a vessel retrofit are significant, but they are often justified by the long-term benefits.

Funding for retrofits can come from internal reserves, loans, or even government grants, especially for projects that improve environmental performance. By investing in retrofits, shipping companies can extend the service life of their vessels, achieve better fuel efficiency, lower emissions and improved compliance with safety and environmental standards. This not only reduces operating expenses and environmental impact it also enhances the competitive positioning of the company in a market that is increasingly focused on sustainability and regulatory compliance.

For the purposes of this report, retrofitting vessels is the process of replacing engine and oil-fuel-related systems with nuclear propulsion systems. This process generates the cost from the propulsion system conversion, shipyard work and supplier work. These costs are all CAPEX-related.

The important consideration for retrofitting is that the nuclear reactor and other energy-conversion and safety components must fit within the vessel of interest. Therefore, size and weight allowances should be considered. As mentioned earlier, large vessels such as bulk carriers, tankers and container ships may be more suitable for installing nuclear propulsion systems, even at a relatively low installed power. However, for ferry, cruise and ro-

ro vessels, the application of nuclear propulsion systems is challenging as they would likely suffer from cargo weight or volume loss if retrofitted with relatively large and heavy reactor systems compared to the original power arrangements. For offshore, general cargo and car carriers, the application of nuclear systems may be possible at relatively large installed powers (Houtkoop K. C., 2022).

However, for quantifying retrofit costs of nuclear propulsion systems, the uncertainty is relatively high, since there is limited experience from which to draw. Therefore, retrofitting has not been included in this analysis.

2.5.6 Techno-Economic Conclusion

The TCO of nuclear-powered vessels appears to be lower than that of vessels running on conventional fuel oils over a 25-year period. This analysis focused solely on new builds, as retrofitting is not considered practical at this time due to limited data about the costs and suitability of reactors to replace conventional power systems directly.

While uncertainties are inherent in any techno-economic analysis involving emerging fuels and technologies, nuclear energy introduces further complexities due to limited data on merchant vessels using nuclear power. Despite these limitations, the case studies on container ships, bulk carriers, liquified gas carriers, and oil tankers demonstrate that TCOs for nuclear-powered and VLSFO-fuelled vessels are similar in the early years of operation. However, as carbon costs and fuel expenses rise, the TCO for VLSFO-fuelled vessels increases over time, creating a cost advantage for nuclear-powered vessels. The advancement of nuclear technology, with potential CAPEX reductions, could also enhance the appeal of nuclear propulsion. It is noted that since decommissioning cost is not included in the analysis, this needs to be studied further, and it may have a negative impact on the TCO nuclear-powered vessels. However, many studies on conventional fuels do not include decommissioning/scarping costs explicitly in their Total Cost of Ownership (TCO) calculations. This is because the decommissioning process for these vessels is simpler (less costly) and often partially offset by residual value.

The potential for higher vessel speeds with minimal additional OPEX due to nuclear power also presents fleet optimisation opportunities for operators. This flexibility could improve overall fleet utilisation and profitability and deserves further exploration.

Moreover, the zero CO_2 emissions during nuclear-powered vessel operation provide an additional environmental benefit, aligning with global climate objectives and enhancing public and regulatory acceptance. These environmental advantages position nuclear propulsion as an attractive alternative for shipping companies aiming to reduce emissions long-term.

To summarise, nuclear technology integration in the maritime industry could be considered a compelling business case. However, future studies should consider decommissioning costs and residual values for a comprehensive lifetime cost analysis, ensuring a balanced view of both economic and ecological impacts. Including these elements in future analyses, as well as the use of TRISO fuel, could enhance the accuracy of TCO comparisons.

3. Safety and environmental regulations, standards and guidelines

Nuclear energy and its uses are a mature but still evolving technology. As a result, many different organisations and nations have established standards, studies, regulations and best practices for production of fuel, construction of reactors and plants, environmental protection and much more related to the use of land-based nuclear power plants for electricity generation.

However, the use of nuclear power for merchant marine applications has been limited to three demonstration vessels that operated in the late 1900s. While some regulations were established at that time, including the SOLAS Chapter VIII, many regulations have since been removed or have remained without update since their initial publication. Also, since that time, nuclear technology engineering and safety regulations have advanced under continuous research and lessons learned from years of operating experience.

An implication of using advanced reactor technologies for merchant marine applications is the fact that international regulations are generally lacking to address the technology and its use in the industry. In general, the research and development for nuclear technologies has overtaken the realities of regulatory boundaries, leaving some major gaps in the regulatory landscape that may need to be addressed before the technology can develop further. However, existing international guidance and regulations for land-based nuclear technology and practices may be adopted or used foundations for new or modified maritime regulations.

With the knowledge that updating or creating new international regulations is known to be administratively burdensome and time consuming, it may prove more likely that individual nations will approach regulatory development first, or in partnership with one or more nations to support a maritime trade environment. For example, specific trade routes within '*green corridors*' may be arranged between port nations that are in regulatory agreement on the use and operations of nuclear power for merchant vessel propulsion.

This chapter introduces a non-exhaustive list of regulations, standards and publications that may be applicable, either directly or indirectly, to the use of nuclear power in civilian and commercial operations.

3.1 International

While individual nations have set up their own regulations for domestic entities to adhere to, there are also international organisations, focused on peaceful and scientific purposes, that are recognised by member states that publish general and specific requirements. The functions of these regulatory agencies span from being broadly applicable to industry, or to one economic sector, e.g., maritime industry.

3.1.1 International Atomic Energy Agency (IAEA)

Established in 1957, the IAEA is a regulatory body under the United Nations and created to regulate and promote the peaceful use of nuclear activities and their safety. The agency is concerned with the overarching principles of nuclear power, such as construction, waste disposal, energy production, etc., but also as regulations relate to specific sectors. There are many technical publications, recommendations and standards for design and operation of nuclear power plants that may be relevant to the use of nuclear power for merchant vessels, but the IAEA's publications are not meant for floating applications or merchant propulsion uses. Below, relevant IAEA regulations are expanded upon (IAEA, 2024).

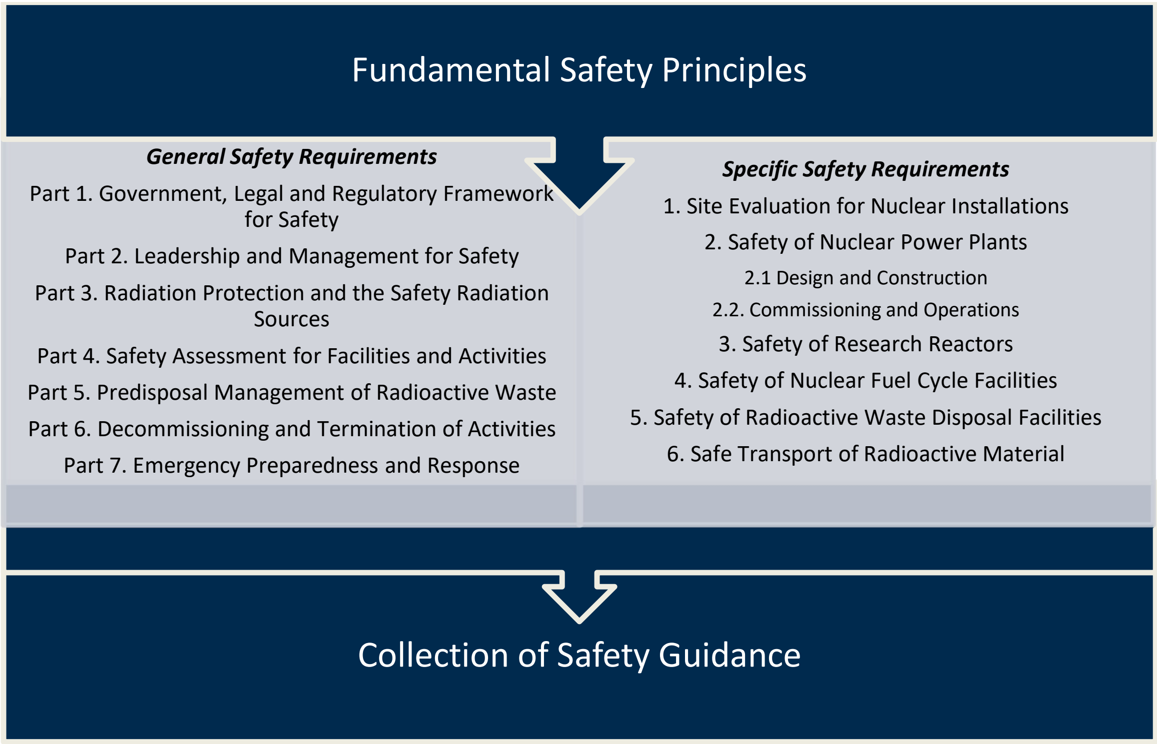


Figure 12. The long-term structure of the IAEA Safety Standards Series (IAEA, 2024).

General Safety Requirements (GSR) Part 5 Predisposal Management of Radioactive Waste

Predisposal of Radioactive Waste is defined as covering all the steps in the management of radioactive waste from its generation up to disposal, including processing (pretreatment, treatment and conditioning), storage and transport. GSR Part 5 provides safety requirements for facilities that manage radioactive waste before disposal, including the transport of radioactive material.

For considerations on the generation of radioactive waste and used fuel on a conceptual nuclear-powered vessel, design and operations should consider IAEA GSR Part 5 for onboard waste-predisposal activity and preparation for either discharge to the environment ('*dilute and disperse*') or stored and transported to a temporary or permanent disposal facility ('*delay and decay*' or '*concentrate and contain*') (IAEA, 2009).

Specific Safety Requirements (SSR) Part 6 Regulations for the Safe Transport of Radioactive Material

SSR Part 6 establishes standards of safety which provide an acceptable level of control of the radiation, criticality and thermal hazards to people, property, and the environment that are associated with the transport of radioactive material. This is addressed by requiring the achievement of:

1. Containment of the radioactive contents
2. Control of the external dose rate
3. Prevention of criticality
4. Prevention of damage caused by heat

Although the regulations do not explicitly apply to the transport of fuelled reactors, given that any merchant vessel using nuclear propulsion will be required to hold and transport nuclear material, SSR Part 6 should be considered as an inherent part of the design, manufacture, maintenance, packaging, preparation and storage of all new builds and converted vessels to protect the health and safety of all persons and environments (IAEA, 2018).

Convention on the Physical Protection of Nuclear Material (CPPNM)

The CPPNM was signed in 1979 by a select set of countries and went into force in 1987.

Composed of 23 Articles and two Annexes, the document outlines the rules, regulations, procedures and responsibilities of the signatories. It covers the protection of nuclear materials -- for example, from theft or the use of the materials to injure or worse -- and the punishments for the crimes it describes. Additionally, it covers the procedures of punishment for matters where international issues are considered, such as extradition.

The grades of physical protection required by the convention are outlined in its Annex 1 for different categories of materials. The materials that are specifically addressed by this convention are outlined in Annex 2 with radiation forms and category classifications by weight (IAEA, 1980).

These regulations are not specific to marine applications, although they are applicable. However, they could be adapted to cover these regulations because they address international transport between nation states. Additionally, these regulations could be expanded upon so that more specific topics, such as commerce and vessels using the nuclear material as propulsion, could be included as addendums to the convention.

United Nations Treaty on the Non-Proliferation of Nuclear Weapons (NPT)

Adopted in 1968 upon international agreement of the global dangers of '*nuclear war*', the United Nations' *Nuclear Non-Proliferation Treaty* entered into force in 1970 and was extended indefinitely in 1995. 191 States have joined in the Treaty, including the five nuclear-weapons states (NWS): China, France, Russia, the UK and the United States. While encouraging the development of peaceful uses of nuclear energy, the Treaty establishes an understanding of the responsibilities for Signatories to administer and manage nuclear weapons or nuclear material or information that may be used for nuclear weapon development or dissemination. It was designed to prevent the spread of nuclear material for harm and promote cooperation for the peaceful use of nuclear energy.

The NPT also establishes a regime of safeguards set by the IAEA for member States, where inspections are done to verify compliance with the Treaty's Articles and ensure that safeguards are in place to account for fissile or nuclear material and prevent its use or dissemination for weapons use. Non-nuclear weapon states (NNWS) are those that are Signatories that are not NWS, which are fully subject to IAEA inspection and verification of compliance, as agreed upon their ratification of the Treaty.

The NPT establishes international protocols for the management of nuclear materials and calls for the signatories (nations) of origin of nuclear material to account for their safeguards and protection against use for weapons purposes. This includes the strict accountability of nuclear material (including forms of uranium, fissile or fertile material, and spent nuclear fuel) across national boundaries (or traded) to be for peaceful uses or final storage/disposal. (IAEA, 1970)

Convention on Nuclear Safety (CNS), 1996

The CNS Convention was formed to commit the signatories to a regime of accountability for the operational safety of merchant nuclear power plants. Parties must submit reports subject to '*peer review*' by other signatories at the IAEA. However, it does not explicitly mention floating nuclear applications. However, it's scope may be expanded to include floating nuclear power plants or nuclear-powered vessels or form the basis of a new convention in the future (IAEA, 1994).

Convention on Early Notification of a Nuclear Accident (CENNA), 1986

Following the Chernobyl nuclear plant accident, this Convention was organised to establish mechanisms and requirements for Signatories to report accidents that result (or may result) in an international release that may affect another State. However, the Convention does not clarify the type of accident or type of nuclear facility, and therefore it may be interpreted to be applicable for floating nuclear power plants or nuclear-powered merchant vessels (IAEA, 1986).

Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (CACNARE), 1986

Related to CENNA, the CACNARE allows for the right of any State to request assistance from the IAEA or other Member States if they encounter a nuclear accident or radiological emergency. CENNA and CACNARE encourage partnership (bilateral or multilateral) arrangements to implement safe practices of the notice and response to nuclear accidents that may affect multiple States. Signatories of CACNARE can meet the requirements of the Convention by establishing inter-governmental agreements or some other type of regional-level cooperation in the event of an incident. Therefore, it generally may apply to floating nuclear applications (IAEA, 1986).

Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (Joint Convention), 2001

Addressing the issue of spent fuel and radioactive waste management on an international scale, the Joint Convention also establishes a '*peer review*' oversight for the management of spent fuel or radioactive waste from civilian nuclear reactors. For a nuclear-powered vessel concept needing to manage its irradiated fuel, the Joint Convention may apply to the State of where the material was supplied and the State(s) with Jurisdiction over the location of the licensed, operating nuclear-powered vessel (IAEA, 1997).

3.1.2 International Maritime Organisation (IMO)

SOLAS Chapter VIII & Resolution A.491(XII)

Within the IMO's safety-related regulations for international shipping, the *International Convention for the Safety of Life at Sea* (SOLAS, 1974, as amended) regulations for nuclear-powered vessels are found in Chapter VIII. Originally written and adopted for use by the merchant nuclear-powered vessels of the 1950s to 1960s, Chapter VIII is specific to vessels except '*ships of war*' and requires the reactor installation be subject to approval by the Flag Administration; it emphasises protection from radiation sources. It is stated that the installation of the reactor should be designed to consider the normal and accidental marine environments where it is designed to operate.

SOLAS Chapter VIII refers to the more detailed and comprehensive *Code of Safety for Nuclear Commercial Ships* (Resolution A.491(XII)), which was adopted by the Assembly in 1981. It is applicable to conventional types of vessels propelled by nuclear-propulsion plants with pressurised light water-type reactors. The Code noted this restriction on applications and recognised that review would be necessary as technology progresses, for example, where vessel designs include advanced nuclear propulsion using other reactor types. However, interests in updating the Code faded as the merchant nuclear-powered vessels at the time were decommissioned. The Code reflects nuclear-industry practices of '*defence-in-depth*' concepts supported by independent safety systems to withstand single-failure events.

SOLAS Chapter VIII and Resolution A.491(XII) offer precedents for the future of merchant nuclear-powered vessels, but some work may remain for IMO members to initiate and execute the revision and modernisation to current safety standards, as well as on adding applications for other types of reactors.

Work led by the World Nuclear Transport Institute (WNTI) has started to produce a series of gap analyses to recommend updates to the IMO Resolution A.491(XII); these were presented at the IMO Maritime Safety Committee (MSC) 108 in May 2024 (WNTI, 2024) (WNTI). The initial work is expected to continue at the IMO, including the formation of a working group to update the resolution.

INF Code and Dangerous Cargoes

The IMO *International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes Onboard Ships* (INF Code) was first published in 1961 based on the IAEA principles of radioactive transport; it is now mandatory for vessels carrying packaged, irradiated nuclear fuel, high-level radioactive wastes, or plutonium (IMO, 2019). This code is applied in coordination with the IMO *International Maritime Dangerous Goods Code* (IMDG) and may also apply parts of the IMO *International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk* (IBC Code).

International codes applicable to dangerous cargoes, such as the INF, IMDG and IBC Codes, function to identify and reduce the risks of carrying potentially hazardous materials either in packaged or bulk forms. These codes also address the prevention of pollution to the environment from the cargoes, or the accidental release of the cargo. Provisions include packing, container traffic and stowage, segregation, additional damage stability, fire protection and structural resistance (IMO, 2019). The INF Code requires vessels carrying INF Cargo to have a shipboard emergency plan to address the procedures to be followed in case of an incident.

The IMDG Code provides an extensive list of dangerous goods, including information on risks, packing, stowage and segregation and properties or observations. Radioactive material is categorised as '*Class 7*', as defined in 2.7 of the IMDG Code. However, '*radioactive material that is an integral part of the means of transport*' is explicitly excluded from the group. That is, nuclear fuel used for vessel propulsion is not covered.

Provisions for the transport of nuclear material are derived from the IAEA Regulations for the Safe Transport of Radioactive Material, 1996 edition, (Revised) Safety Standards Series No. TS-R-1 (ST-1, Revised) (ISBN 92-0-104996-X), which includes requirements for shipowners and those handling radioactive materials. '*Class 7*' materials include various types of radioactive material -- including low specific activity (LSA) material, surface contaminated objects (SCO) -- and a breakdown of the materials by radiation-activity levels (IMO, 2016).

The INF, IMDG and IBC codes apply to the carriage of radioactive material as cargoes on cargo vessels; therefore, they exclude vessels which use radioactive material for propulsion. However, the codes offer an established framework based on IAEA standards for the handling of radioactive material, which may be adopted for vessels using nuclear power for propulsion and the associated handling of nuclear fuel/used fuel and other radioactive wastes.

ISM Code

The IMO *International Safety Management Code* (ISM) was developed to provide administrative structures for basic safety management to shipping companies and shipowners; the structures are designed to protect the operation of vessels and prevent pollution. The code was made mandatory in 1998 and introduced the new SOLAS Chapter IX.

The ISM Code requires owners to develop safety-management systems onboard to communicate safety risks and instruct the safe operation of vessels. It requires clear responsibilities to be established onboard and within the management organisation. Noting that not every shipowner is the same, the Code was developed in broad terms to be applicable to different types of management arrangements (IMO, 2019).

While the ISM Code does not explicitly discuss the operation of nuclear-powered vessels, it may be used as a starting point for vessel crew and shipowners to clearly define roles and responsibilities for protection if incidents occur.

ISPS Code

The IMO *International Ship and Port Facility Security Code* (ISPS) is implemented by SOLAS Chapter XI-2 "*Special measures to enhance maritime security*" and it was developed following the incidents of September 11, 2001, in the U.S. It focuses on establishing security measures for governments, ports and shipping companies. In years following its implementation, it was updated to include specific provisions for protection from piracy and armed robbery, as well as provisions for long-range onboard identification and tracking systems.

The code provides requirements for vessel security, vessel security assessments, ship security plans, record keeping, and defined roles and responsibilities of onboard personnel, as well as the roles of governments and port facilities (IMO, 2019).

While the ISPS Code does not specifically discuss the security of nuclear-powered vessels, or of those ports to which a nuclear-powered vessel may visit, it provides an international framework for maritime industries to identify security risks and take preventative measures against security incidents. The IMO may update the ISPS Code if specific security requirements are necessary to address nuclear-powered vessels travelling internationally.

Related to the ISPS Code and security risks, the IMO has also issued MSC-FAL.1-Circ.3-Rev.2 Guidelines on maritime cyber-risk management to encourage the adoption of measures to protect vessels, ports and companies from cyber risks.

SUA Convention

IMO *Convention for the Suppression of Unlawful Acts against the Safety of Maritime Navigation* (SUA Convention) and 2005 Protocol to the SUA were established to facilitate appropriate response to persons who commit unlawful acts against vessels or fixed platforms located on the continental shelf (IMO, n.d.). Although the SUA Convention does not apply to the transport of nuclear material (assumed to be covered by the NPT), it may form a framework to be updated to include unlawful acts against nuclear-marine applications (vessels or offshore units).

Revised GHG Strategy

Since the adoption of the *Initial IMO Strategy on Reduction of GHG Emissions from Ships* in 2018, to remain current with the options that could support the decarbonisation of shipping, the organisation has continued to assess emerging technologies and the availability of alternative fuels. In that time, the will among member states has increased regarding the level of ambition for the IMO's GHG-reduction goals; by adopting the *2023 IMO Strategy on Reduction of GHG Emissions from Ships*, the maritime industry committed to achieving net-zero emissions 50 years sooner than previously agreed.

The IMO's revised GHG strategy is a comprehensive work package consisting of targets, workplans, reviews and impact studies all aimed at achieving decarbonisation *'by or around'* 2050: the targets set new levels of ambition for overall emissions and carbon-intensity, as well as indicative checkpoints along the way.

Achieving these targets will require a basket of mid-term measures to be developed to steer the maritime industry towards full decarbonisation by 2050. However, to get the balance of the proposed measures right, a comprehensive impact assessment will be carried out in parallel.

In July 2023, the IMO's 80th meeting of the Marine Environment Protection Committee (MEPC 80) adopted the following levels of ambition for the international shipping in the revised GHG strategy (all reductions refer to the 2008 levels):

1. ***carbon intensity of the ship to decline through further improvement of the energy efficiency for new ships***
   to review with the aim of strengthening the energy-efficiency design requirements for ships;
2. ***carbon intensity of international shipping to decline***
   to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008;
3. ***uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to increase***
   uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5% (striving for 10%) of the energy used by international shipping by 2030; and
4. ***GHG emissions from international shipping to reach net zero***
   to peak GHG emissions from international shipping as soon as possible and to reach net-zero GHG emissions 'by or around' (i.e. close to 2050), accounting for the different national circumstances, whilst pursuing efforts towards phasing them out as called for in the vision consistent with the long-term temperature goal set out in Article 2 of the Paris Agreement.

Also, indicative checkpoints were set:

- Total annual GHG emissions reduction by 20%, striving for 30%, by 2030.
- Total annual GHG emissions reduction by 70%, striving for 80%, by 2040.

Several of the levels of ambition give leeway for the exact date or amount of implementation, such as the targets that strive for a higher value, or the net-zero target on or around 2050. While the targets are ambitions and will be challenging to achieve, the use of nuclear power may help the maritime industry to meet them.

To achieve the above, the IMO is expected to evaluate candidate mid-term measures which will be decided and enter into force at the earliest by 2027. These will include a technical measure, i.e., a goal-based marine fuel standard regulating the reduction of the GHG intensity of fuels and an economic measure, i.e., a GHG emission-pricing mechanism. Regarding the exact framework for the latter, there are divergent views and proposals. Both the technical and economic measures should consider the well-to-wake emissions of fuels as per the Marine Fuel Life Cycle GHG Guidelines (LCA Guidelines), initially adopted by MEPC 80 (Resolution MEPC.376(80)). These guidelines have been further revised and adopted in MEPC 81 ((Resolution MEPC.391(81)) and will be used to derive well-to-wake carbon factors for fuels.

The various fuels are expected to be assigned a range of carbon factors, depending on their production pathways. These developments are expected to encourage the update of alternative fuels with low GHG emissions. However, the well-to-wake emissions of nuclear power, as well as electricity derived from nuclear power have yet to be defined.

At the same time, nuclear power as a fuel is expected to help vessels meet the existing IMO measures, such as those held in the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), which currently focus on tank-to-wake emissions.

3.1.3 International Organisation for Standardisation (ISO)

ISO Technical committee 85 (ISO/TC 85) covers the subjects of nuclear energy, nuclear technologies and radiological protection. The focus is on "*standardisation in the field of peaceful applications of nuclear energy and nuclear technologies, and in the field of the protection of individuals and the environment against all sources of ionising radiations*" (Secretariat ISO/TC 85, 2018). Many standards may be applicable to merchant nuclear maritime; and some are listed below for reference.

- ISO 10648 Series – Containment enclosures
- ISO 11665 Series – Measurement of radioactivity in the environment – Air: radon-222
- ISO 1709:2018 Nuclear energy – Fissile materials – Principles of criticality safety in storing, handling and processing
- ISO 19443:2018 Quality management systems – Specific requirements for the application of ISO 9001:2015 by organisations in the supply chain of the nuclear energy sector, supplying products and services important to nuclear safety (ITNS)
- ISO 20890 Series – Guidelines for in-service inspections for primary coolant circuit components for light water reactors
- ISO 2889:2023 Sampling airborne radioactive materials from the stacks and ducts of nuclear facilities
- ISO 2919:2012 Radiological protection – sealed radioactive sources – General requirements and classification

3.1.4 International Association of Classification Societies (IACS) and other Classification Societies

3.1.4.1 International Association of Classification Societies (IACS) Members

Serving as a non-governmental organisation at the IMO, IACS's mission is to set up, review and advance requirements for the design, construction, maintenance and survey of vessels and other marine facilities. It assists regulatory bodies and standards organisations in the maturation, implementation and clarification of regulations and industry standards for vessel design, construction and maintenance. A primary purpose of the association is to create Unified Requirements (URs) for resolving circumstances connected to, or under the umbrella of, specific rule requirements and practices of its member classification societies. It focuses on vessel designs, construction and operation, helping to provide further consistency and safety throughout the maritime industry. While there are no URs for nuclear-powered vessels those URs previously developed for vessels can provide frameworks for classification societies to adapt to, or address, new nuclear-propulsion challenges. Hence, individual classification societies can expand their unique guidelines for nuclear energy, based on IACS's broad framework.

American Bureau of Shipping (ABS)

As a member of IACS, ABS has worked to progress marine safety, service and solutions since its founding in 1862. ABS has an extensive history of setting standards for maritime safety and regulations, including for using nuclear energy on vessels. Currently, ABS has a stronghold in actively researching and developing nuclear-propulsion standards, along with initiatives and publications for addressing the associated challenges and opportunities.

In 1959, the *NS Savannah* project was the first nuclear-powered merchant vessel. It was classed under the ABS 1962 "*Guide for the Classification of Nuclear Ships*" (Nuclear Engineering International, 2022). This endeavour set the stage for the society's growth in the commercial field of nuclear power. Although the ABS rules for nuclear-powered vessels have been retired, ABS continues to play a role in research activities, including research for the U.S. DOE Office of Nuclear Energy's demonstration project on advancing nuclear technology for marine applications. It has conducted independent research with the Herbert Engineering Corp. to investigate the conceptual arrangement of two standard vessel classes, a 14,000 TEU post-Panamax container ship and a 157,000 DWT Suezmax tanker (ABS & Affiliated Companies, 2022).

ABS also has provided research and expertise for floating offshore nuclear power barges with HD Korea Shipbuilding & Offshore Engineering (KSOE) and KEPCO Engineering and Construction Company (KEPCO E&C) (Bahtić, 2023). In line with its overall goal to support safety and operational standards, ABS released the 2024 *Requirements for Nuclear Power Systems for Marine and Offshore Applications* (American Bureau of Shipping, 2024), a set of class rules applicable to non-nuclear propulsion (power plant services) applications, and continues to develop publications and guidance on design, construction and maintenance to help the maritime and nuclear stakeholders to design, develop and eventually Class nuclear-powered vessels.

Det Norske Veritas (DNV)

Originating in Norway in 1864, DNV constantly promotes safety and sustainability in the maritime industry, including activities around nuclear merchant shipping. DNV participates in research and standard development for nuclear energy in the maritime industry, contributing research projects and publications to increase the understanding of the risks associated with nuclear-powered vessels. Due to such involvement, DNV published its Maritime Forecast to 2050, which included studies on how nuclear propulsion can be an option that reduces GHGs (DNV, 2021). The register also has entered into a partnership with the Norwegian NuProShip project to identify the practicality of designing a smaller version of the LeadCold SMR Sealer for use in merchant vessels (Emblemsvåg, 2024).

Lloyd's Register (LR)

Formed in 1760, Lloyd's Register is considered the world's first classification society. In 1956, LR supplied consultancy and inspection services to the first nuclear power station (UK's Calder Hall), which generated electricity on an industrial scale (POWER, 2016). As part of LR's efforts to support maritime decarbonisation, it has also undertaken nuclear power-related feasibility projects with research and publications on MSR, microreactors, PWRs, VHTRs/HTGRs and LMCRs (lead and sodium).

LR has published related titles, including: "*Shipping Nuclear: Preparing for Remote Power on Demand*"; "*Offshore and Shipping Opportunities for Nuclear*"; and "*Fuel for thought: Nuclear Report*." In these publications, LR explores the technological readiness levels, potential applications and drivers for nuclear fuel in the shipping sector. Moreover, it has joined Zodiac Maritime, HD KSOE and KEPCP E&C in a joint-development project that focuses on advancing knowledge of nuclear-propulsion vessel designs for bulk carriers and container ships (Bunker Market, 2023). In collaboration with RINA, LR was a co-founding member of the Nuclear Energy Maritime Organisation (NEMO) (Baker, 2024).

Registro Italiano Navale (RINA)

Since its inception in 1861, RINA has been based in Italy and has served as one of the first classification societies. RINA supports a multidisciplinary background, providing consulting services for conventional and nuclear power plant designs, expertise that can later help further land-based and maritime nuclear-energy challenges. Regarding the nuclear sector, this society in 2022 published the "*Guide for Nuclear Installation on Board of Marine Units*" offering general and basic requirements on nuclear installations on marine units. (RINA, 2023). These requirements are agnostic to reactor technology or the type of marine unit. The guide has references to the unit's hull, stability, fire protection, machinery, electrical and automation systems (RINA, 2023). In collaboration with Lloyd's Register, RINA co-founded NEMO with the focus of helping to create standards and rules for the deployment, operation and decommissioning of floating nuclear power for future applications.

Additionally, RINA is working with Newcleo and Fincantieri on feasibility studies for nuclear naval propulsion, explicitly focusing on exploring closed fuel cycle mini-reactor design applications in large vessels to expend and frequently burn all nuclear fuel (RINA, 2023).

Bureau Veritas (BV)

BV was founded in 1828 in Antwerp, Belgium, where it provides testing, inspection and certification, and offers services to nuclear projects worldwide. In 2022, BV started a collaboration with ThorCon, a developer of nuclear power technology for Technology Qualification, and entered into an agreement to help build a 500MW molten-salt nuclear power barge for deployment in Indonesia (Bureau Veritas, 2022). BV also cooperates with Centre for Strategic Energy Resources (CSER) to initiate nuclear-energy policy (Gulf Oil & Gas, 2024). CSER, a non-partisan organisation, supports the exchange of empirical/evidence-based knowledge, analysis and development to stimulate energy transitions (CSER, n.d.). As a founding member of NEMO and through its various collaborations, BV is showcasing its engagement in advancing nuclear energy integration and policy advocacy.

3.1.4.2 Russian Maritime Register of Shipping (RS)

Since its establishment in 1913, the initial focus of the Russian Maritime Register of Shipping (RS) has expanded to include nuclear-powered vessels and offshore structures. A pivotal moment in its history included the commission of the Lenin nuclear-powered icebreaker in 1959 (The Maritime Executive , 2014). The register's involvement with nuclear-powered surface vessels solidified its role in establishing the safety and operational standards for the nuclear-propulsion systems on vessels. The RS remains influential in shaping regulations governing nuclear-powered vessels to align with global standards, regional needs and technological advancements. The standards and regulations below are applicable to merchant nuclear marine applications:

- Rules for the Classification and Construction of Nuclear Support Vessels (NSV) Rules 2017 (ND No. 2-020101-101-E)
- Rules for the Classification and Construction of Nuclear Ships and Floating Facilities (ND No. 2-020101-168-E)
- Rules for the Classification and Construction of Nuclear Ships and Nuclear Support Vessels (ND No. 2-020101-169-E)
    - Part I Classification: Outlines a framework for classifying and constructing nuclear-powered ships and floating facilities.
    - Part II Safety Standards: Provides safety standards for nuclear-powered vessels by setting general safety requirements and basic measures to protect the ship, crew and the environment from radioactive materials.
    - Part III Hull: Lays out requirements and design principles for the hull structure of nuclear ships and support vessels. Ensuring the vessel's structural integrity and safety in various operational conditions.
    - Part IV Stability Subdivision; Highlights stability and subdivision requirements specific to nuclear ships and support vessels. This works to make sure the vessel maintains stability and structural integrity under various conditions, such as damage scenarios.
    - Part V Fire Protection: Provides fire-protection requirements for nuclear-powered ships and support vessels. It guarantees that vessels are adequately protected against fire hazards, both structural fire protection and firefighting equipment.
    - Part VI Nuclear Steam Supply Systems: This Section displays standards and requirements for the design, construction, and operation of nuclear-steam supply systems on nuclear ships and support vessels. The systems must operate safely and efficiently in various conditions.
    - Part VII Special Systems: Delivers requirements for various special systems on nuclear ships and support vessels. Systems must operate safely and effectively, maintaining integrity and protecting the environment.
    - Part VIII Electrical and Automation Equipment: Sets requirements for electrical and automation equipment for system function, reliability and safety under varying operational conditions.
    - Part IX Radiation Safety: Supplies requirements for radiation safety where there are protection measures, monitoring systems and handling procedures put in place to ensure the safety of the crew, passengers and the environment from radiation hazards.
    - Part X Physical Security: Defines requirements for the physical security of the vessel and the protection of nuclear materials, nuclear plants, and radioactive waste onboard.

3.1.5 Civil Liability, Insurance, and Restrictions

At present, there are international frameworks established to provide compensation for damage arising from nuclear power-based incidents. Additionally, there is liability coverage for incidents related to loss-of-coolant accidents (LOCA), damages from nuclear material during transport, and associated issues. These frameworks also outline the scenarios where a state can or cannot invoke jurisdictional immunity, i.e. where a local regulation can supersede treaties, conventions, etc.

In practice, the regulation in place by different authorities mainly applies to transporting nuclear materials and waste and therefore it is not so relevant to specific incidents that may occur from using nuclear propulsion. However, there is legislation for nuclear incidents that occur on land, which hold the operator responsible for liability issues. These frameworks could, therefore, be adapted to be more specific to nuclear-powered vessels and to outline clear guidelines on the states that are liable when an incident occurs in port or at sea.

For the time being, merchant nuclear-powered vessels cannot be insured on the conventional insurance market. Thus, a special type of insurance, or sovereign guarantees would be required. The potential lack of insurance may have serious side-effects on the financial viability of nuclear-powered vessels. At the same time, different States may have different interpretations on what is safe and secure, requiring some ports to prohibit the entrance of nuclear-powered vessels. This will imply significant restrictions on chartering and trade for those vessels. The wide acceptance of nuclear-powered merchant vessels may take time and may require pilot projects in national waters, or between states, to prove the concept is safe. However, existing regulation for nuclear reactors could be modified to directly include the shipping sector.

Some of the larger pieces of legislation are expanded upon, but there should be special reference to the *Convention on Third Party Liability in the Field of Nuclear Energy* of 29 July 1960; the *Convention Supplementary to the Paris Convention* of 1963; and the *Convention on Civil Liability for Nuclear Damage* of 1963. All of these have been amended by protocols. The latter is based on the principle of exclusive liability of the operator of the nuclear installation. Additionally, there is the *Convention on Supplementary Compensation for Nuclear Damage* (CSC), but this legislation has only a few signatories and is not yet in force. It is noted that based on the current language, the procedures for incidents are not covered by these conventions and the processes involved (Civil Liability, IAEA, 2009). To oversee such conventions and related civil liability issues, the IAEA established the *International Expert Group on Nuclear Liability* (INLEX) in 2003. Finally, the *Convention on Limitation of Liability for Maritime Claims* 1976 (LLMC Convention) explicitly excludes nuclear-powered vessels from its scope; in short, it does not offer protection to shipowners with nuclear-powered vessels.

3.1.5.1 Brussels Convention on the Liability of Operators of Nuclear Ships and Additional Protocol

This convention was adopted at the *Diplomatic Conference on Maritime Law* in 1962. It establishes an international regime for nuclear-powered vessel liability. Although not ratified and enforced yet, it establishes a framework by which future regulators can establish legislation for nuclear-powered vessels. The convention consists of 28 articles relating to liability, compensation, and implementation (NEA, n.d.).

The article topics are as follows:

Article I	Details definitions of terms as used in the document
Article II	Details the absolute liability of nuclear damage and where the exemptions for operators exist
Article III	Numerically limits the financial liability of the operator per nuclear incidents and requires continuing insurance or other financial security
Article IV	Consolidates all damage as nuclear damage if other damage is not reasonably separable
Article V	Details time limits for rights of compensation and minimum allowable period of expiry for individual national laws
Article VI	Details that compensations made by individual Contracting States shall no result in the liability of the operator exceeding the amount specified in earlier articles
Article VII	Details joint liability when more than one operator is involved in a nuclear incident
Article VIII	Excludes damage occurring directly from an act of war, hostility, civil war, or insurrection
Article IX	Establishes that compensation as detailed in paragraph 2 of article III shall be exclusively available for compensation
Article X	Details the options available to claimants as to where litigation can be held
Article XI	Extensively details procedures where damage exceeds the limitations set forth by the convention

Article XII	Mandates that Contracting States are to undertake whatever measures necessary to ensure implementation of convention provisions
Article XIII	Details that convention applies to nuclear damage caused by a nuclear incident occurring by nuclear fuel, radioactive products, or waste from a nuclear ship flying the flag of a Contracting State
Article XIV	Declares that the convention supersedes any other international conventions in force or open for signature
Article XV	Mandates that Contracting States undertake all necessary measures to prevent a nuclear ship flying its flag from operating without a license and procedures should a non-licensed, flagged, ship have a nuclear incident
Article XVI	Declares where in a vessel's life the convention applies
Article XVII	Declares that convention doesn't affect Contracting States' laws on access to its waters
Article XVIII	Details conditions for when a claim can be brought against the insurer
Article XIX	Details procedures for incidents that occur prior to the termination of the convention, should it occur
Article XX	Establishes that disputes between Contracting Parties can be arbitrated if not settled through negotiation and can be sent to international court if arbitration fails
Article XXI	Allows for any Contracting Party to declare itself not bound by article XX
Article XXII	Opens the convention for signature
Article XXIII	Declares ratification to the Belgian government
Article XXIV	Establishes that the convention comes into force three months after ratification
Article XXV	Allows for States not present at conference to accede to the convention
Article XXVI	Establishes procedure for the revision of the convention
Article XXVII	Allows for the denunciation of the convention by any contracting party and establishes a timeline for denunciation
Article XXVIII	Details responsibilities of the Belgian government to notify Contracting States if specific events occur

3.1.5.2 Vienna Convention on Civil Liability for Nuclear Damage

This convention lays out minimum acceptable standards of financial protection arising from nuclear incidents. It only covers damages caused from peaceful uses of nuclear power and only establishes the standards for the Contracting Parties. The general framework establishes that liability falls with the operator and the injured party is not required to prove fault or negligence from the operator. Liability must be covered by insurance, claims must be resolved within a reasonable time, and victims must be treated equally regardless of status or class. Finally, cases must be tried in the territory where the incident occurred. While the convention is solely for land-based nuclear operations and the shipment of nuclear materials it does provide a framework that could be amended or replicated for marine applications (IAEA, n.d.).

3.2 Regulations for EU Member States

Europe has created a coalition that is solely focused on the use, regulation, inspection and safety of nuclear power. It is a separate community that includes 27 member states from the EU and two associate states -- the United Kingdom and Switzerland -- that conform to the nuclear policy governed by the treaty that established the *European Atomic Energy Community* (Euratom). The community was established in 1957, post-WWII, to create a specialist market for nuclear power in Europe. The treaty established the baseline framework for civilian nuclear activities, the commissioning and decommissioning of plants and other infrastructure using nuclear material and wastes, the health and safety of workers and affected communities, etc. The main authority for EU nuclear issues is the Directorate-General for Energy (ENER) (Euratom, 2024).

3.2.1 Council Directive 2006/117/Euratom

Council Directive 2006/117 is related to the supervision and control of shipments of radioactive waste and spent fuel (Euratom, 2018).

3.2.2 Council Directive 2011/70/Euratom

Similar to the 2006/117 directive, this is an amendment to the original Euratom treaty passed in 2011, based on the IAEA safety standards, to establish a community framework for the responsible and safe management of radioactive waste and spent fuels. With as a basis, individual Euratom member states can decide on more specific processes for the waste. For example, France generally reprocesses fuel for reuse and resale, while countries such as Sweden and Finland have final repositories for long-term storage (Euratom, 2018).

3.2.3 Council Directive 2013/59/Euratom (The New Basic Safety Standards Directive)

Having entered into force in 2013, this directive consolidated five existing directives -- and updated many regulations to the latest scientific knowledge -- on the basic safety standards for the protection from ionising radiation of workers and the public. Member states are expected to enforce the directive and are welcome to adopt more stringent regulations and establish legislation for licencing and operation (Euratom, 2024).

3.2.4 Council Directive 2014/87/Euratom - Nuclear Safety Directive

As a 2014 amendment, the Nuclear Safety Directive establishes a community framework for the safety and the reduction of safety risks related to nuclear installations. This directive mandates establishing and maintaining national legislation, regulations and organisational frameworks for nuclear safety by every member state (Euratom, 2024).

3.2.5 Commission Delegated Regulation 2022/1214

Act that amended the Delegated Regulation 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation 2021/2178 as regards specific public disclosures, acknowledges that nuclear-energy related activities are low-carbon activities that can contribute to the decarbonisation of the Union’s economy.

3.2.6 Fit-for-55

On 14 July 2021, the European Commission presented ‘*Fit-for-55*’ (Figure 13 below), a package of measures that seeks to align EU policies on climate, energy, land use, transport and taxation in such a way that the continent’s net GHG emissions can be reduced at least 55% by 2030 (compared to 1990). It contains proposals for revising regulations and directives and some new policy initiatives.

With nuclear power being part of the energy mix, the targets will be easier to achieve. Nuclear power also may be used for producing clean electricity and, therefore, to produce renewable fuels.

Figure 13. The European Commission's '*Fit-for-55*' package

3.2.7 FuelEU Maritime

As part of the '*Fit for 55*' package, the EC launched the FuelEU Maritime Initiative to increase demand for renewable and low-carbon fuels (RLF) on vessels sailing to and from EU ports. It also sought to reduce the emissions from navigation and at berth, and to support EU and international climate objectives.

FuelEU Maritime sets a harmonised regulatory framework in the EU and aims to increase the share of renewable and low-carbon fuels used in the fuel mix for international maritime transport. The fuels include liquid biofuels, e-liquids, decarbonised gas (including bio-LNG and e-gas), decarbonised hydrogen and its derived fuels (including methanol and ammonia), and electricity.

The initiative will contribute to wider goals by pursuing specific objectives to:

- Enhance predictability by setting a clear regulatory environment for the use of RLF in maritime transport
- Stimulate technology development
- Stimulate production of RLF on a larger scale with high technology-readiness levels (TRLs) and reduce the price gap between current fuels and technologies
- Create demand from vessel operators to bunker RLF or connect to electric grid while at berth
- Avoid carbon leakage

FuelEU Maritime will require vessels of 5,000 GT and above to gradually reduce the GHG-intensity limits of energy used onboard (against the 2020 benchmark average value) by:

- 2% as of 2025
- 6% as of 2030
- 14.5% as of 2035
- 31% as of 2040
- 62% as of 2045
- 80% as of 2050

This will cover 100% of the energy used on intra-EU voyages and 50% of the energy on extra-EU voyages. In 2028, the Commission will review whether the 5,000 GT threshold should be lowered and if the regulation's requirements should be tightened.

Depending on the GHG intensity of a vessel compared to the GHG-intensity target, a compliance balance will be calculated. If the compliance balance is negative, then a penalty (in Euros) will be calculated for each vessel. A positive compliance balance will create a surplus.

Nuclear power as a fuel is expected to eliminate tank-to-wake GHG emissions from vessels, while the well-to-tank emissions still need to be defined. It is noticed that FuelEU includes a '*non-exhaustive*' table of types of technologies to be considered as zero-emission technologies. Nuclear power is not included in this table.

3.2.8 EU ETS

Another important part of the '*Fit-for-55*' package includes the EC's decision -- under Directive 2023/959 -- to extend the scope of the *EU Emissions Trading System* (EU ETS) to maritime transport; this was established by Directive 2003/87/EC in the European Parliament. The system has two principles: setting a ceiling on the yearly maximum amount of GHG emissions; and enabling the trading of EU emission allowances. These principles aim to contribute to the wider EU goal to eliminate at least 55% of the continent's net GHG emissions by 2030 (compared to 1990).

From 2025, shipping companies will have to surrender EU emission allowances based on the EU monitoring, reporting and verification (MRV) data of the previous year. If the number of allowances prove insufficient, additional allowances can be acquired, or a reduction of the carbon emissions will be needed. For each tonne of CO_2 equivalent that has been emitted without surrendering allowances, shipping companies will have to pay a penalty of €100.

To ensure a smooth transition of the maritime industry to the EU ETS scheme, companies had to surrender allowances for 40% of the verified emissions in 2024, and they will have to surrender allowances for 70% in 2025. From 2026 onwards, the target moves to 100% of the verified emissions.

Since shipping companies will be paying for the CO_2 they emit, this system can stimulate lower output; it will be up to them to determine the method by which that is achieved.

While nuclear power as a fuel is not explicitly mentioned under the EU ETS framework, since EU ETS is considering the tank-to-wake emissions, nuclear power expected to have a zero CO_2 emission factor under this scheme.

3.2.9 Renewable Energy Directive (RED)

The Renewable Energy Directive (RED) is an EU instrument that aims promote the use of energy from renewable sources. The second phase of RED (RED II – Directive EU/2018/2001) set an overall target to use at least 32% renewable energy by 2030, including a specific '*RES-T*' target of at least 14% renewable energy in the final energy consumption (level of energy consumed after losses) from transport (road and rail) by 2030.

The renewable energies in transport can consist of biofuels, RFNBOs (renewable liquid and gaseous fuels of non-biological origin) and include recycled carbon fuels meeting the sustainability requirements. With respect to renewable fuels in maritime industry, the RED II has been allowing member states to apply those fuels towards their RES-T target.

The impact assessment of RED II identified an additional challenge specific to the shipping sector: the juxtaposition of the shipowners' and operators' incentives does not work to stimulate the deployment of renewable fuels.

In response, and to introduce incentives for the maritime and aviation sectors, fuels supplied to either sector are measured at 1.2 times their energy content (except for fuels produced from food and feed crops) when demonstrating compliance with the renewable-energy target. By this 20% extra counting, there are implications for fuel volumes; as lower fuel volumes are required to meet the target, the amount by which GHG emissions will be reduced may be adversely impacted.

Because of the higher ambitions of the European Green Deal for reducing net GHG emissions by at least 55% by 2030, the RED was revised. The new RED III (Directive EU/2023/2413) entered into force on the 20th of November 2023. This is to be implemented by all member states in their national laws by the 21st of May 2025. To achieve the 2030 target, RED III increased the overall binding target for renewables in the EU energy mix to 42.5%, aiming for 45% (from the previous 32% target).

Regarding the transport sector, member states will need to set an obligation to fuel suppliers so that the amount of renewable fuels and renewable electricity supplied to the whole sector (including shipping and aviation) will lead to either a share of at least 29% of renewables within the final consumption of energy in the transport sector by 2030 or a 14.5% reduction of GHG intensity in transport from the use of renewables by 2030.

Considering the regulatory and technological constraints on using these fuels in the shipping sector, for the purpose of the calculation of the GHG-intensity reduction and the renewable energy share in transport, the energy supplied to the maritime transport sector will be capped at 13% of a member state's gross final consumption of energy.

As already mentioned, nuclear power is expected to play a key role in this fuel transition and in the production of electricity. However, nuclear power is not included in RED, i.e., well-to-tank emissions still need to be defined.

3.3 Other National Regulations

Due to maturity of nuclear technology and its various applications for peaceful uses, there has been a long-recorded history of triumphs and failures in the industry. As a result of this, a wide disparity of opinions and policy exists not just between political unions and nations, but between people themselves. This disparity resulted in some states investing heavily in nuclear technology and its integration into their major sectors; some states restricting or prohibiting its use and/or production; and some states that are either introducing the technology, are exploring its introduction, or are reconsidering it after a period of restrictions.

Subsections 3.3.1 through 3.3.6 discuss national regulations, their nuclear regulatory structure and their positions regarding the technology. Subsection 3.3.6 includes short summaries of nations known to have cautious policies regarding nuclear technology and which likely will not be engaged in developing or implementing nuclear technologies unless social drivers or changes in perception influence regulatory changes.

3.3.1 Canada

Nuclear regulation in Canada began with the Atomic Energy Control Act of 1946, following the conclusion of WWII. Acting as a basis for expanded legislation, the regulations were reformed under the *Nuclear and Safety and Control Act* of 1997 and implemented under the newly established *Canadian Nuclear Safety Commission* (CNSC). The CNSC is responsible for the country's compliance with international nuclear treaties. Today, 15% of Canada's energy comes from nuclear power. The country is also the world's largest exporter of uranium and the largest producer of radioactive medical isotopes (CNSC-CCSN, 2024).

Nuclear Safety and Control Act (NSCA)

This is the primary act that governs the Canadian nuclear industry. This law establishes the CNSC and bestows upon it the jurisdiction to propose and enforce all regulation shown below (CNSC-CCSN, 2024).

- **General Nuclear Safety and Control Regulations**

  This regulation lays out the general requirements with respect to licence applications and renewals, exemptions, obligations of licensees, prescribed nuclear facilities, equipment and information, contamination, record-keeping and inspections (CNSC-CCSN, 2024).

- **Administrative Monetary Penalties Regulations**

  Regulations setting out the list of violations that are subject to administrative monetary policies under the NSCA, the method and criteria by which the penalty amounts are determined and the way notices of violations must be served (CNSC-CCSN, 2024).

- **Radiation Protection Regulations**

  Regulations that define the '*as low as reasonably achievable*' principle and regulations for limits of radiation doses, action limits, requirements for labelling and signage and reporting (CNSC-CCSN, 2024).

- **Class I Nuclear Facilities Regulations**

  Regulations that lay out the application requirement for site-preparation licences, personnel certifications, record-keeping and that and sets timelines for regulatory reviews (CNSC-CCSN, 2024).

  Class II Nuclear Facilities and Prescribed Equipment Regulations

  Regulations that lay out the requirements for licence applications, certification of prescribed equipment, radiation protection and record-keeping (CNSC-CCSN, 2024).

- **Nuclear Substances and Radiation Devices Regulations**

  Regulations that lay out the requirements for the licencing and certification of nuclear substances and radiation devices, use of radiation devices and record-keeping (CNSC-CCSN, 2024).

- **Packaging and Transport of Nuclear Substances Regulations, 2015**

  Regulations that lay out requirements for licences to transport nuclear substances and record keeping, as well as requirements for the design and certification of packages, special forms for radioactive materials and other prescribed equipment (CNSC-CCSN, 2024)

- **Nuclear Security Regulations**

  These regulations are structured in two parts. Part I defines the requirements for security-related information and the general obligations for applications. It also includes information about the security requirements for high-security sites. Part II provides security-related requirements for licencing and operation of lower-risk facilities (CNSC-CCSN, 2024).

- **<u>Nuclear Non-proliferation Import and Export Control Regulations</u>**

  Regulations for a licence application to import or export controlled nuclear substances, controlled nuclear equipment, or controlled nuclear information, in addition to licencing exemptions from licensing for certain import and export activities (CNSC-CCSN, 2024).

3.3.2 Japan

Nuclear regulation in Japan started in 1955 following the expansion of knowledge for nuclear power worldwide post-WWII. As a baseline, Japan passed the 21-Article Atomic Energy Basic Law that would be expanded in subsequent legislation and implemented by the Japanese Atomic Energy Commission, and later the Nuclear Safety Commission. Following the Fukushima incident in 2011, the Japanese government began a widespread reformation of nuclear regulation around the country, as well as inspections of all commissioned power plants; it also moved implementation of those activities to the newly formed Nuclear Regulation Authority (NRA) (OECD-NEA, 2017).

<u>Atomic Energy Basic Act (AEBA)</u>

Forming the basis of nuclear legislation in Japan, this act generalises objectives for research and development, as well as the use of nuclear energy. Broadly, it covers the mining and control of nuclear material, protection from hazards and compensation for exposure, and it establishes the *Nuclear Regulation Authority* (NRA). Finally, it lays out a framework for continuing regulation for nuclear activities to be established in subsequent acts (OECD-NEA, 2017).

<u>The NRA Establishment Act</u>

An extension of the AEBA, this law establishes the NRA as the authorised nuclear regulator and its responsibilities (OECD-NEA, 2017).

<u>The Compensation Act</u>

An extension of the AEBA, this law establishes protection and compensation guidelines for all persons suffering from nuclear damage (OECD-NEA, 2017).

<u>The Radiation Hazards Prevention Act</u>

This law establishes licencing regulations, via the NRA, for the use, sale, lease, waste management, etc., pertaining to radioisotopes and ionising radiation-generating equipment in the context of radiological protection (OECD-NEA, 2017).

<u>The Nuclear Emergency Act</u>

This law establishes the regulations regarding response measures for nuclear disasters to protect personal property and prevent the loss of life and personal injury (OECD-NEA, 2017).

<u>The Reactor Regulation Act</u>

This law establishes the general guidelines for the management of radioactive waste resulting from nuclear reactor operations. Additionally, it regulates the different types of nuclear activities, including control and accounting for internationally controlled materials (OECD-NEA, 2017).

The Act for Final Disposal of High-Level Radioactive

This law establishes the *Nuclear Waste Management Organisation* of Japan (NUMO) and regulates the geological disposal of high-level radioactive materials (OECD-NEA, 2017).

3.3.3 Republic of Korea

The first commercial nuclear power plant in Korea was the Kori Nuclear Power Plant in 1978; it was followed by 19 more facilities being commissioned, accounting for 22% of country's total electrical generation capacity. In 2011, as a reaction to the Fukushima Disaster, Korea reformed much of its regulation, beginning with the *Act on the Establishment and Operation of the Nuclear Safety and Security Commission* (NSSC) and the *Nuclear Safety Act* that the NSSC oversees.

Act on the Establishment and Operation of Nuclear Safety and Security Commission

This law establishes the *Nuclear Safety and Security Commission* (NSSC), which, as a central government organisation, reports directly to the Prime Minister. Its purpose is to protect citizens from radiation hazards caused by production or use by proposing and enforcing regulation for nuclear activities. (NSSC, 2024).

Nuclear Safety Act

This is the primary national law that establishes the framework for nuclear activities and is enforced by the NSSC. General topics are covered under this regulation with some expanded upon in subsequent acts. Topics include a comprehensive plan for nuclear safety, construction of electricity-generating reactors and related facilities, the operation of electricity-generating reactors and related facilities, the construction and operation of research reactors, use of nuclear materials, disposal and transport of nuclear waste, etc. (NSSC, 2024).

- **Act on Physical Protection and Radiological Emergency**

  This regulation expands upon the legislation passed under the Nuclear Safety Act. It lays out a framework for the physical protection of nuclear materials and facilities, radiation-disaster prevention measures and supplementary provisions via local governments and special institutions (NSSC, 2024).

- **Act on Protective Action Guidelines Against Radiation in the Natural Environment**

  This regulation expands upon the legislation passed under the Nuclear Safety Act. It lays out a framework managing source materials, byproducts and processed products. Additionally, there is coverage for the installation and operation of radiation-monitoring devices (NSSC, 2024).

3.3.4 The United Kingdom

The United Kingdom (U.K.) has a history of nuclear legislation going back to the *Atomic Energy Act* of 1946, following WWII, in which the allies set the initial regulation regarding management of nuclear technologies, and the *Atomic Energy Authority Act* of 1954 that set up the United Kingdom Atomic Energy Authority over nuclear activities in the state. Since then, there have been multiple legislations that expand on the initial rules set forth by the UK in their Office for Nuclear Regulation (ONR) (OECD-NEA, 2024).

The UK Energy Act

- **Energy Act 2004**

  The first of three laws set up in the 21st century to govern nuclear activities, among other forms of energy. This act focuses on the decommissioning and clean-up of installations and sites used for, or contaminated by, nuclear activities. Additionally, the act sets regulations relating to the civil nuclear industry and radioactive waste (OECD-NEA, 2024).

- **Energy Act 2008**

  The second of three laws, this act regulates the security of equipment, software and information relating to nuclear matters. Additionally, this act expands on the management and disposal of waste produced during the operation of nuclear installations (OECD-NEA, 2024).

- **Energy Act 2013**

  The most recent of three laws, this act established the *Office for Nuclear Regulation* (ONR) and its functions within the scope of jurisdiction. The office is now the singular regulator in the UK under the office of the Department for Work and Pensions (OECD-NEA, 2024).

The Nuclear Safeguards Act

- **Nuclear Safeguards Act 2000**

  This act expresses compliance and the implementation of the UK's duties to the Additional Protocol as set forth by the IAEA and Euratom. Additionally, it provides the legal basis for IAEA safeguards inspections (OECD-NEA, 2024).

- **Nuclear Safeguards Act 2018**

  This act was presented as a part of the UK's exit from the European Union. It makes minor changes to the *Energy Act 2013* and sets forth the same regulations seen in the *Nuclear Safeguards Act 2000* under purview of the ONR (OECD-NEA, 2024).

The Environmental Permitting (England and Wales) Regulations 2010

Part of a larger regulation on environmental protection, this law establishes expanded regulations for the control of radioactive material and the disposal of waste. Many of these regulations were previously covered under the *Radioactive Substances Act 1993*, which has since been largely repealed (OECD-NEA, 2024).

Health and Safety at Work etc Act 1974 – Ionising Radiations Regulations 1999

A subsection of the *Health and Safety at Work Act*, the *Ionising Radiations Regulations* sets regulations that dictate appropriate precautions for persons working near ionising radiation, as well as standards for smoke detectors in ionisation chambers (OECD-NEA, 2024).

3.3.5 United States of America

Nuclear regulation in the United States began at the end of WWII. After the war, there was consideration that the use of nuclear power could be used for civilian purposes and for the overall advancement of humanity. As such, the *Atomic Energy Act* of 1946 (and later 1954) created the *Atomic Energy Commission* (AEC) and empowered it to study, regulate and promote the use of nuclear energy for civilian use. The committee largely succeeded in this regard by introducing many reactor types, promoting nuclear use in medicine and becoming responsible for what would later be known as '*The Bandwagon Market*', a period of rapid growth of nuclear energy in society using power plants.

However, conflicting activities within the AEC began to raise concerns about safety administration and independent licencing procedures. As a result, it was concluded that all AEC functions could not be handled by a solitary group, so the US Congress dissolved the AEC under The *Energy Reorganisation Act* of 1974; the primary regulatory functions of safety and security were transferred to the newly created Nuclear Regulatory Commission (NRC), while the other activities were designated to the US Energy Research and Development

Administration, which would later become the Department of Energy. This reorganisation effectively separated the roles of nuclear technology research proponents and development from the role of regulator (NRC, 2010).

All U.S. regulations are captured in the *Code of Federal Regulations* (CFR) or published in other US codes; discussion is provided below regarding the mechanisms for nuclear technologies and the applications within the US code.

Nuclear Regulatory Commission (NRC)

Following the Fukushima disaster, the NRC created the Diverse and Flexible Coping Strategies that require plants to account for external events beyond design bases. These strategies are now implemented at all commissioned plants in the US (NRC, 2024).

- **10 CFR 37 Physical Protection of Category 1 and Category 2 Quantities of Radioactive Material**

  This establishes guidelines on the security of Category 1 and Category 2 radioactive material from theft or diversion. It lays out specific requirements for access to, the use of and transport of nuclear materials. Definitions to each category depends on the material (e.g. plutonium, americium, iridium, etc.) and can be found in Appendix A to 10 CFR Part 37 (NRC Regulations, 2024).

- **10 CFR 62 - Criteria and Procedures for Emergency Access to Non-Federal and Regional Low-Level Waste Disposal Facilities**

  This establishes the requirements for submitting a request to the NRC for the emergency disposal of low-level radioactive waste. Additionally, it covers the process for an extension, and the procedure to prevent the repetition of the emergency (NRC Regulations, 2024).

- **10 CFR 71 – Packaging and Transportation of Radioactive Material**

  This establishes the requirements for packaging, preparation for shipment and transportation of licenced nuclear material, as well as the procedure for gaining NRC approval of any shipments (NRC Regulations, 2024).

- **10 CFR 73 – Physical Protection of Plant and Materials**

  This establishes the requirements for the creation and maintenance of a physical-protection system and arrangement for special nuclear material in transit, and the plants at which they are used (NRC Regulations, 2024).

- **10 CFR 74 - Material Control and Accounting of Special Nuclear Material**

  This covers the requirements for reporting and recordkeeping of low and high significantly strategic special nuclear material and the enforcement of the regulation (NRC Regulations, 2024).

- **10 CFR 76 – Certification of Gaseous Diffusion Plants**

  This part establishes the requirements that will govern the operation of the certain parts of specific plants that are leased by the United States Enrichment Corporation. These requirements are for the protection of the public health and safety from radiological hazards and provide for the common defence and security (NRC Regulations, 2024).

- **10 CFR 110 – Export and Import of Nuclear Equipment and Material**

  This part describes the licencing, enforcement and rulemaking for the export and import of nuclear equipment and material, as well as for the criminal liability to the licencees or applicants subject to these activities. Additionally, it lays out rules for persons involved in the import and export of specific materials such as U-235 and deuterium (NRC Regulations, 2024).

- **Price-Andersen Act**

  The *Price-Andersen Act* added section 170 of the *Atomic Energy Act*. This amendment to the act guarantees that there is a mechanism in place such that damage compensation to the public would be available should an incident occur. The act lays out specific premiums per reactor per annum. The act specifically covers small modular reactors such that a plant using multiple of these types of reactors would be considered only a single reactor for its premium obligations. However, this is limited to plants generating less than 1.3 GW and using reactors with a capacity under 300 megawatts (Congressional Research Service, 2024).

Department of Energy (DOE)

Following the dissolution of the AEC, the US Energy Research and Development Administration (ERDA) was formed. It was tasked to manage naval reactors, energy development programmes and other nuclear activities. However, after the 1973 oil crisis, the US government decided that energy policy should be consolidated under one branch. The ERDA was merged with the Federal Energy Administration and the Federal Power Commission to create the Department of Energy (DOE). Since then, the DOE has overseen the same functions as the ERDA, while concurrently promoting energy conservation and development of alternative energy sources (2024).

- **DOE O 461.1 C Packaging and Transportation for Offsite Shipment of Material of National Security Interest**

  This standard covers the regulation of activities involving the packaging and shipment of radioactive materials by way of commercial operators for the DOE. This documents broadly states that the contract shall be done in compliance with standards set by the Department of Transportation (DOT) and the NRC except where alternative standards are allowed in the regulation (EPA, 2024).

- **10 CFR 835 - Occupational Radiation Protection**

  This standard establishes the radiation protection standards, limits and programme requirements for protecting individuals from occupational ionising radiation (EPA, 2024).

Environmental Protection Agency (EPA)

The EPA was established in 1970 after the adoption of the *National Environmental Policy Act* of 1969. Its core objective is the regulation and protection of the land, air and waters of the U.S. It was formed after consolidation of several other divisions, bureaus and commissions, including part of the Bureau of Radiological Health. Additionally, the EPA absorbed some of the responsibilities of the AEC after its dissolution. From this, and subsequent acts, the EPA has responsibility for regulating radiation in the country's environment (EPA, 2024).

- **42 U.S.C. §7401 et seq. (1970) Clean Air Act**

  This act is U.S. law that regulates air pollution under the EPA. Section 112 covers hazardous air pollutants such as radionuclides and any other radioactive pollutants (EPA, 2024).

- **33 U.S.C. §1251 et seq. (1972) Clean Water Act**

  The act is U.S. law that regulates water pollution under the EPA. It sets standards for pollutants including radionuclides. Subchapter III Subsection F deals with the illegality of discharge of radiological and high-level radioactive waste (EPA, 2024).

- **Marine Protection, Research, and Sanctuaries Act**

  This act is integrated as U.S. law regulated under the EPA. It facilitates the permitting of ocean dumping of low-level waste by way of both houses of Congress and expressly forbids the ocean dumping of high-level waste (EPA, 2024).

- **Nuclear Waste Policy Act**

  This act is integrated as U.S. Law regulated under the EPA and directs the agency to develop environmental standards that allow for the safe storage of nuclear waste at specially selected locations (EPA, 2024).

Department of Commerce (DOC)

The DOC, established in 1908, is responsible for creating the conditions for economic growth and opportunity. More specifically, it oversees the International Trade Administration (established in 1980) which oversees imports and exports of goods to and from other countries. Among these, it regulates some nuclear activities not covered by the NRC (DOC, 2024).

- **15 CFR 744.5 - Restrictions on certain maritime nuclear propulsion end-uses**

  This law is enforced by the DOC. It summarises the prohibitions regarding shipping's use of nuclear propulsion without licencing all while encouraging the participation in projects related to civil maritime nuclear propulsion. (EPA, 2024).

Department of Transportation (DOT)

- **49 CFR Part 173 Subpart I - Class 7 (Radioactive) Materials**

  Regulated by the DOT, Subpart of Title 49 sets the requirements for packaging and transporting radioactive materials by offerors and carriers (EPA, 2024).

- **49 CFR Part 176 Subpart M - Detailed Requirements for Radioactive Materials**

  Regulated by the DOT, this Subpart of Title 49 sets requirements for the storage, segregation distances, hazard care, and contamination control of radioactive materials as well as requirements during international transportation (EPA, 2024).Price-Andersen ActThe *Price-Andersen Act* added section 170 of the *Atomic Energy Act*. This amendment to the act guarantees that there is a mechanism in place such that damage compensation to the public would be available should an incident occur. The act lays out specific premiums per reactor per annum. The act specifically covers small modular reactors such that a plant using multiple of these types of reactors would be considered only a single reactor for its premium obligations. However, this is limited to plants generating less than 1.3 GW and using reactors with a capacity under 300 megawatts (Congressional Research Service, 2024).

3.3.6 France

In France, the largest share of its energy generation comes from nuclear power at 71.67% of total output (IAEA PRIS, n.d.). This is accomplished through their 56 reactors in 18 separate sites (WNA, 2024). In fact, this is the highest for any country in the world. And because the country is so invested in nuclear technology, they are also one of the only countries with a reprocessing site at the COGEMA La Hague. This is all regulated though the Nuclear Safety Authority (ASN) who is responsible for the safety of French nuclear activity. This group took over from the General Direction for Nuclear Safety and Radioprotection in 2006. Since, they have established new regulations including a sweeping declaration in 2012 requiring safety upgrades to all the nation's reactors after a report found troubling consequences should a loss of coolant or power were to occur (Nature, n.d.).

3.3.7 Russia

Russia is one of the oldest players in nuclear energy with their first nuclear power plant, and the world's first, coming into operation in 1954 (WNA, 2024). At the time, operations were overseen by the Federal Atomic

Oversight Service, but this was succeeded by the Federal Service for Environmental, Technological and Nuclear Supervision (Rostekhnadzor) in 2004 (Rostekhnadzor, n.d.). Further, all civilian reactors are overseen by Energoatom (Rosenergoatom, n.d.).

Russia stands out as the only nation with a nuclear-powered cargo ship, the Sevmorput. This vessel is the only remaining nuclear-powered merchant vessel in operation. Built in 1988, this 260-meter vessel runs on a KLT-40 nuclear reactor and is managed by Rosatom, the government group that oversees many sections of nuclear activities. It is built in collaboration by the Ministry of the Merchant Marine and Ministry of the Shipbuilding Industry, both groups in the marine vessel regulation sphere. It was expected to be in service for at least 15 years and had a price tag of approximately $215M (Rosatom, 2012).

3.3.8 Nuclear-Cautious Nations

While the above-listed Countries and others have established generally supportive frameworks for managing nuclear material and the peaceful uses of nuclear technology, others may perceive nuclear technology apprehensively. The nations listed below are those coastal states that have established cautious approaches or restrictions against using nuclear technology or handling nuclear material. Many of these policies were driven, at least in part, by public perception and political decisions to avoid nuclear technology or nuclear material. They may be subject to change in the future according to political drivers.

Unless national policies change, it can be assumed that nuclear-cautious nations will be those where it may not be possible for a nuclear-powered vessel to call (i.e., may be more likely to be denied entry) without special approval or international agreement. This operational restriction may negatively impact the economic feasibility of a nuclear merchant vessel.

3.3.8.1 Australia

The use of commercial nuclear energy within Australia is expressly forbidden except for the production of medical radioisotopes. Despite having rich uranium resources, Australia only allows regulated mining and exportation of uranium (Kitchen, 2023). This prohibition originates from the *Australian Radiation Protection* and *Nuclear Safety Act* of 1998 and the *Environmental Protection and Biodiversity Conservation Act* of 1999. Following those acts, the Australian Radiation Protection and Nuclear Safety Agency was formed to regulate the use of radiation and nuclear materials (Gibson, 2024). Nuclear-powered vessels are allowed into Australian ports only if they fit the Defence Operations Manual's (OPSMAN1's) criteria. OPSMAN1 contributes information for condition procedures and responsibilities that must be upheld by nuclear-powered vessels visiting Australian ports (Arpansa, n.d.). These vessels are permitted entry once assessed and approved as adhering to strict environmental and safety criteria.

3.3.8.2 Denmark

While it is not expressly illegal to use nuclear energy, the production of nuclear energy has been prohibited since 1985. Danish research reactors are being decommissioned, although private industry is still working on the development of small nuclear reactors (Shaw, 2024). Denmark possesses no nuclear weapons or nuclear power plants, having three research reactors, one under decommissioning and the others fully decommissioned. Additionally, the Danish National Institute for Radiation Protection oversees monitoring and tracking of 11,000 radiation sources (Vestergaard, 2012). The country also holds some of the oldest acts of legislation governing nuclear materials, managing controls on radioactive substances, nuclear installations and safety and environmental aspects. Furthermore, Denmark regularly provides funds to the IAEA's Nuclear Security Fund (Vestergaard, 2012).

3.3.8.3 Germany

Germany has been phasing out nuclear energy since 2011, shutting down its three remaining plants on April 15, 2023. The prospect of any new nuclear plants is now expressly banned by law (WNA, 2024). After the Federal

Republic of Germany renounced the use of nuclear weapons, the *Germany Atomic Energy Act* announced in December 1959 (in Section 7) that no other licencing would be distributed for constructing and operating nuclear power plants and reprocessing facilities (Federal Ministry for the Enviornment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), n.d.).

From 1968 through 1979, the GKSS Research Centre Geesthacht tested engines for nuclear-powered vessels, leading to the operation of *Otto Hahn*, a nuclear-powered research and trading vessel (Gail H. Marcus, 2021). The *Atomic Energy Act* mentions a law in Section 25a regarding the liability of reactor ships. While there are no specific regulations against the entry of nuclear-powered vessels into the country's ports, it can be assumed that any such vessel would be under strict regulations and closely monitored.

3.3.8.4 Greece

Although Greece has the Greek Atomic Energy Commission to govern its nuclear activities, it has decided not to not implement nuclear power due to the high risks of earthquakes and the country's small size (ENSREG, 2024). Greece signed the *Convention on Nuclear Safety* (effective in 1997), which assured that no nuclear power plants would be built now or in the future (Greek Atomic Energy Commission, 2010). There is a nuclear research reactor (licenced for extended shutdown) and two sub-critical assemblies for research and education (one fully decommissioned and one in operation). A nuclear-powered French aircraft carrier (*Charles de Gaulle*) was allowed in the port of Souda in February 2023 and again in May 2024 (Kokkinidis, 2024).

3.3.8.5 Ireland

The production of energy from nuclear sources within the borders of Ireland is prohibited by law, although there is an appetite to reconsider this position (Loughlin, 2023). Ireland chose not to develop a nuclear power industry and had no plans to change due to its concerns regarding public health and safety, environmental protection/security and the lack of long-term management capabilities for the significant quantities of radioactive waste. This decision is reflected by the absence of nuclear-power stations, defence reactors for research, or spent nuclear reactor fuel in storage or waiting for treatment. The *Radiological Protection Act* of 1991 and Regulations of 2019 and European Communities (Supervision and Control of Certain Shipments of Radioactive Waste and Spent Fuel (2009)) regulate nuclear safety in the country and address the shipment of radioactive waste (IAEA, 2022). Ireland does not allow the cross-border movement of spent nuclear fuel from other countries in its territories and waters (IAEA, 2022).

3.3.8.6 Israel

Israel does not currently rely on nuclear power in its energy infrastructure and the Israeli government has stated that, after the Fukushima disaster, nuclear energy is not being considered (CACNP, 2024).

3.3.8.7 Italy

Nuclear power is banned in Italy by law, and this has been confirmed by subsequent national referendums (WNA I. , 2024). Having been one of the first countries to use nuclear technology for civil power generation, Italy now has no nuclear power reactors in operation and is not planning a nuclear power programme. The main activities currently being undertaken include waste management, the decommissioning of installations and the operation of a few research reactors; radiation is also used in medical, industrial and research fields. In 2009, there was an attempt to restart the nuclear programme, but in 2011 it was rejected in a referendum (IAEA, 2020). There is still, however, research conducted by several agencies, institutions and universities to support Italy's participation in international projects. There is significant public concern about allowing nuclear-powered vessels to enter Italian ports.

3.3.8.8 Lithuania

Although not explicitly illegal, there are no commissioned reactors in Lithuania and referendums show wide public opposition to the construction of new plants (WNA L. , 2024). Lithuania has two nuclear-power reactors under decommissioning and several spent-fuel and radioactive-waste management facilities under construction or in operation. The development of a new nuclear power plant in Visaginas was cancelled in 2016. The National Integrated Energy and Climate Plan of the Republic of Lithuania and National Energy Independence Strategy do not project the development of nuclear power to continue in the country (IAEA, 2020). Lithuania's State Nuclear Power Safety Inspectorate is the regulatory body overseeing nuclear regulation and radiation safety and security (State Atomic Energy Safety Inspectorate (VATESI), n.d.). It is anticipated that Lithuania will not permit nuclear-powered vessels to visit its ports.

3.3.8.9 New Zealand

New Zealand has a designated nuclear-free zone in all territorial sea, land and airspace. The *New Zealand Nuclear Free Zone, Disarmament and Arms Control Act* of 1987 expressly prohibits nuclear-powered vessels to enter within a 12-nautical mile radius of the country's territorial waters. It has also banned the dumping of radioactive waste within the zone (WNA N. Z., 2024).

3.3.8.10 Uruguay

Although Uruguay has two departments that regulate the use of nuclear power, it is explicitly prohibited by law (Uruguay, 2024). Uruguay has only radiological installations for medical, industrial, agricultural, investigatory and teaching applications. Through Article 2 Act 17.033 of 20 November 1998, innocent passage is allowed if vessels of all states align with the United Nations *Convention on the Law of the Sea* of 10 December 1982, other international law and all regulations imposed by Uruguay (United Nations). For any vessels that are nuclear-powered or transporting dangerous substances, precautionary measures dictated by the country's executive authority and regulations must be followed. To enter its waters, rigid safety and environmental regulations must be met. In addition, Article 3 Act 17.033 of 20 November 1998 outlines a border zone -- from the outer edges of its territorial sea to 24 nautical miles from Article 14's baseline -- where Uruguay can control, prevent, or punish any violations of its laws (United Nations).

3.4 Available National and International Guidelines

3.4.1 American Society of Mechanical Engineers (ASME)

ASME is recognised globally as a provider of engineering standards, practices of assessment and quality assurance. Originally providing standards for fossil fuel-powered plants and components, its application for use in the design and construction of nuclear power plants shifted its focus to creating specific codes for nuclear power plants. Below is a representative list of ASME codes and standards relevant to conventional and advanced nuclear power applications; these may offer a foundation for future codes or standards specifically applicable to marine applications (ASME).

Boiler and Pressure Vessel Code (BPVC) Section III – Rules for Construction of Nuclear Facility Components

This section within the ASME BPVC covers materials, design, fabrication, examination, testing and the overpressure protection required for the components of a nuclear facility. It also includes the requirements for quality assurance, certification and authorised inspection for components. Contents are listed below for reference:

- Subsection NCA – General Requirements for Division 1 and Division 2
- Appendices
    - Division 1
        - Subsection NB – Class 1 Components
        - Subsection NC – Class 2 Components
        - Subsection ND – Class 3 Components
        - Subsection NE – Class MC Components
        - Subsection NF – Supports
        - Subsection NG – Core Support Structures
    - Division 2 – Code for Concrete Containments
    - Division 3 – Containment Systems for Transportation and Storage of Spent Nuclear Fuel and High-Level Radioactive Material
    - Division 5 – High Temperature Reactors

Boiler and Pressure Vessel Code (BPVC) Section XI – Rules for Inservice Inspection of Nuclear Power Plant Components

Once the requirements for construction are met (Section III), this section applies to the examination, operational testing, inspection, repair and replacement of components specific to light water-cooled nuclear power plants.

Both the ASME Section III and Section XI refer to other applicable BPVC Sections.

NQA-1 – Quality Assurance Requirements for Nuclear Facility Applications

NQA-1 provides a standard for carrying out quality assurance programmes for the siting, design, construction, operation and decommissioning of a nuclear power plant.

OM – Operation and Maintenance of Nuclear Power Plants

Specific to light water reactor power plants, this ASME standard provides the requirements for testing and examination of components to assess operational suitability, including the responsibilities, methods, intervals, criteria, corrective action, qualification and documentation.

Others

ASME offers other standards and guidelines that may be applicable, some of which are listed below:

- QME-1 – Qualification of Active Mechanical Equipment used in Nuclear Power Plants
- RA-S – Probabilistic Risk Assessment for Nuclear Power Plant Applications
- HRT-1 – Rules for Hoisting, Rigging, and Transporting Equipment for Nuclear Facilities
- AG-1 – Code on Nuclear Air and Gas Treatment

3.4.2 ASTM International

Originally known as the American Society of Testing and Materials, ASTM International is a globally recognised standards organisation for a variety of materials, systems and components, including those used for nuclear technology applications. The categories of nuclear-technology standards available from ASTM are listed below;

the full list is available online, where other categories of standards may also be applicable (ASTM International, 2024).

- Behaviour and Use of Nuclear Structural Materials
- Dosimetry, Dosimetry Applications and Dosimetry Systems
- Fuel and Fertile Material Specifications
- Methods of Test
- Neutron Absorber Materials Specifications
- Nuclear Processing
- Nuclear Radiation Metrology
- Radiation Dosimetry for Radiation Effects on Materials
- Radiological Protection for Decontamination and Decommissioning of Nuclear Facilities and Components
- Spent Fuel and High-Level Waste

3.4.3 National Fire Protection Association (NFPA)

Internationally recognised, the NFPA produces standards for fire protection related to a variety of industries and uses, including the examples below specifically for nuclear applications (NFPA, 2024).

- NFPA 801, Standard for Fire Protection for Facilities Handling Radioactive Materials
- NFPA 803, Standard for Fire Protection for Light Water Nuclear Power Plants
- NFPA 806, Performance-Based Standard for Fire Protection for Advanced Nuclear Reactor Electric Generating Plants Change Process

3.4.4 Nuclear Energy Institute (NEI)

Founded in 1994, the Nuclear Energy Institute (NEI) is a nuclear industry trade association in the U.S. that represents the nuclear technologies industry. Its core directive is to promote the use and growth of nuclear energy through efficient operations and effective policy. In this regard, the NEI works on legislative and regulatory issues such as for nuclear plant maintenance, fuel storage and new-build considerations.

The NEI directly represents the nuclear industry's interests to the U.S. Congress and the NRC by publishing research papers, public and private testimony, statistical reports, etc. Its purview spans every corner of the nuclear community, including commercial-electricity generation, transportation of radioactive materials and nuclear-waste management. The following is a representative list of some of the work that the NEI has published that may be relevant to the use of nuclear power in the maritime industry (NEI, 2024). Although primarily focused on U.S. activity, NEI references may be useful to international industries.

Policy Options for States to Support New Nuclear Energy

This publication outlines the transition to a clean energy system that utilises nuclear energy. It lays out options for different U.S. states to consider as they expand legislation to include nuclear energy to meet various decarbonisation goals (NEI, 2022a).

IG-02 for NEI 20-08: Contracting and Risk Sharing

This publication outlines the best practices for reducing the project schedule length and design risk for the purposes of economic competitiveness. It is focused on new nuclear projects, both first of a kind and any number of a kind, including SMRs and advanced reactors (NEI, 2022b)

Establishing a High Assay Low Enriched Uranium Infrastructure for Advanced Reactors (HALEU)

This report outlines the information for the introduction and construction of HALEU infrastructure in the U.S. It outlines the current infrastructure, the international supply, the fabrication of reactor fuel for HALEU, alternate sources, existing legislation and the projects underway (NEI, 2022c).

NEI 20-04, "The Nexus Between Safety and Operational Performance in the U.S. Nuclear Industry"

This report concerns the connections between U.S. industry performance and plant safety. It explores historical performance improvements. In this regard, the performances related to the NRC Reactor Oversight Process, worker safety improvements and trends in risk matrices (NEI, 2022d).

NEI 18-04 Rev 1 August 2019 Modernisation of Technical Requirements for Licensing of Advanced Non-Light Water Reactors: Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development

This is a detailed report that presents one acceptable method for establishing a series of topics to demonstrate that a specific design provides reasonable assurance of adequate radiological protection.

3.4.5 World Nuclear Transport Institute (WNTI)

Combining a group of common interests in nuclear transport industry, the WNTI was founded on April 28, 1998, by members such as British Nuclear Ltd., Cogema and the Federation of Electric Power Companies. The WNTI allows companies involved in the transportation of radioactive material to collaborate and share knowledge on global best practices for safe, secure, efficient and sustainable transportation (WNTI). The organisation actively engages with the IAEA as a consultant non-governmental organisation (NGO), influencing shipping regulations and offering training programmes and workshops for the newest safety and security protocols. In 2024, the WNTI worked on a gap analysis related to the code of safety for nuclear merchant vessels (MSC 108-INF.21) (WNTI).

3.4.6 American Nuclear Society (ANS)

As a non-for-profit association started in 1954, the ANS pushes the progression of nuclear science and technology. The organisation provides nuclear professionals with the tools to exchange ideas, conduct research and advocate for nuclear energy's peaceful and beneficial use. Hosting a variety of specialised disciplines such as physics, nuclear safety, operation and power, the group signifies the growth of the nuclear field (ANS). In addition, it has participated in national/international initiatives with government, academia, research laboratories and private industry. The alliance distributes its expertise by sponsoring activities such as peer reviewed journals, trade publications, annual meetings, technical programmes, topical meetings, position statements, consensus standards, professional divisions and congressional fellowship.

3.4.7 World Association of Nuclear Operators (WANO)

Founded in 1986 after the Chernobyl disaster, WANO came together when leaders of the world's commercial nuclear reactors put competitive and regional differences aside. The association was formed with the mission for members to work together to assess, benchmark and improve overall performance, increasing the global safety and reliability of nuclear power plants (WANO, n.d.). The goal was assisted through WANO's mutual support, exchange of information and ambition of best practices. All members can benefit from operational safety and reliability improvements through services such as peer reviews, access to technical support and a global library of operating experience. Unlike regulatory bodies, WANO will not advise companies on the selection of initial reactor designs. With members involved with 430 reactors worldwide, WANO fosters a culture of learning by sharing information openly (WANO, n.d.).

GL 2018-01 Independent Oversight

Developed with IAEA to support nuclear operators by creating a function of independent oversight to help secure safety-management systems for nuclear facilities (WANO, 2018).

3.4.8 World Nuclear Association (WNA)

Established on May 15, 2001, by the Uranium Institute, the WNA is a trade association dedicated to the nuclear fuel cycle. The WNA seeks to stimulate the growth of the nuclear sector by linking individuals in the value chain, representing the industry's position in world forums and providing authoritative information, while simultaneously influencing target markets (WNA, n.d.). The organisation publishes reports and analyses on nuclear technology, economics, safety and environmental impacts. By engaging with policy-makers, regulators and the public, the WNA promotes the benefits of nuclear energy. This is performed through activities such as organising conferences, maintaining a diverse information library and coordinating industry initiatives to address shared challenges. The WNA provides an information library on reactor technologies, the economics of nuclear power, waste management and hydrogen production, with country profiles (WNN, 2021).

3.4.9 Nuclear Energy Maritime Organisation (NEMO)

In 2024, co-founding members RINA and Lloyd's Register organised marine and nuclear stakeholders, including HD KSOE, CORE POWER, BWXT Advanced Technologies, TerraPower, Onomichi Dockyard, Westinghouse Electric Company, VARD Group, Bureau Veritas and JEIL Partners to create the NEMO. The NEMO's mission is to convene expert stakeholders to help regulators create progressive standards and rules for the development, operation and decommissioning of floating nuclear power (RINA, 2024). The NEMO's involvement would allow the standards that are generated to be based on quality specifications for safety, security and environmental justice. The NEMO seeks to foster collaboration, knowledge sharing and advocacy among its members and stakeholders, allowing them to network and connect with regulators (RINA, 2024).

3.5 Gap Analysis

The uncertainties or lack of specific guidelines to consider nuclear power in marine vessel designs and operations prevent adoption of the technology. Table 9 below summarises the gaps that need to be closed.

Table 9. Gap analysis legend.

No gap or changes needed to address nuclear power as an alternative power for shipping
Small gaps or minor changes to address nuclear power as an alternative power for shipping
Medium gaps or some challenging changes required to address nuclear power as an alternative power for shipping
Large gaps or many challenging changes required to address nuclear power as an alternative power for shipping

Table 10. Synopsis on regulatory gap analysis for nuclear power as an alternative power for shipping

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
Sustainability and Emissions Regulations	EU '*Fit-for-55*' FuelEU Maritime	- Not explicitly listed as a technology considered as zero-emissions.
	EU Emissions Trading System (ETS)	- Nuclear power as energy source is not directly mentioned. - Only focused on tank-to-wake emissions, does not incorporate emissions from production.
	US Clean Air Act	- Regulates air pollution and hazardous air pollutants such as radionuclides and any other radioactive pollutants. - May be referred to or used for maritime nuclear applications.
	US Clean Water Act	- May be referred to or used for maritime nuclear applications.
	US Marine Protection, Research and Sanctuaries Act	- May be referred to or used for maritime nuclear applications.
	EU Energy Taxation Directive (ETD)	- Shipping sector is fully exempt from directive. - Member states independently implement national policy.
	IMO Strategy on Reduction of GHG Emissions 2023	- Does not specifically apply to nuclear reactors or enforce their use on vessels. - May need to be modified or updated to consider nuclear energy.
	MARPOL Annex VI EEDI, EEXI, CII & DCS	- No explicit provision in IMO regulations and guidelines for the direct use of a nuclear carbon factor in EEDI, EEXI, CII and DCS. - Provision for well-to-wake emissions considerations should be accounted for in these instruments. - Minor gap to cover direct use of a nuclear as considered for carbon factor.
Nuclear Fuel Standards [including supply chain, manufacturing, recycling, and disposal]	Boiler and Pressure Vessel Code (BPVC) Section III – Rules for Construction of Nuclear Facility Components, Division 3	- Covers materials, design, fabrication, examination, testing, quality assurance and required overpressure protection for nuclear-facility components, including containment systems for transportation and storage of spent nuclear fuel and high-level radioactive material.

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
		- May not specifically apply to the transport and storage of spent nuclear fuel and high-level radioactive material on the vessel from which it was produced. - May be referred to in marine specific standards. - Additional modifications or updates may be needed to address technical integration of nuclear technology with vessel structures and systems.
	ASTM International Set of Technology Standards for Fuel and Fertile Material Specifications and Spent Fuel and High-Level Waste	- May be referred to in marine specific standards.
Marine Design Standards	SOLAS Chapter VIII & Resolution A.491	- Applicable to pressurised water reactors for propulsion only. - Outdated and should be updated, modernised and applicable to more types of advanced reactors.
Nuclear Reactor Design Standards	Boiler and Pressure Vessel Code (BPVC) Section III – Rules for Construction of Nuclear Facility Components	- Requirements needed for the packaging and transportation of radioactive materials by offerors and carriers. - Not applicable to the management of nuclear material handling on marine vessels. - May be referred to by other codes or standards or updated to include onboard handling of nuclear material.
Transportation & Handling [of Nuclear Material, including Radioactive Waste]	IAEA - SSR Part 6 Regulations for the Safe Transport of Radioactive Material	- Establishes the general guidelines for the management of radioactive waste resulting from the operation of nuclear reactors. - Not applicable to the management of nuclear material handling on marine vessels.
	IMO International Maritime Dangerous Goods (IMDG)	- Establishes the Nuclear Waste Management Organisation of Japan (NUMO) and regulates the geological disposal of high-level radioactive material.
	Council Directive 2011/70/Euratom	- Requirements for licences to transport, nuclear substances and recordkeeping, and for the design and certification of packages, special form

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
		radioactive materials and other prescribed equipment. - Not applicable to the management of nuclear material handling on marine vessels.
	US 10 CFR 71 – Packaging and Transportation of Radioactive Material	- Applicable to cargo only. - No gaps to allow nuclear marine applications.
	US 10 CFR 110 – Export and Import of Nuclear Equipment and Material	- Framework for management of source materials, byproducts, and processed products. Additionally, there is coverage for the installation and operation of radiation monitoring devices.
	US DOE O 461.1 C Packaging and Transportation for Offsite Shipment of Material of National Security Interest	- Applicable to Cargo only. - May be referred to in marine standards or updated to include specific provisions for nuclear maritime operations.
	Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management, 2001	- May be applied to merchant nuclear-powered vessels or floating nuclear power plants.
	US 10 CFR 835 - Occupational Radiation Protection	- Related to the supervision and control of shipments of radioactive waste and spent fuel.
	UK Health and Safety at Work etc Act 1974 – Ionising Radiations Regulations 1999	- Establishes expanded regulations for the control of radioactive material and the disposal of its waste.
	US Nuclear Waste Policy Act	- Provides safety requirements for facilities that manage radioactive waste before disposal, including the associated transport of radioactive material.
	49 CFR Part 173 Subpart I - Class 7 (Radioactive) Materials	- Sets requirements for the storage, segregation distances, hazard care and contamination control of radioactive materials. - May be referred to in marine standards or updated to be applicable to nuclear marine applications.

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
	Japan Reactor Regulation Act	- Requirements needed for the packaging and transportation of radioactive materials by offerors and carriers. - Not applicable to the management of nuclear material handling on marine vessels. - May be referred to by other codes or standards or updated to include onboard handling of nuclear material.
	Japan Act for Final Disposal of High-Level Radioactive Waste	- Establishes the general guidelines for the management of radioactive waste resulting from the operation of nuclear reactors. - Not applicable to the management of nuclear material handling on marine vessels
	Canada Packaging and Transport of Nuclear Substances Regulations, 2015	- Establishes the Nuclear Waste Management Organisation (NUMO) and regulates the geological disposal of high-level radioactive material.
	IMO International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC)	- Requirements for licences to transport, nuclear substances, recordkeeping as well as requirements for the design and certification of packages, special form radioactive material and other prescribed equipment. - Not applicable to the management of nuclear material handling on marine vessels.
	Act on Protective Action Guidelines Against Radiation in the Natural Environment	- Applicable to cargo only. - No gaps to allow nuclear marine applications.
	IMO - International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium, and High-Level Radioactive Wastes on Board Ships (INF)	- Framework for management of source materials, byproducts, and processed products. Additionally, there is coverage for the installation and operation of radiation monitoring devices.
	Council Directive 2006/117/Euratom	- Applicable to Cargo only. - May be referred to in marine standards or updated to include specific

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
		provisions for nuclear maritime operations.
	UK Environmental Permitting (England and Wales) Regulations 2010	- Related to the supervision and control of shipments of radioactive waste and spent fuel.
	IAEA - GSR Part 5 Predisposal Management of Radioactive Waste	- Establishes expanded regulations for the control of radioactive material and the disposal of its waste.
	US 49 CFR Part 176 Subpart M - Detailed Requirements for Radioactive Materials	- Provides safety requirements for facilities that manage radioactive waste before disposal, including the associated transport of radioactive material.
Quality Assurance	Boiler and Pressure Vessel Code (BPVC) Section XI – Rules for Inservice Inspection of Nuclear Power Plant Components	- Applicable for the examination, operational testing, inspection, repair, and replacement of components specific to light water-cooled nuclear power plants. - Not applicable to all types of reactor technology.
	ASME NQA-1 – Quality Assurance Requirements for Nuclear Facility Applications	- Provides a standard for carrying out quality-assurance programmes through siting, design, construction, operation and decommissioning of a nuclear power plant. - Not applicable to marine facilities.
	US 15 CFR 744.5 - Restrictions on certain maritime nuclear propulsion end-uses	- Summarises prohibitions of shipping using nuclear propulsion without licencing.
	IMO - International Safety Management Code (ISM)	- Provides administrative structures for basic safety management to shipping companies and shipowners to protect the operation of vessels and prevent pollution. - May be used by marine operators. - Does not include specific provisions for nuclear marine applications.
	ASME OM – Operation and Maintenance of Nuclear Power Plants	- Provides requirements for testing and examination of components to assess operational suitability, including responsibilities, methods, intervals,

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
		criteria, corrective action, qualification and documentation.
Licencing, Nuclear Administration, Civil Liability, and Insurance	US 10 CFR 74 - Material Control and Accounting of Special Nuclear Material	- Covers the requirements for reporting and recordkeeping of low and high-level nuclear materials as well as the enforcement of the regulation.
	Japan Compensation Act	- Establishes protections and compensation guidelines for all persons suffering from nuclear damage.
	Convention on Nuclear Safety (CNS) 1996	- Not directly applicable to nuclear-powered vessels but may be interpreted or updated for use by floating nuclear applications.
	Japan Radiation Hazards Prevention Act	- This law establishes licencing regulations, via the NRA, for the use, sale, lease, waste management, and more for radioisotopes and ionising radiation-generating equipment in the context of radiological protection.
	Japan Nuclear Emergency Act	- Establishes the regulations regarding response measures for nuclear disasters to protect personal property and prevent the loss of life and personal injury.
	Canada General Nuclear Safety and Control Regulations	- Establishes the general requirements with respect to licence applications and renewals, exemptions, obligations of licensees, prescribed nuclear facilities and equipment and information, contamination, record-keeping and inspections.
	Canada Administrative Monetary Penalties Regulations	- Lists violations that are subject to administrative monetary policies, the method and criteria by which the penalty amounts will be determined and how notices of violations must be served.
	Canada Class I Nuclear Facilities Regulations	- Requirements for site preparation licence applications, personnel certifications, record-keeping and sets timelines for regulatory reviews.

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
	Canada Class II Nuclear Facilities and Prescribed Equipment Regulations	- Requirements for licence applications, certification of prescribed equipment, radiation protection and record-keeping.
	Euratom Treaty	- Original treaty that established the Euratom and lays out the baseline regulations for all Euratom members to follow and build upon.
	Korea Nuclear Safety Act	- Establishes the framework for nuclear activities in Korea that are enforced by the NSSC. - Encompasses broad regulations over all aspects of nuclear power on land.
	Japan Atomic Energy Basic Act (AEBA)	- Generalises objectives for research and development, as well as the usage use of nuclear energy. - Encompasses broad regulations over all aspects of nuclear power on land.
	UK Energy Act 2004	- Sets regulations relating to the civil nuclear industry and radioactive waste. - Encompasses broad regulations over all aspects of nuclear power on land.
	Canada Nuclear Non-proliferation Import and Export Control Regulations	- Regulations for a licence application to import or export controlled nuclear substances, controlled nuclear equipment, or controlled nuclear information, in addition to exemptions from licencing for certain import and export activities. - Not specific to maritime.
	Brussels Convention on the Liability of Operators of Nuclear Ships and Additional Protocol	- Liability framework for vessels using nuclear energy for propulsion. - Not put in force, but a baseline piece of legislation that could be used in the future. - Specific to Marine.
	Vienna Convention on Civil Liability for Nuclear Damage	- General framework for when nuclear energy incidents occur. - Covers liability obligation, financial limits, and more.

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
		- Not specific to marine but could be easily adapted to include it.
	Price-Andersen Act	- Amendment to the Atomic Energy act, this legislation sets minimum acceptable obligations for when nuclear incidents occur in the United States. - Not marine specific and some work would be needed in order to adapt the industry into it.
Risk / Safety / Environmental Assessment	Council Directive 2014/87/Euratom - Nuclear Safety Directive	- Establishes a community framework for the safety and the reduction of safety risks of nuclear installations.
	US CFR 62 - Criteria and Procedures for Emergency Access to Non-Federal and Regional Low Level Waste Disposal Facilities	- Establishes requirements to submit a request to the NRC for the emergency disposal of low-level radioactive waste.
	US 10 CFR 76 – Certification of Gaseous Diffusion Plants	- Establishes requirements that will govern the operation of certain portions of specific plants that are leased by the United States Enrichment Corporation.
	Canada Nuclear Substances and Radiation Devices Regulations	- Requirements for the licencing and certification of nuclear substances and radiation devices, use of radiation devices and record-keeping.
	Canada Radiation Protection Regulations	- Regulations that define the '*as low as reasonably achievable*' principle and regulations for limits on radiation doses, action limits and requirements for labelling, signage and reporting.
	Convention on Nuclear Safety (CNS)	- Convention that allows for accountability by other convention signatories - Not directly related to marine, but could be expanded upon
Security and Safeguards	IAEA Treaty on the Non-Proliferation of Nuclear Weapons (NPT)	- Establishes international agreement on the peaceful use of nuclear material and establishing national safeguards to nuclear material. - Does not address the issue of a mobile nuclear power plant operating over multiple national jurisdictions but will be important to consider for

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
		operational arrangements of nuclear-powered merchant vessels.
	IAEA - Convention on the Physical Protection of Nuclear Material (CPPNM)	- Establishes legal obligations regarding the physical protection of nuclear material used for peaceful purposes during international transport, the criminalisation of certain offences involving nuclear material and international cooperation.
	IMO - International Ship and Port Facility Security (ISPS)	- Focuses on establishing security measures for governments, ports and shipping companies. - Does not include nuclear applications but does not pose gap for nuclear marine applications.
	IMO – Convention for the Suppression of Unlawful Acts Against the Safety of Maritime Navigation, Protocol for the Suppression of Unlawful Acts Against the Safety of Fixed Platforms Located on the Continental Shelf	- Established response to facility to unlawful acts against vessels and offshore platforms. - Does not include nuclear applications but may be interpreted or updated to include specific provisions for nuclear marine units.
	US 10 CFR 37 Physical Protection of Category 1 and Category 2 Quantities of Radioactive Material	- Establishes guidelines on the security of Category 1 and Category 2 radioactive material from theft or diversion.
	US 10 CFR 73 – Physical Protection of Plant and Materials	- Establishes requirements for the establishment creation and maintenance of a physical-protection system and arrangement for special nuclear material in transit and the plants at which they are used.
	UK Energy Act 2008	- Regulates the security of equipment, software and information relating to nuclear matters.
	Korea Act on Physical Protection and Radiological Emergency	- Framework for the physical protection of nuclear materials and nuclear facilities, radiation disaster prevention measures, and supplementary provisions via local governments and special institutions.

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps
	Korea Nuclear Security Regulations	- Defines security-related information requirements and general obligations for applications.
	IAEA Treaty on the Non-Proliferation of Nuclear Weapons (NPT)	- Establishes international agreement on the peaceful use of nuclear material and establishing national safeguards to nuclear material. - Does not address the issue of a mobile nuclear power plant operating over multiple national jurisdictions but will be important to consider for operational arrangements of nuclear-powered merchant vessels.
	Convention on Early Notification of a Nuclear Accident	- Convention legislated to establish mechanisms for signatories to report accidents that may result in a nuclear release that will affect another country. - Can be applied to marine nuclear systems.
	Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (CACNARE)	- Convention that allows for signatories to request assistance from the IAEA or other nations if there is a nuclear accident or radiological emergencies. - Directly applicable to marine nuclear systems.
	Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (Joint Convention),	- Convention to address the issue of spent fuel and radioactive waste on an international scale. - Establishes a peer review system for spent fuel management. - Directly applicable to marine nuclear systems.

3.6 Regulation Conclusions

Substantial regulatory work is required for the adoption of nuclear power on merchant vessels. Primarily, this includes addressing the gaps in legislation for the use of the technology in propulsion and general marine use, navigating through the scope of nuclear cautious nations, and bringing awareness to nuclear power as a viable option for the maritime industry. The inclusion of nuclear power may require the modernisation of regulatory frameworks to promote safety, environmental protection and the efficient integration of technology. There will be also the need to reflect on an adequate liability regime to ensure wider acceptance of these technology. While regulatory drivers may push for nuclear power according to its potential benefits related to emission-reduction goals, not every nation is as accepting of this infrastructure. Unfortunately, there is no way of compiling a list of nations that accept or prohibit nuclear-powered vessel. It could be assumed that the nuclear-adverse countries are likely to be the ones that would not allow a merchant nuclear-powered vessel to enter port. However, experience from the Navy shows that exceptions can be made. Similarly, in the context of merchant shipping, arrangements could be made between shipowner, Flag Administration, and port or destination state. In any case, in countries with a low tolerance for nuclear applications, addressing the public perception surrounding nuclear power is paramount to the continuance of the technology's trajectory. By introducing harmonised and precise regulations, port nations can assure smooth, safe and cooperative operations to accept merchant nuclear-powered vessels while maintaining international coordination.

Active participation from industry and regulatory bodies is imperative to continue creating and updating regulations. Class societies can help in this regard by offering a variety of expertise and knowledge of marine applications and can prove instrumental to aid the deployment of nuclear technology in the maritime industry. Combined with industry, regional and national involvement in aligning regulations and the assistance of class, first movers and promotional incentives for nuclear power could influence the establishment of new solutions that are sustainable and efficient.

4. Risk Assessment Using Nuclear Power in Merchant Vessels

The safety regulations for using nuclear power in shipping are still in development, as described in Section 3. As part of this study, HAZID assessments were carried out for generic vessel types; they are intended to be used to contribute to discussions regarding safety and risk management for vessels using nuclear power. This part of the study offers an analysis of some of the key safety aspects if nuclear power is to be used as a fuel for marine vessels and their many fuel-system configurations. Three vessel types were considered:

- A Cruise Ship with a LFR
- A Bulk Carrier with a VHTR/HTGR
- A Container Ship with a VHTR/HTGR

The purpose of this study is to identify the potential major hazards related to the operational configuration of a nuclear-powered vessel at an early stage of concept development, review the effectiveness of the safety measures and, where required, expand them to achieve tolerable levels of residual risk.

Early identification and assessment of hazards can provide essential input for concept development at a time when any changes in the design are usually less expensive. Typically, the problems are earmarked for action outside the workshop. The outcomes will help EMSA to draft recommendations to develop and adapt procedures and regulations. They also will promote awareness about the hazards associated with the use of nuclear power as an alternative power for shipping.

In that context, HAZID workshops were undertaken to evaluate and summarise the key aspects of safety as it pertained to the installation of nuclear power onboard a vessel. The workshops included participation from a multi-disciplinary ABS team, shipowners, a shipyard, an engine manufacturer and a port operator.

4.1 Nuclear Power Safety

Aside from the safety objectives set by SOLAS and other maritime regulations, the most important safety objective for nuclear-powered vessels defined by the regulator (IAEA Safety of Nuclear Power Plants: Design No. SSR-2/1 (Rev. 1) and NRC Safety fundamental SF-1) is *to protect the individual, society and the environment from the harmful effects of ionizing radiation (sic).*

To meet this objective, safety measures must be taken to:

- Control the radiation exposure of crew, people and the release of radioactive material into the environment by providing effective biological shielding.
- Restrict the likelihood of events that might lead to mild or severe nuclear accidents resulting in the release of radioactive sources. Mitigate the consequences of events that can lead to the release of radioactive gaseous, solid, or liquid elements, if they occur.

As discussed in Section 2.1.1.1, there are four primary types of radiation: α Alpha, β Beta, γ Gamma and Neutron. In Figure 14 details are shown of their penetrating power and how to stop them. Typically, a very detailed design-stage shielding calculation is done in line with the requirements of nuclear regulator’s design-verification process.

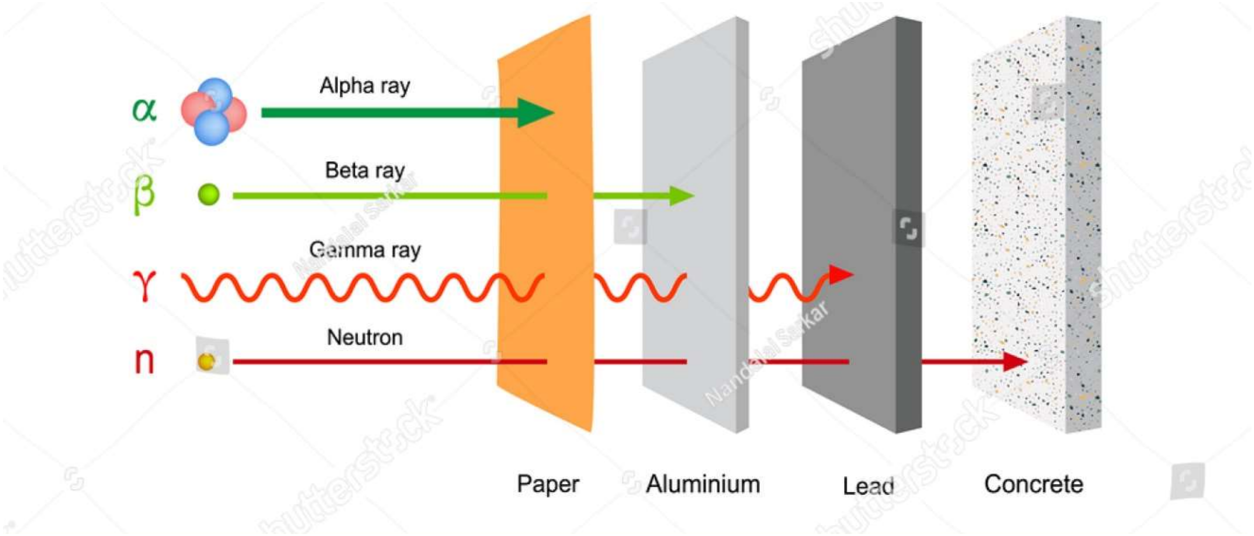


Figure 14. Penetrating power of Alpha, Beta and Gamma rays through paper, aluminium, lead and concrete ©Shutterstock/Nandalal Sarkar

Because ionising radiation has an impact on the shielding materials themselves, their selection – and that of all materials used as '*barriers*' associated with the reactor – are critical in adherence to the '*defence-in-depth*' design principle (see below for details). Effective radiation protection is a combination of good design, high quality construction and proper operation.

To satisfy the safety principles, all operational states of a nuclear power plant (and any associated activities) need to ensure that any exposures to radiation within the installation, or exposures from planned releases of radioactive materials, are kept below the prescribed dose limits and as low as reasonably achievable. In addition, measures need to be taken to mitigate the radiological consequences of any accidents when they occur.

For marine applications the dosage limits for radiation will follow the same requirements that are prescribed in existing regulation developed for stationary nuclear power plants. The measurement of radiation levels and exposure will be actively monitored for crew, passengers and the general public, and for all vessel spaces potentially involved in the normal and off-normal operations of a nuclear reactor. There are many regulatory requirements developed by the IAEA and the NRC to follow. However, the existing regulations were developed for land-based, fixed applications.

As most marine applications would not be stationary, this report will focus on identifying the additional risks that are involved when utilizing nuclear technologies. The '*defence-in-depth*' principle is the foundational safety strategy for the nuclear industry. Adherence to the principle requires several layers of redundant, resilient and independent barriers to prevent the release of radiation/radioactive material to the environment. The objectives of '*defence-in-depth*' are (IAEA, 2024a) (IAEA, 2024b):

- To compensate for human and component failures,
- To maintain the effectiveness of the barriers by averting damage to the facilities and the barriers themselves, and
- To protect the public and the environment from harm if these barriers prove not to be fully effective.

The figure below provides a general overview of '*defence-in-depth*', which is explained in detail in *Basic Safety Principles for Nuclear Power Plants* 75-INSAG-3 Rev. 1, INSAG-12, IAEA:

Strategy	Accident Prevention			Accident Mitigation	
Operational state of the plant	Normal operation	Anticipated operational occurrences	Design Basis and complex operating status	Severe accidents beyond the design basis	Post-severe accident situation
Level of defence-in-depth	Level 1	Level 2	Level 3	Level 4	Level 5
Objective	Prevention of abnormal operation and failure	Control of abnormal operation and detection failure	Control of accidents below the severity level postulated in the design basis	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents, including confinement protection	Mitigation of radiological consequences of significant release of radioactive materials
Essential features	Conservative design and quality in construction and operation	Control, limiting and protection systems and other surveillance features	Engineered safety Features and Accident procedures	Complementary measures and accident management, including confinement production	Off-site emergency response
Control	Normal operating activities		Control of accidents in design basis	Accident management	
Procedures	Normal operating procedures		Emergency operating procedures	Ultimate part of emergency operating procedures	
Response	Normal operating systems		Engineered and safety features	Special design features	Off-site emergency preparations
Condition of Barriers	Area of specified acceptable fuel design limit		Fuel failure; Severe fuel damage	Fuel melt; Uncontrolled fuel melt	Loss of confinement
	Normal		Postulated Accidents	Emergency	

Figure 15. Overview of '*Defence in Depth*' Principle (Source: 75-INSAG-3 Rev. 1, INSAG-12, IAEA)

For marine applications, the compartment boundary, which is the vessel's structure where the reactor is placed, will require more work from the strength and survivability perspectives to defend against internal (e.g., loss-of-coolant induced explosion) and external (e.g., collision, grounding, sinking, etc.) risks.

For a nuclear-powered vessel, additional safety principles would include:

- The safeguarding of the ship, not only with respect to hazards, originating from the operation of a nuclear reactor, but also to those arising from interactions between the nuclear-propulsion plant and the remainder of the ship, including its cargo, the sea and the vessel's environment.
- Restricting the likelihood of events that might lead to a loss of coolant of the nuclear-reactor core, uncontrolled nuclear chain reactions, production of radioactive sources.
- Mitigating the consequences of these events if they occur.

4.2 Risk Assessments for Nuclear Power Plants

For a nuclear power plant, qualitative and quantitative risk assessments will be required; this process starts from the plant's design to its end-of-life disposal. The IAEA defines a safety assessment as:

"The systematic process that is carried out throughout the design process to ensure that all the relevant safety requirements are met by the proposed (or actual) design of the plant. This would include also the requirements set by the operating organisation and the regulators. Safety assessment includes, but is not limited to, formal safety analysis.

The design and the safety assessment are part of the same iterative process conducted by the plant designer which continues until a design solution meets all the requirements for management of safety, the principal technical requirements, the plant design and plant system design requirements (cf. for example Ref. 5) and that a comprehensive safety analysis has been carried out.

Regarding safety analysis, a safety analysis of the design for the nuclear power plant shall be conducted in which methods of both deterministic analysis and probabilistic analysis shall be applied the design basis for items important to safety and their links to initiating events and event sequences shall be confirmed. It shall be demonstrated that the nuclear power plant as designed is capable of meeting acceptable limits for accident conditions. The safety analysis shall provide assurance that 'defense in depth' has been implemented to provide assurance that uncertainties have been given adequate consideration" (sic).

To adhere to these criteria, additional design information and data would be needed for marine applications, which is not currently available. However, in a broader context that recognises that the use of nuclear power on merchant vessels (and other marine applications) is a new concept where technologies are in development, a high level preliminary HAZID is still very valuable. It provides an early-stage opportunity to identify the high-level risks associated with the functional and operational requirements for its use in vessel propulsion and power generation.

The findings will be very valuable for designers and regulators to consider from an early stage, as they may impact upon the proposed technologies and require adjustment. They will be considered in subsequent probabilistic and integrated safety assessments. There are many new risks to be considered because nuclear power generation for merchant marine applications are a comparatively new field. For example, the requirements for unprecedented power-loading variations and ranges for marine will impact the performance of the nuclear power plant; as will accidental conditions such as flooding and sinking. So, an early-stage qualitative risk assessment will become an important component of developing the associated new technologies and applications.

4.3 HAZID Objectives, Process, Scope and Assumptions

This subsection explains the common objectives, methods and scope, etc., for all vessel types included in this study.

4.3.1 Objectives

This HAZID study is to identify the '*high-level*' risks in the design, integration and operation of the nuclear-power plant on a cruise ship.

The study objectives are to:

- Identify potential hazards inherent in the nuclear technology use and power generation
- Identify the potential and new hazards, which will require mitigation introduced by using nuclear electric power generation for on board utilisation and propulsion.

- Determine potential consequences of the hazards.
- Identify safeguards that can prevent hazards, through control and/or mitigation (at each stage of the project).
- Propose recommendations to eliminate, prevent, control, or mitigate the hazards.
- Provide early safety and risk considerations for design and safety-management requirements.
- Provide a clear basis for major accident event screening for future safety assessment studies.
- Evaluate the safety performance compared to current practices under the existing nuclear regulatory framework (NRC and IAEA) and goals and function as defined under IMO and SOLAS.

The findings from the HAZID study will be tabulated in a risk register, which will include:

- Potential hazardous scenarios, including causes, consequences and existing or planned safeguards.
- The risk rankings of scenarios will be evaluated with respect to '*consequence severity*' and '*event likelihood*'.
- Recommendations for an inherently safer design or risk-mitigation measures to reduce the estimated risk.

4.3.2 Common Scope

The scope is to identify risks related to use of lead-cooled fast reactor SMR technology for main power plant on a cruise ship, and a type of reactor that can be defined as VHTR or HTGR (as their operating temperature of approximately 850°C satisfies both definitions) for a bulk carrier and a container ship.

The operating modes that will be considered are listed in the corresponding tables of '*nodes*' for each study.

4.3.3 HAZID Workshop Methodology

A HAZID assessment is an extremely useful tool for performing high-level risk assessments of specific systems. ABS has used this approach in numerous risk-assessment projects, as standalone analyses and to compare similar situations.

The workshops were held via videoconference. After each workshop, a brief review was conducted with the participants. A flow diagram for the overall HAZID process is shown in Figure 16 below.

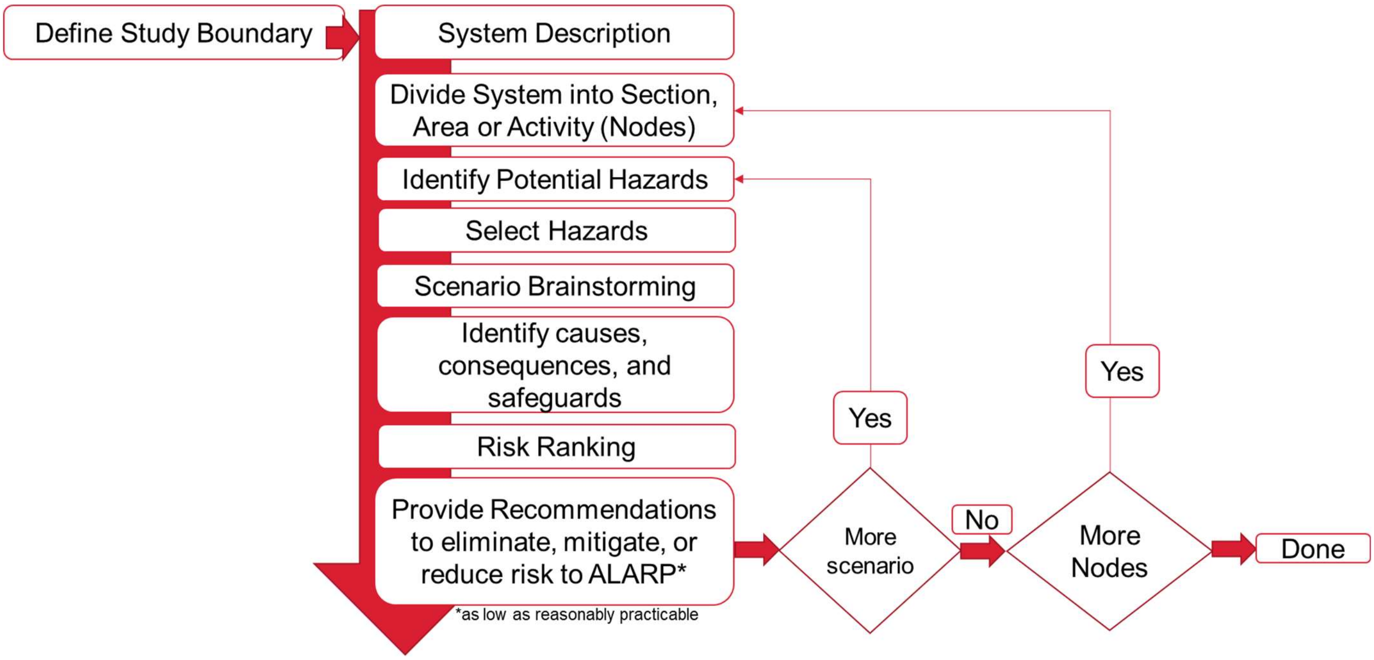


Figure 16. HAZID process.

During the workshops, a '*facilitator*' guided subject-matter experts through a structured discussion to identify and risk-rank the hazards. Participants were asked to provide input on preloaded scenarios (e.g., modifying, adding, or removing risk scenarios) within the hazard register, as well as to discuss the location of the scenario on a risk matrix. These discussions guided the focus areas, nodes and hazards to be considered before the study could be considered complete.

HAZID team members used a workshop environment to identify and analyse the boundaries of the study and to brainstorm the potential '*what if*' scenarios in each node. For clarity, a '*node*' is a clearly defined, manageable section or system to be discussed in the brainstorming activity. '*Guidewords*' are a set of conditions, such as '*high pressure*' or '*vessel collision*', that help to streamline brainstorming activity and identify potential hazards. Guidewords and sub-categorisations were used to identify the potential threats and the present controls that could be used to limit or prevent their impact. Where required, recommendations were generated.

The HAZID analysis was conducted in sessions, which individually addressed each arrangement, process and operation on the vessels.

4.3.4 Limitations

The risk assessment was limited to a '*simplified-HAZID*' analysis following the methodology described in this subsection. In most cases, the use of nuclear technologies for electricity production on board of merchant vessels is at an early concept-development stage, making HAZID the most appropriate way to identify the risks.

This high-level HAZID concept provides a baseline to identify potential nuclear-powered vessel hazards and risks, and to develop recommendations. Design variations -- such as the location of reactor compartment, radiation shielding/control, venting and steam/electrical generation arrangements -- were considered to develop the baselines, but an evaluation of how those variations increased or lowered the general risk environment relative to the base case was not undertaken.

Given that old regulations and restrictions on utilisation by various government laws of nuclear technologies and the lack of specialised studies/information on modern marine applications, the HAZID study will focus on nuclear-reactor support systems, their integration with a ship, radiation control/exposure and functional requirements.

Nuclear technology will have to be certified by nuclear regulatory authorities and the marine community may have to comply with these certifications. The nuclear regulators will certify the reactors for safe operations under normal and off-normal conditions, as well as under postulated design basis accident conditions. The nuclear regulators will certify whether the '*defence-in-depth*' safety principle of a given nuclear reactor design is in compliance with safety standards. This safety principle will be followed, making the independence of the different levels of defence a key element.

The adaptability of a typical nuclear plant designed for land-based applications to comply with the requirements of marine applications is beyond the scope of this HAZID assessment. This issue is recognised, and the developers of nuclear technologies are working on SMR and microreactor technologies, which can be designed for marine applications (5-100 MWe). Most of these technologies are under development and at various levels of technological readiness, so the availability of related information is very limited.

This HAZID assessment will focus on the additional requirements that need to be addressed, those which may or may not be addressed by nuclear regulatory authorities, and which are based on experience from highly regulated, fixed land-based assets with high security protection. Limited information was available for the support systems, which required the experience of subject-matter experts (SME) to guide the analysis of the risks.

It is expected that nuclear regulators will require to update existing regulations and guidance addressing reactor operation and transport/storage of nuclear fuels in the context of marine applications with additional safety studies and engineering analyses as part of their approval processes. The key safety studies required by regulators include deterministic safety analysis (DSA) and/or probabilistic safety analysis (PSA). One major component of nuclear regulation is verification to compliance with existing nuclear regulation and safety assessments.

The workshop teams identified a number of potentially significant hazards related to the nodes for the systems that were analysed. There may be additional hazards that were not identified, so further safety assessments should be conducted for each vessel due to the reactor design, radiation aspects and other risks, which are greatly impacted by the general reactor layout and the type of each asset.

Limitation of the Cruise Ship concept

In this concept, limited information was available for the lead-cooled fast reactor (LFR) technology since the technology provider did not participate in the workshop; so, this study has to broadly rely on SMEs for technological expertise. The knowledge of the SMEs participating in this project, many of whom were familiar with such technology, was key in the identification of risks for use on the passenger ship. Once the specific technology provider is selected, additional risks may need to be evaluated.

It is assumed that the proposed LFR SMR technology will be compliant with safety standards under regulations and guidance of appropriate nuclear regulatory authorities that ultimately will issue a combined license to construct and operate the nuclear reactor.

For radiation control and radiation shielding, the nuclear technology provider and shipyard will work together to provide shielding that meets regulatory requirements and reduces dose rates within the allowable limits deemed acceptable by the nuclear regulator. Shielding and radiation control is also assumed to follow the requirements developed by the NRC and IAEA. Similarly, the shipyard will follow the design principles of '*defence-in-depth*' as required by the regulator authority. The LFR SMR technology utilises a Rankine vapor power cycle with water/steam as the working fluid and the steam-power plant technology is not new and was only examined at very high level except radiation aspect of fluid and in accidental situation.

Limitations of the Bulk Carrier Concept

The concept of integrating the nuclear reactor with the vessel was at the preliminary stage of development, therefore not many details were available. However, information on specific nuclear technology was available.

It is assumed that the proposed VHTR/HTGR technology, which is currently under '*detailed design*' stage (IAEA, 2024c), will be approved and certified by the nuclear regulator. The prototype has been demonstrated in an operational environment qualifying it to TRL 6 (as per NASA definition of TRL) (IAEA, 2024c). However, the design was optimised for stationary applications and specializing it to marine specific applications will need further consideration.

For radiation control and radiation shielding, the nuclear technology provider and shipyard will work together to provide shielding that meets regulatory requirements and stays within the allowable dose rate limits that are deemed safe by nuclear regulators. Shielding and radiation control is also assumed to follow the requirements developed by the NRC and the IAEA. Nuclear designs may or may not utilise energy storage systems represented, for example, by Lithium-ion type electric batteries. These batteries may be utilised to boost the reactor peak power requirements and increase the reactor ability to supply a highly variable electrical load demand for marine application. The provision of Lithium-Ion battery storage was not considered at this stage.

It is also assumed that back up electric power – including that for the vessel uninterruptible power system -- will be provided and installed in safe places for system availability in line with future regulatory requirements.

Limitations of the Container Ship Concept

The concept of integrating the nuclear reactor with the vessel was at the preliminary stage of development, therefore not many details were available. However, information on specific nuclear technology was available.

The limitations are similar to those applicable to the Bulk Carrier Concept, as described above.

4.3.5 Risk Ranking

A risk matrix, found in Appendix II – HAZID Risk Matrix, was used for a high-level evaluation of the risks from each hazardous scenario and their impact on personnel injury and disease, the asset, the environment and reputations. In selected cases where a scenario has multiple impacts -- such as environmental and personnel injury -- the '*overall*' impact is assessed. The process used to rank the risks included a:

- Consequence review: To identify the most credible worst outcome for each scenario, the team determined the outcome's location on a consequence axis factoring.
- Likelihood review: The team determined the location of the undesired outcome along a frequency axis, considering the probability of failure for the preventive, detection and recovery safeguards.
- Risk: The intersection of the likelihood and consequence ratings produces the risk level for that specific hazard scenario.
- Action: The risk ranking was used to help assess whether the current controls and safeguards are adequate; if not, additional safeguards/controls were identified to potentially reduce the risk (or identify areas where further review or analysis would be required to better understand the risk and potential mitigating measures) and recorded as '*actions*' to be taken

4.3.5.1 Grouping Systems/Areas for HAZID

Drawings for each vessel HAZID were reviewed, while recognising that designs integrated with vessel infrastructures were at the preliminary stages and that not all information was currently available. To derive maximum benefit, it was determined that the focus should be on GA-related issues (general arrangement) and operational aspects. In terms of systems and areas, the following were considered (where applicable):

- General arrangement
- Reactor compartment

- Cooling, Steam turbine and auxiliary system
- Radiation control
- Control room
- Ventilation and Venting systems
- Safety systems: fire and gas detection, firefighting, Personal Protective Equipment (PPE)

4.3.5.2 Modes of Operation

For this study, each mode of operation will be considered for the lifecycle of the vessel. The modes included (but were not limited to): nuclear fuel loading/removal, port departure, port entry, cargo loading/unloading in port, voyage (ballasted/loaded), standing by, maintenance, overhaul, emergency/upset situations, simultaneous operations, passenger loading/unloading in port and passenger volumes, dry-docking, disposal of radioactive material, storm condition, etc.

4.3.6 Hazards

At a high level, the HAZID study considers various modes of reactor and vessel operation including system start-up, shutdown, full load/partial load conditions, upset condition, emergency shutdown and standby mode, etc.

Consideration for the nuclear-related hazards will be a key part of the HAZID study as it supports the basis for the development of design concepts and provides a basic understanding from where risk-tolerance criteria can be established to '*As Low As Reasonably Practicable*' (ALARP) requirements.

4.3.6.1 Scenarios

The list of scenarios that guided the team in brainstorming the '*What-If/HAZID*' discussion can be found in the section below. The nuclear technology-related hazards were the focus.

4.3.6.2 Global Hazards

Below is a list of risks that were considered in the HAZID workshop to develop proper risk identification for the global hazards that might evolve from system integration.

- Natural and Environmental Hazards - Climatic extremes, lightning, seismic events, erosion, subsidence, etc.
- Movement/Floatation Hazards - Grounding, collision.
- Effect of Facility on Surroundings - Proximity to adjacent installation, proximity to transport, proximity to population, etc.
- Effect of Manmade Hazards - Security hazards, social/political unrest, etc.
- Infrastructure - Communication, supply support, mutual aid, emergency services, etc.
- Environmental Damage - Discharges to air/water, emergency discharges, water disposal, etc.
- Health Hazards – Disease, carcinogens, toxic effects and occupational hazards.

Note: In several cases for the listed 'guidewords', there may not be a specific impact on that hazard category/guideword (either direct or indirect), in which case a record of 'No significant issue identified' or 'No direct or indirect hazardous impact, not considered further' was noted.

4.3.6.3 System Hazards

- Process Hazards - (flammable/toxic fluids), e.g., the release (loss of containment) of flammable inventory (for each area of the systems), ruptures, start-up/shutdown issues, etc.
- Utility Hazards - e.g., Fire-water system, fuel oil, heating/cooling mediums, power supply, drains/sumps, air, nitrogen, chemical injection, etc.
- Venting: normal and abnormal (e.g. air circulation may have radiation potential)
- Ventilation: normal and abnormal (air circulation)
- Maintenance Hazards - e.g., Maintenance philosophy, provisions for safe maintenance, etc.

- Interface Issues – process, instrumentation, utilities, structural, etc.:
- Emergency Response - Access/egress, communication (alarms [audible/visual], call-points, CCTV, radio), fixed/portable fire-fighting equipment
- Other Hazards - Lifting operations, structural failure, rotating machinery, cold/hot surfaces, etc.
- Other '*issues of concern*' or items requiring coverage as required.

4.3.6.4 Nuclear Technology Hazards

Key nuclear characteristics and related hazards to be considered are:

- Licencing
- Regulation
- Radiation & Radiation shielding.
- Coolant Leakage (Lead)
- Uncontrolled Reaction
- Potential Energy & Kinetic Energy
- Nuclear Waste Storage, Handling, & Disposal
- Loss of Essential Supporting Systems
- Fuel Charging & Refuelling
- Removal of Spent fuel.
- Decommissioning
- Training
- Security
- Terrorism and Hijacking
- Emergency Response
- Impact on passengers onboard, embarkation, disembarkation, normal movement
- Impact on Ports
- Human Factor(s)

4.3.6.5 Study Failure Causes

4.2.6.5.1 Equipment Failure Causes

- Wear and tear
- Erosion
- Stress and Strain
- Fatigue
- Corrosion
- Impact
- Fire

4.2.6.5.2 Process-Failure Causes

Selected guidewords and key parameters will be used to prompt the HAZID team to show all probable causes that may lead to a hazard.

The guideword/parameter combinations are based on deviations from the principle parameters of the process, as these could lead to the worst hazardous conditions.

The guideword/parameter combinations proposed for this study are named below:

- No/Low Flow.
- More/High Flow.
- Reverse/ Misdirected Flow.
- More/High Pressure.
- Less/Low Pressure.
- More/High Temperature.
- Less/Low Temperature.
- More Level.
- Less Level.
- Less Viscosity.
- Compositional Change.

- Contamination.
- Relief Failure.
- Instrumentation Failure.
- Sampling Failure.
- Corrosion/Erosion.
- Service Failure.
- Maintenance.
- Start-up and Shutdown.
- Static.
- Outside Conditions.
- Release.
- Human Error.
- Loss of Power.

4.3.7 General Assumptions – Applicable to all HAZID studies

There were several critical assumptions made about the workshops based on current documentation; some were deemed of such importance to be considered '*assumptions*' rather than '*recommendations*'. Most were considered 'safeguards' in the workshop records. The most common critical assumptions are listed below. Any assumption specifically applicable to a particular vessel type was listed within its HAZID section.

- The vessel will be designed to built-in compliance with class and statutory regulations.
- The nuclear system and reactor will be certified by nuclear regulatory agency (the NRC in the US, and other international nuclear regulatory authorities etc.); class or maritime regulators will not be involved except if additional marine risks need to be considered by those agencies during the approval process.
- Nuclear technology will be certified for marine applications for each type of vessel.
- The operation of the nuclear reactor will be governed and controlled by the nuclear regulatory authority and the technology provider.
- Licencing for operation and entry into ports will be control by governmental agencies and the nuclear regulator.
- The nuclear technology considered are SMR technologies, which are at a developmental stage and at various levels of technological readiness.
- Nuclear fuel loading and removal of spent fuel will be licensed by a nuclear regulator and handled by the reactor provider and/or a licenced operator.
- Allowable limits to radiation exposure will follow regulatory guidelines, such as those provided by international regulatory authorities (e.g., the NRC) and utilisation of nuclear materials and technology are limited to peaceful purposes as monitored by the IAEA.
- Manning for the operation of nuclear technologies will be governed by the shipowner and/or the technology provider with training certified by the nuclear regulatory authority issuing the licence to construct and operate the reactor.
- Information on the support and auxiliary systems is currently not available, so it will be considered later in the developmental stage.
- Bunkering for liquid fuel will be performed in accordance with existing practices.

4.4 HAZID Results – Findings and Recommendations

All high-level risks were considered and the safeguards required by codes/standards/regulations were identified; the risk rankings were developed and listed in the risk register's appendix for the vessel types.

They were all listed for consideration and may help to inform future prescriptive requirements and to develop safer designs and arrangements. The recommendations are listed for each vessel in the appendix:

- Appendix III – List of Recommendations – Cruise Ship with
- Appendix V – List of Recommendations – Bulk Carrier with
- Appendix VII – List of Recommendations – Container Ship with VHTR/HTGR

As nuclear technology is developed for land-based applications, re-assessing those technologies for marine applications is one of the main goals of the HAZID; A high-level summary of the important recommendations which will require further study and research is listed below:

- Since issues such as onboard equipment density/congestion/space availability will be challenging, radiation shielding, and exposure prevention need to be further investigated; the proximity of crews in permanently manned spaces is much closer than for typical land-based applications.
- Design and material selection for radiation shielding and the insulation of the reactor and its compartment should cover scenarios that include a total flooding of the compartment, or an alternate justification should be provided.
- Considering radioactivity, end-of-life disposal is to be considered during the ship-design process to facilitate safe handling, removal and disposal of any parts, equipment and materials that might be contaminated with radiation.
- When assessing the possibility of a fire breaking out inside the reactor compartment and the potential for radiation leakage, the principles of the initial vessel design should focus on minimising the possibility of fire by recommending the appropriate materials. The strength requirements for reactor compartment against explosion or accident have yet to be determined; there will be further research to examine the regulatory requirements.
- Appropriate means are to be provided to fight fire in reactor and machinery compartment and structural design is to consider fire load in design.
- Further study is to be conducted on the location of the nuclear reactor to provide the highest possible protection against any external risks (e.g. collision, flooding, grounding, dropped object etc.).
- The reactor and its systems should consider the potential impact of accelerations such as induced by seismic events etc. during the design stage, but also while the vessel is in a shipyard, dry-dock, port or channel etc.
- Vessel design and construction should consider the sequences for installing a nuclear reactor, for fuelling/refuelling it (if applicable), and for removing the reactor module (during refuelling, maintenance, or replacement [some nuclear designs require refuelling every 8-10 years]), in accordance with guidance set by the technology provider. Due to licencing issue at shipyards and the requirements of regulatory agencies, the installation of a reactor and its system may occur at a different location. This may require special provisions for the vessel section where the reactor module is to be installed (to facilitate construction) and maintenance and salvage sequences; this may in turn pose challenges for construction and design.
- Vessel applications for nuclear technologies are likely to impose additional loads, on the nuclear propulsion plant (NPP), as well as its machinery and systems (primary, secondary and auxiliary). Considerations should be given to the vessel's various operational modes (normal, upset and accidental

operating conditions), motion and dynamic loads, vibrations, structural flexibility, marine environment, systems and equipment spacing, collision, stranding, grounding, capsizing, heavy listing, sinking in shallow and deep waters, compartmental flooding and earthquake loads during dry-docking.

- The reactor and its systems supports, and structure should be designed to ensure it stay in place during dynamic loads, the vessel's maximum heel/rolls, sinking, capsizing, flooding, of the reactor compartment, etc.; anti-floatation support and additional structures should be considered.
- Vessel routings and traffic should be studied to minimise the probability of grounding, striking rock formations, collisions.
- A probabilistic damage-stability assessment should be conducted to account for the potential effects of hull penetration and to test the '*crash worthiness*' of the vessel and its nuclear system.
- Consideration should be given to designing the reactor and its systems for the marine environment, and operation in damage condition (e.g., during a 22.5° roll and ±10° heave, or 30° damage etc.]
- There is the possibility of a reactor compartment flooding, so the vessel's design needs to consider this possibility. Vessels are currently designed to IMO/SOLAS/Class requirements for damage penetration; this needs to be reconsidered from the perspective of the additional safety measures required due to presence of nuclear systems and radiation risk.
- The changing conditions from a vessel's submergence and the ability of reactor barriers to withstand those potentially crushing pressures (and other flooding scenarios) need to be considered to prevent barrier crushing and minimise the possibility of radiation leakage; this includes all penetration into the nuclear compartment and its reactor (including cabling).
- The possibility of steam explosions during flooding (if seawater contacts the hot surfaces of the reactor) should be further investigated and mitigation measures are to be taken to minimise the potential damage.
- Unusual vessel motions can produce very high sloshing loads for liquids inside the reactor vessel and auxiliaries for reactor designs relying on water, heavy water, lead, sodium or salt as working fluid and coolant. These motions may have the potential to damage the reactor core/vessel and its internal control mechanisms, components and machinery. Reactor designs will need to consider these loads and their impact on the reactor and its components for the life of their designs. As this could greatly impact safety, detailed inspection, maintenance and monitoring regimes should be considered.
- The reactor and its systems should be designed to meet the design life of the vessel (typically, 30 years); the possibility of reusing the reactor for another project should be investigated to potentially improve economics.
- Any structures or materials with elements that could be activated by exposure to neutrons should be avoided; the current related regulations should be followed.
- The installation and removal of onboard nuclear power plant while it is loaded with fuel should be further studied, along with procedures developed for all possible cases related to design and construction.
- A study of '*dropped objects*' should assess all phases, including construction, installation, maintenance and removal to prevent damage to the reactor and its systems.
- For cargo and container ships, etc., cargo-handling operations bring dropped-object risks that need to be further investigated.
- Detailed procedures for sea and reactor trials should be developed with the original-equipment manufacturer, shipyard, owner and regulator.

- Emergency-shelter plans should be considered, including any port restrictions. International legislation will be needed.
- An environmental impact study for flooding, sinking and/or capsizing events as well as loss of reactor containment should be conducted to consider the impact of radiation leaks on the environment and marine life.
- The reactor will need to be certified for use in a marine environment. The maritime industry will have to develop the functional lifecycle requirements for reactors to operate in such environments.
- A process for selecting the appropriate shipyards (to construct and service) these specialised vessels will require a detailed study that includes nuclear regulation, security and proliferation matters, design and construction requirements for NPP-related systems, licencing requirements for the OEMs and regulatory agencies, including specialised licencing requirements.
- Inspection and maintenance regimes for the reactor and its systems should be further studied as most equipment needs to be installed in tight spaces and often operate close to each other.
- Nuclear-powered vessels travel internationally where there are bespoke regulations related to export, licencing, non-proliferation, etc. Legislation will need to be developed that allows vessels to travel between countries or jurisdictions; similarly, standards and regulations governing technology owners and OEMs will need to facilitate trade and trading routes.
- Marine salvage operations should be considered from the design stage. Detailed operational procedures and emergency plan are to be developed for salvage companies to protect the environment and people from exposure to radiation. Salvage operations for specific vessel designs and dose rates (radioactivity) should be further investigated, and proper procedures and training instructions developed for the salvage crew. Concerned regulatory agency, port/local authority and technology provider is to be consulted in plan development. Salvage operations will need to be planned for the vessel's operational lifecycle and detailed procedures developed.
- Safe operation of nuclear reactors requires the potential for human error to be reduced as much as possible, so a detailed human-factor engineering study will be needed.
- Nuclear regulations and guidance from technology providers suggests that specialised training will be needed to operate NPP; special accreditation also will be needed from the regulator. A special training programme in cooperation with regulators and technology providers should be developed, as well as a certification requirement for crews and operators.
- Given that the maritime industry has no-to-limited knowledge pertaining to nuclear construction and quality requirements, more training and related cooperation should be developed between shipyards, specialised equipment providers, regulators and class societies.
- Legislation requirements should be developed for external threats and risks such as cyber threats, hijacking, piracy, terrorism and attacks involving flying objects (missiles, planes, drone, etc.). Vessel designers and technology developers will need to consider these threats for the design and lifecycle operation of a vessel for all modes of operation.
- Emergency plans for all levels of radiation leaks are to be developed and incorporated into the vessel design.
- Developing maritime regulations for nuclear-powered vessels will be a long and challenging process. The maritime industry and interested parties will need to engage nuclear regulators and government agencies from the beginning to initiate the rule-making process.

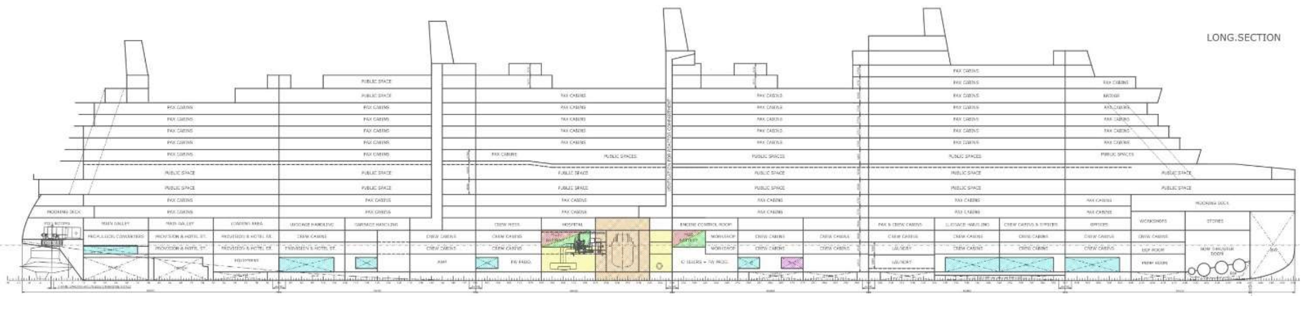
4.4.1 The Nuclear-Powered Cruise Ship

The cruise ship in this study is presented as being powered by onboard lead-cooled fast reactor (LFR) SMR technology. The proposed vessel is a typical cruise ship with electrical propulsion and a capacity for 9,000 passengers and crew. Figure 17 provides the proposed general arrangement of the ship. Figure 18 provides the general arrangement and details of the nuclear compartment. The concept considers two independent reactors to maintain power in scenarios where one of the reactors may become unavailable. Table 11 below presents the most important particulars.

Table 11. Most important particulars of the concept.

Reactor	2 x Lead Fast cooled SMR Reactors	Power 45 MWe/110 MWt Fuelled for 25 full-power reactor-yr Diameter 5.5m Height 8m Weight 1,000 tonnes (200 tonnes + 800 tonnes lead)
Steam Turbine	4 x Steam Turbines	Power 25 MWe Steam interconnector between reactors
Diesel Generator	none	
Auxiliary Generator	One Auxiliary Diesel Generator	Power 6MWe Not configured to power propulsion
Battery	2 x Batteries Power	5MWh from 4 x 1.25 MWh
EDG	1x EDG	
Propulsion	3 x Azipod Propellers	Power 20MWe

The nuclear technology is installed in mid-ship near to the bottom of the vessel. The ventilation from the space containing the nuclear reactor and steam turbine is routed to the top of the vessel, in mid-section, through a funnel.



Reactor compartment & cofferdam around the reactor compartment. Limited access.

Steam turbines, condensers and other supporting equipment.

Figure 17. General arrangement of a proposed cruise ship with nuclear reactor

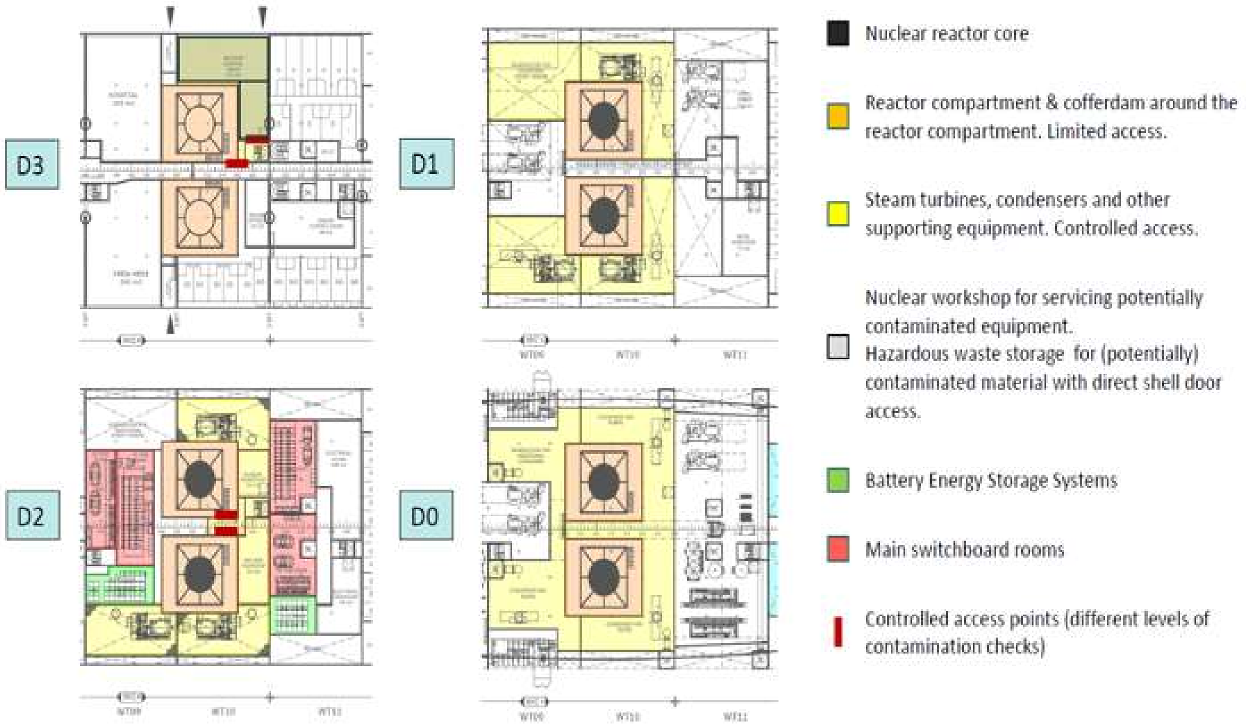


Figure 18. General arrangement and details of nuclear compartment

The LFR SMR technology utilises a Rankine vapor power cycle with water/steam as the working fluid. Steam plant turbines and generators are installed next to reactor room. The reactor and all piping and components that have the potential to emit radiation will have insulation and shielding for radiation. To attenuate neutrons emitted from the pressure vessel, the wall in the containment room will be made from steel and the cofferdam will be filled with borated water, concrete or other suitable materials. The materials selected should contain no elements that can be activated by neutrons. This will be assured at the design stage, and it will need to meet the requirements of the regulatory authority (e.g., NRC) for radiation shielding, material selection and radiation monitoring. When the reactor is functioning, radiation in the reactor room should be maintained within the allowable limits set by the regulator; generally, only radiation workers and personnel with dosimetry equipment should be allowed in the room when the reactor is at power.

4.4.1.1 Assumptions – Cruise Ship

In addition to the assumptions listed in Subsection 4.3.7, other assumptions from the cruise ship workshop are listed below:

- As the support systems for marine applications of an LFR reactor are not properly defined, it is assumed that reserve spaces provided will be sufficient for additional systems.
- Any vents or ventilation from the reactor compartment -- or from machinery spaces related to nuclear -- will be double-walled with the annulus pressurised and with appropriate shielding to minimise any radiation leaks.
- The proposed vent or ventilation discharge from the reactor compartment will be further studied.
- The reactor will be designed to match the operational load profiles of the ship.

- Propulsion and powering arrangements will comply with '*safe-return-to-port*' regulations during the design stage.
- The supply of nuclear fuel is outside the scope of this study.
- It is assumed that the reactor will be designed for marine applications on a cruise ship.
- The compartments for the reactor and related machinery will be provided with radiation shielding; this is to be determined by the designer at later stage.
- Currently, a cofferdam around the reactor compartment was proposed, which may be filled with borated water or concrete.
- In places where radiation can be anticipated, the reactor's pressure boundary and piping will have appropriate shielding. Even so, some neutrons can be expected to escape and be captured by the steel wall and cofferdam. Reactor compartment and machinery compartment temperature management, ventilation and vent arrangement will be of a bespoke design and sufficient radiation monitoring and filtering will be provided.
- The potential for passenger exposure to radiation was considered, but more information will be needed from the technology provider

4.4.1.2 Conclusions and Recommendations

For the workshop's recommendations to be feasible, conditions were assumed and listed in the assumption section. For some nodes, at the time of this writing, there was not enough information available, precluding the attribution of a risk ranking for some hazards. However, the activities associated with those scenarios were discussed and, where feasible, recommendations were made.

The HAZID register identified the hazards and documents the recommendations from the workshop's discussions. The results of the workshop are to be analysed and incorporated into future concept developments. A complete list of recommendations and the HAZID register are in Appendix III – List of Recommendations – Cruise Ship with and Appendix IV – HAZID Register – Cruise Ship with . System- and operational-level nodes, along with the scenarios associated with each node, were discussed. When the risk was considered '*high*' or '*extreme*', recommendations were developed.

The HAZID register identifies the hazards and documents the recommendations from the workshop's discussions. Forty-two (42) '*extreme*' and fifty-four (54) '*high*' risk scenarios were identified that will require mitigation measures (design improvement, dedicated interfaces, preventive/mitigating barrier, procedural measure etc.) to bring risk down to ALARP level. Refer to summary in Table 12 below.

Given the lack of clear regulatory guidance, law restrictions, combined with the challenges associated with the implementation of new technologies etc. many risks, currently grouped under high and extreme ranking, will require more detailed investigation to accurately quantify, confirm, mitigate or resolve them.

Table 12. Cruise ship - HAZID risk-ranking summary.

Key system level HAZID nodes	Risk Ranking of Hazards Identified			
	Low	Moderate	High	Extreme
General Vessel Arrangement		1	3	
Licencing & Approval Process				
Ship Construction				
Global Hazards		5	22	24
Global Hazards - Ship Operation				
System Hazards			2	4
System Hazards - Power & Propulsion		1	3	4
System Hazards - Vent & Ventilation		8	5	
Maintenance and Inspection				2
System Hazards – Dry-docking			6	1
System Hazards - Dropped Object & Energy Release			2	1
System Hazards - Firefighting System (FFS)			3	
Nuclear Technology Hazards			6	6
Nuclear Technology Hazards - Lead Fast Reactors		1	2	2
Nuclear Technology Hazards - Impact on Ports				
Nuclear Technology Hazards - Ship Recycling & Salvage				
Finance Risk & Liability				
Total	**-**	**16**	**54**	**44**

There were many risks identified as '*extreme*' due to lack of information and the design being at a very early stage of development. It was concluded that -- with recommendations identified -- those risks can be addressed. There are LFR SMR nuclear technology risks and challenges, which need to be addressed first, and the technology will need to be qualified for use in marine applications. Appendix III – List of Recommendations – Cruise Ship with LFR provides a summary of the recommendations from the HAZID register with applicable nodes for the HAZID scenarios.

Considering that the design level is at a very early stage for the vessel and nuclear technology, the majority of the high-level risks, findings and recommendations are listed in Subsections 4.4 and 4.5. These recommendations are applicable for the three vessel types. Therefore, it is recommended that in the future more detailed studies will be carried out on individual vessel types and specific recommendations will be based on detailed integration design of the reactor to the vessel.

4.4.2 The Nuclear-Powered Bulk Carrier

The bulk carrier is presented as powered by an onboard reactor design based on the VHTR/HTGR technology[17]. The vessel is an existing typical bulk carrier of 208,000 DWT. Figure 20 and Figure 21 provide the general arrangement and details of the compartment that would be dedicated to house the reactor components altogether with radiation shielding and auxiliaries. The concept proposes to install two HOLOS Monolithic (HOLOS-Mono) integral reactor units as these are optimised to supply 10 MWe nominal power each for approximately 8 years without refuelling. The HOLOS-Mono is a scaled-up version of the HOLOS-Quad configuration. These two units would be coupled as parallel synchronised electric generators to supply variable power in place of the main engine. Each unit represents one fully independent operational reactor capable of producing load-following power, currently optimised for power ramp up/down rate of 1 MWe/minute. Table 13 below presents the most important specifications.

Table 13. Vessel power & propulsion data

Reactor Module (integral monolithic – 2 independent reactor units)	2 Units	Microreactor (22 MWth – 10 MWe) / each
Main Engine (at present design)	1	B&W 6G70ME-C9.2
MCR (at present design)	-	16,200 kW @ 73 rpm
NCR (at present design)	-	12,300 kW @ 66.6 rpm

The vessel's existing auxiliary generator and EG will be retained. If required, an auxiliary electric storage system (ESS) represented by Lithium-Iron Phosphate battery system (or equivalent) will be installed to increase the load-following rate (e.g. should vessel operations require higher than 1 MWe/minute power rate increase) and efficiency of the system, while providing black-start and ballast power for each of the units to start independently of the availability of alternate onboard electric power sources.

The reactor units will be installed in the engine room, one at the port and one at the starboard side. Both units will be installed in individual reactor compartments. Detailed information for reactor design is provided below.

10 MW_e Containerised Electric Power Unit

The HOLOS-Mono configuration supplying 10MWe is designed by HolosGen to entirely fit in a standard ISO 40' container. Figure 19 shows a typical general arrangement of such a reactor. The main characteristic is that the reactor core is loaded with a self-contained, qualified, Accident Tolerant Fuel referred to as TRISO fuel with a thermal-to-electric power conversion system integrated and sealed within the primary pressure vessel forming the high-pressure boundary (A) as shown in Figure 19. Helium, with a relatively low inventory, represents the core-coolant and working fluid of the power conversion system. The primary pressure vessel is welded shut (no seals) and further surrounded and sealed by a secondary pressure vessel representing the low-pressure boundary (B), also containing Helium at low pressure to represent a redundant and independent additional barrier. The combined primary and secondary pressure vessels house all the components (eliminating the traditional balance of the plant represented by most nuclear technologies) with hydraulic ports for the connection to the vessel cooling water and representing the footprint of the fully operational HOLOS-Mono generator unit. This unit is fully comprised within the container with standard dimensions forming a controlled pressure boundary (C). The atmosphere within pressure boundary (C) is monitored and passively or actively vented to atmosphere during normal operations. The container is installed inside the reactor compartment (D) which is sealed during unit operations. Although TRISO fuel does not require external containment (the fuel itself is classified by regulatory authorities as '*functional containment*'), the HOLOS-Mono features multiple additional pressure boundaries to further enhance safety in support of the '*defence-in-depth*' principle. The TRISO fuel forming the

[17] As explained, this type of reactor can be defined as VHTR or HTGR (as their operating temperature of approximately 850°C satisfies both definitions).

core is therefore further contained within the primary and secondary pressure boundaries (A) and (B), which are also comprised and monitored within the pressure boundary (C). Appropriate shielding will be installed to surround the areas in the proximity of the core outside of pressure boundary (C) along with supports arrangement to mechanically couple the HOLOS-unit and the shielding structures within the reactor compartment. The shielding materials and thickness ensure a dose rate reduction to safety margins in compliance with regulatory requirements to enable radiation workers to operate, if necessary, within the reactor compartment during unit power operation.

The reactor compartment is provided with necessary ventilation and instrumentation to detect potential radioisotopes (radiation) and filters to trap and contain said radioisotopes through operations in compliance with safety standards as, for example, adopted for merchant fleets of nuclear-powered ice breakers. Pressure boundary (B) is also provided with internal shields to attenuate irradiation effects during power operations and decay-heat passive removal. The pressure boundary represented by Container (C) is provided with a vent system to evacuate the Argon gas, normally contained in the air mixture, that might undergo irradiation. Radioactive Argon results from neutron irradiation and decays naturally with a half-life of less than 2 hours. Provisions during installation of the shields prevent air from circulating in the proximity of the reactor pressure vessel sections housing the core. Similar provisions are applied to the reactor compartment housing the reactor(s) equipping merchant nuclear-powered icebreakers and navy nuclear-powered vessels (safely operated for several years). During operations, a cooling fluid is thermally coupled via heat exchangers (HEX 1 and HEX 2) to the Brayton power conversion system for the purpose of rejecting thermal energy to the environment. For the application shown in Figure 19 , the cooling fluid is clean water normally utilised for similar purposes (cooling of the combustion engine equipping the ship). The black-start and ballast batteries, in this design are integrated with the Digital Instrumentation & Control system to enable autonomous start of the unit, power conditioning and support to load follow electric power production. HOLOS-Mono is currently optimised to maintain a net unit efficiency >40% for power demand >3MWe. The cooling water utilised by the integral power conversion system through heat exchangers HEX 1 and HEX 2 is only thermally coupled to the Helium circulating within the primary pressure boundary (A). The HEX 1 and HEX 2 locations are protected by internal shields to reduce irradiation effects. The cooling water will be provided by the marine system with intermediate circuit through a separation Intermediate-Heat Exchanger (I-HEX). This additional '*defence-in-depth*' barrier minimises the possibility of radioisotope transport through the Helium and through the HEX 1 and HEX 2 into the cooling water without possibility of physically mixing these two fluids.

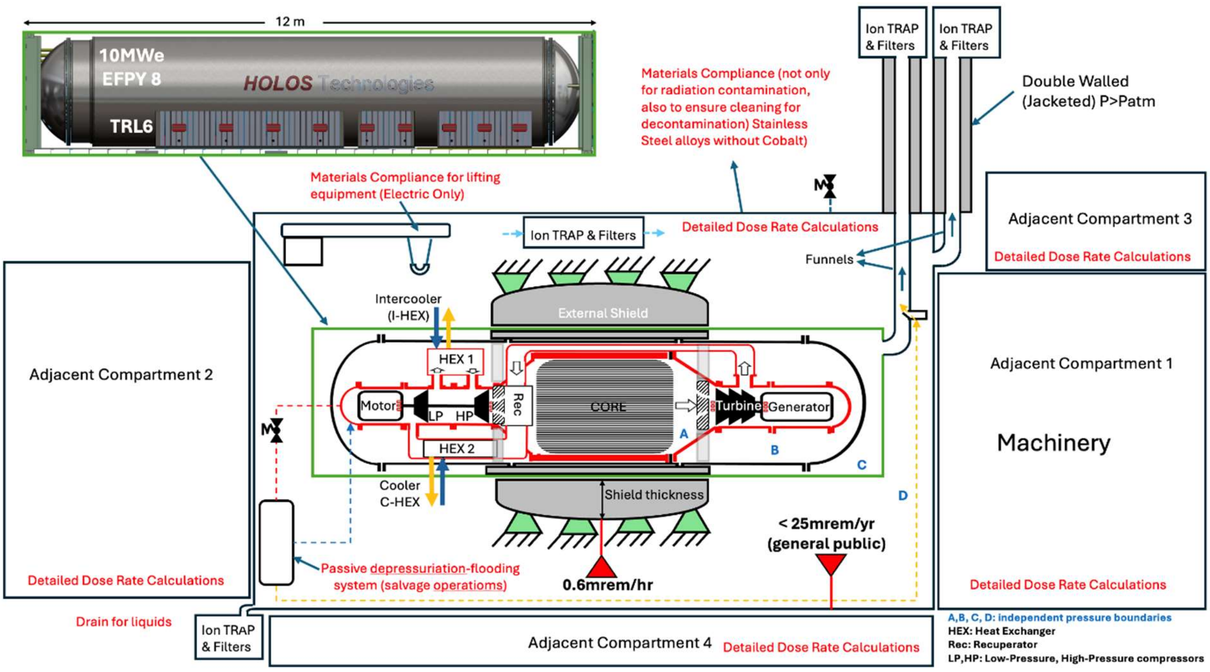


Figure 19. HOLOS-Mono, 10 MWe fully integrated reactor unit general arrangement

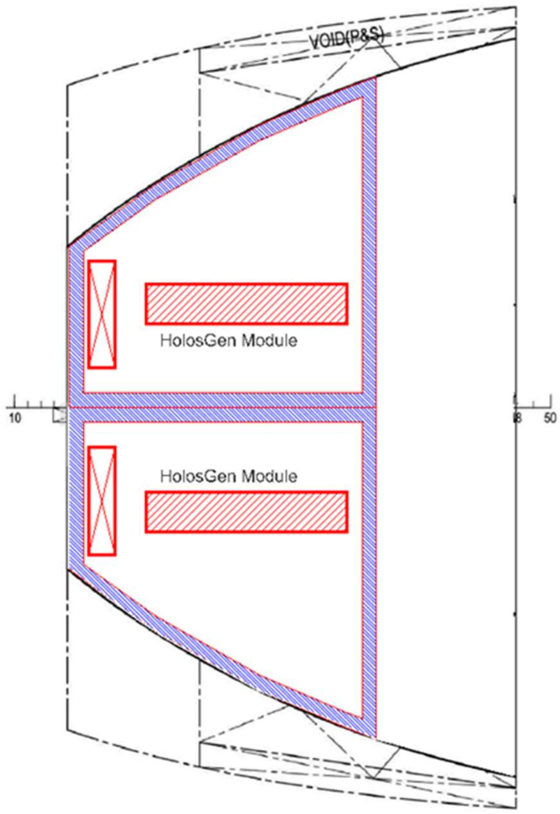


Figure 20. Extract of vessel's general arrangement (E/R Deck 3)

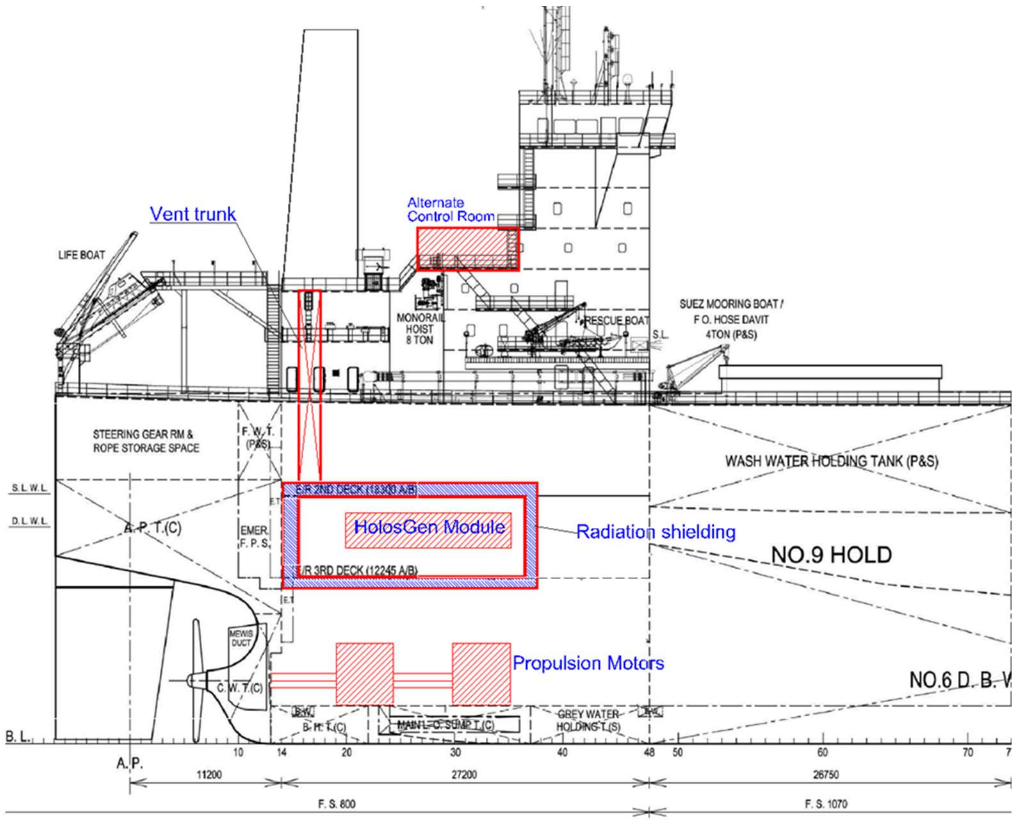


Figure 21. Microreactor's arrangement

4.4.2.1 Assumptions – Bulk Carrier

In addition to the assumptions listed in Subsection 4.3.7, other assumptions from the nuclear-powered bulk carrier workshop are listed below:

- The vessel will be converted for electrical propulsion in compliance with class rules.

- The auxiliaries to support the reactor operations as, for example, water cooling supply, are subjected to the provisions and technical requirements currently adopted for the cooling systems of on-board combustion engines. The water-cooling system to support reactor operations needs to be better defined, to ensure, for example, that the water mass-flowrate and environmental temperatures are compatible under extreme conditions (subzero temperature operations, water freezing induced blockage etc.).

- Black-start and ballast batteries are part of the HOLOS-Mono equipment; however, the capacity of this Electric Storage System may have to be increased to satisfy ship-specific requirements (e.g., rapid power ramp up from cold start up conditions). These aspects may not be considered at this initial stage of integrating HolosGen's design with vessel equipment.

- There is no radiation outside of the reactor compartment during normal, off normal and decay heat removal operations. The reactor design retains radioisotopes even at temperatures in excess of 1600°C. HOLOS-Mono operating temperature is 850°C, and under design basis accident scenarios involving loss of Helium cooling the maximum temperature briefly reached is approximately 1300°C. Further quantifying risks associated with potential radioisotopes migration from TRISO fuel to the environment under ship-specific operations and marine environment design-basis accident scenarios will require specialised studies. As HOLOS-Mono features several additional barriers to the migration of radioisotopes from TRISO fuel to the environment, risks associated with scenarios involving radioactive leakage are inherently reduced. It is assumed that radiation outside the reactor compartment will be none, or within safety margins under credible postulated accident conditions.

4.4.2.2 Conclusions and Recommendations

For the workshop's recommendations to be feasible, conditions were assumed and listed in the assumption section. For some nodes, at the time of this writing, there was not enough information available, precluding the attribution of a risk ranking for some hazards. However, the activities associated with those scenarios were discussed and, where feasible, recommendations were made.

The results of the HAZID workshop are to be analysed and incorporated into future concept developments. A complete list of recommendations and the HAZID register are in Appendix V – List of Recommendations – Bulk Carrier with and Appendix VI – HAZID Register – Bulk Carrier with VHTR/HTGR. System- and operational-level nodes, along with the scenarios associated with each node, were discussed. When the risk was considered '*high*' or '*extreme*', recommendations were developed.

The HAZID register identified the hazards and documents the recommendations from the workshop's discussions. System- and operational-level nodes, along with the scenarios associated with each node, were discussed. Due to the very early stage of the hazard identification process for the bulk carrier concept and HOLOS-Mono design configuration to satisfy marine-specific requirements , thirty-five (35) '*extreme*' and sixty-eight (68) '*high*' risk scenarios were identified that will require mitigation measures (design improvement, dedicated interfaces, preventive/mitigating barrier, procedural measure etc.) to bring risk down to ALARP level as the design progresses to satisfy the requirements of marine-specifics applications. Each of those has recommendations listed in the HAZID register, some of which have already been considered by the designer during concept development and validation activities. Refer to summary in Table 14 below.

Given the lack of clear regulatory guidance, law restrictions, combined with the challenges associated with the implementation of new technologies etc., many risks, currently grouped under high and extreme ranking, require more detailed investigation to accurately quantify, confirm, mitigate or resolve them.

Table 14. Bulk carrier - HAZID risk-ranking summary.

Key system level HAZID nodes	Risk Ranking of Hazards Identified			
	Low	Moderate	High	Extreme
General Vessel Arrangement				
Licencing & Approval Process				
Ship Construction				
Global Hazards		3	28	18
Global Hazards - Ship Operation			2	
System Hazards		4	9	1
System Hazards - Power & Propulsion			2	2
System Hazards - Vent & Ventilation			9	3
Maintenance and Inspection				2
System Hazards - Dry Docking			3	
System Hazards - Dropped Object & Energy Release				
System Hazards - Firefighting System (FFS)			1	2
Nuclear Technology Hazards		2	13	6
Nuclear Technology Hazards – Gas-Cooled Reactors			1	1
Nuclear Technology Hazards - Impact on Ports				
Nuclear Technology Hazards - Ship Recycling & Salvage				
Finance Risk & Liability				
Total	**-**	**9**	**68**	**35**

Based on the current initial stage of risk assessment (preliminary HAZID) for nuclear technology integration with merchant shipping operations, it was concluded that -- with the recommendations identified -- those risks can be addressed. As for all types of nuclear technologies (e.g., gas-cooled, liquid metal-cooled, with fuel melted in a solution etc.), there are VHTR/HTGR-specific microreactor technology risks and challenges which need to be addressed in the context of marine-specific applications and operations – the design is currently optimised, addressed and satisfied the safety requirements for land-based applications. However, marine environment-specific design basis accident scenarios need to be better identified.

Appendix V – List of Recommendations – Bulk Carrier with provides a summary of the recommendations from the HAZID register with applicable nodes for the HAZID scenarios.

Considering that the design integration or retrofitting and supporting activities involving any nuclear reactor design selected for installation, un-install and operation within merchant vessels is at a very early stage for vessel builders and operators, the majority of the high-level risks, findings and recommendations have the tendency to be conservative as listed in Subsections 4.4 and 4.5 and will require a more in-depth analysis with cooperation between naval designers and operators, reactor designers and risk assessors to better understand the operational requirements and limitations). These recommendations are applicable for the three vessel types. Therefore, it is recommended that in the future more detailed studies will be carried out on individual vessel types and specific recommendations will be based on detailed integration design of the reactor to the vessel.

4.4.3 The Nuclear-Powered Container Ship

The container ship is presented as powered by onboard VHTR/HTGR technology. The proposed vessel is a typical container ship of 14,000 TEU. Figure 22 provides a generic sketch of the ship. Figure 23 and Figure 24 provide the general arrangement and details of the nuclear compartment. The concept considers three independent reactors to maintain the availability of power during a reactor failure. Table 15 below present the most important particulars.

Table 15. Vessel power & propulsion data

Reactor Unit (HOLOS-Mono)	3 Modules	Microreactor (22 MWth – 10 MWe) / each
Main Engine (at present design)	1	Hyundai-MAN B&W 8G95ME-C9.5 (Tier II)
MCR (at present design)	-	54,960 x 80 R.P.M.
NCR (at present design)	-	49,464 x 77.2 R.P.M.

Nuclear technology is the same HOLOS-Mono VHTR/HTGR scalable reactor as described in Subsection 4.4.24.4.2.1.

For this container ship accommodation is forward and away from the compartments housing the nuclear reactor. The main engine room and the funnel are located aft. Existing engine is a two-stroke diesel engine with a maximum continuous rated output (MCR) of 55 MW and normal continuous rated output (NCR) of 50 MW. The main engine arrangement is typical with centre line installation directly attached to propeller shaft. The aim is to replace part of the main engine's power with 30 MWe load-following power generated by the nuclear reactor with two motors in series attached to the propeller shaft.

Four generator sets (diesel generators) are positioned on both sides of the main engine. These are expected to meet peak loads rather than average ones. Presently the output of each generator is 4.5 MWe with the aim of being upgraded after the inclusion of the nuclear reactors.

It is proposed to install three HOLOS-Mono VHTR/HTGR nuclear reactor units, each having a power rating of 10 MWe. One will be placed on the centre line, one on starboard and one on the port side on the 3rd deck under the fwd. part of no.9 hold to facilitate access for removal and replacement or reactor units, avoid refuelling onboard, and use existing funnel and casing for supply and exhaust air.

Each reactor unit will be installed in an individual reactor compartment. Reactor compartment will be provided with appropriate shielding and fire rated structures, altogether with cooling arrangement to maintain controlled temperatures. There will be vent and ventilation ducting from the reactor compartments and will be exhausted outside at safe distance from accommodation.

Figure 22. Example sketch of 14,000 container ship

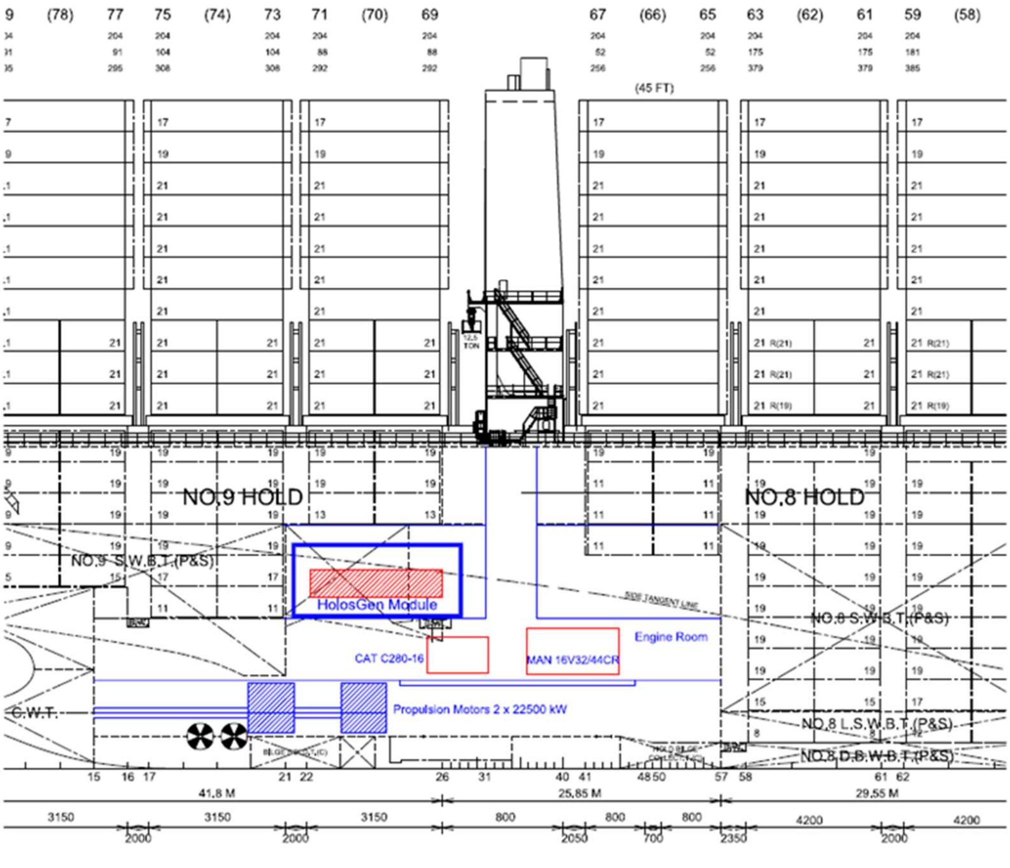


Figure 23. Nuclear compartment arrangement

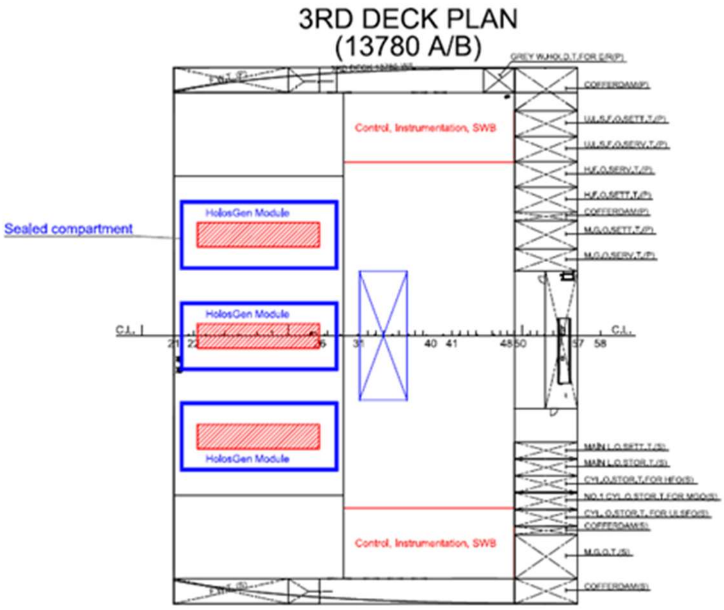


Figure 24. Nuclear compartment arrangement (Deck 3)

4.4.3.1 Assumptions – Container Ship

In addition to the assumptions listed in Subsection 4.3.7, other assumptions from the nuclear-powered container ship workshop are already included in Subsection 4.4.2.1.

4.4.3.2 Conclusions and Recommendations

For the workshop's recommendations to be feasible, conditions were assumed and listed in the assumption section. For some nodes, at the time of this writing, there was not enough information available, precluding the attribution of a risk ranking for some hazards. However, the activities associated with those scenarios were discussed and, where feasible, recommendations were made.

The results of the HAZID workshop are to be analysed and incorporated into future concept developments. A complete list of recommendations and the HAZID register are in Appendix VII – List of Recommendations – Container Ship with VHTR/HTGR and Appendix VIII – HAZID Register – Container Ship with VHTR/HTGR System- and operational-level nodes, along with the scenarios associated with each node, were discussed. When the risk was considered '*high*' or '*extreme*', recommendations were developed.

The HAZID register identified the hazards and documents the recommendations from the workshop's discussions. System- and operational-level nodes, along with the scenarios associated with each node, were discussed. Due to the very early stage of the hazard identification process for the container ship concept and HOLOS-Mono design configuration to satisfy marine-specific requirements, fourty (40) '*extreme*' and fifty (50) '*high*' risk scenarios were identified that will require mitigation measure (design improvement, dedicated interfaces, preventive/mitigating barrier, procedural measure etc.) to bring risk down to ALARP level as the design progresses to satisfy the requirements of marine-specific applications. Each of those has recommendations listed in the HAZID register, some of which have already been considered by the designer during concept development and design validation activities. Refer to summary in Table 16 below.

Given the lack of clear regulatory guidance, law restrictions, combined with the challenges associated with the implementation of new technologies etc. many risks, currently grouped under high and extreme ranking will require more detailed investigation to accurately quantify, confirm, mitigate or resolve them.

Table 16. Container ship - HAZID risk-ranking summary.

Key system level HAZID nodes	Risk Ranking of Hazards Identified			
	Low	Moderate	High	Extreme
General Vessel Arrangement				
Licencing & Approval Process				
Ship Construction				1
Global Hazards		5	22	21
Global Hazards - Ship Operation			2	
System Hazards			6	
System Hazards - Power & Propulsion			3	2
Maintenance and Inspection				1
System Hazards - Vent & Ventilation		4	1	1
System Hazards – Dry-docking			4	2
System Hazards - Dropped Object & Energy Release			1	2
System Hazards - Firefighting System (FFS)			3	
Nuclear Technology Hazards		1	6	6
Nuclear Technology Hazards – Gas Cooled Reactors			2	4
Nuclear Technology Hazards - Impact on Ports				
Nuclear Technology Hazards - Ship Recycling & Salvage				
Finance Risk & Liability				
Total	**0**	**10**	**50**	**40**

Based on the current initial stage of risk assessment (preliminary HAZID) for nuclear technology integration with merchant shipping operations, it was concluded that -- with the recommendations identified -- those risks can be addressed. As for all types of nuclear technologies (e.g., gas-cooled, liquid metal-cooled, with fuel melted in a solution etc.), there are VHTR/HTGR-specific technology risks and challenges which need to be addressed in the context of marine-specific applications and operations – the design is currently optimised, addressed and satisfied the safety requirements for land-based applications. However, marine environment-specific design basis accident scenarios need to be better identified.

Appendix VII – List of Recommendations – Container Ship with VHTR/HTGR provides a summary of the recommendations from the HAZID register with applicable nodes for the HAZID scenarios.

Considering that the design integration or retrofitting and supporting activities involving any nuclear reactor design selected for installation, un-install and operation within merchant vessels is at a very early stage for vessel builders and operators, the majority of the high-level risks, findings and recommendations have the tendency to be conservative as listed in Subsections 4.4 and 4.5 and will require a more in-depth analysis with cooperation between naval designers and operators, reactor designers and risk assessors to better understand the operational requirements and limitations). These recommendations are applicable for the three vessel types. Therefore, it is recommended that in the future more detailed studies will be carried out on individual vessel types and specific recommendations will be based on detailed integration design of the reactor to the vessel.

4.5 Nuclear Power HAZIDs Conclusions

The HAZID studies demonstrated that the major concerns related to nuclear power for marine applications are related to ionizing radiation; external threats; marine accidents; a lack of clear regulations; design and construction requirements for nuclear power plant-related systems; and the licencing requirements for OEMs and regulatory agencies. The ability of shipyards to construct or service these specialised vessels will be of paramount importance.

These issues will require further studies and risk assessments to understand the risks and the additional safeguards that will need to be implemented to prevent or mitigate the major hazards. The HAZID studies identified preventive and mitigative safeguards and recommendations specific to the vessel types. Safeguards stemmed from the *IMO Resolution A 491 (XII) – Code of Safety for Nuclear Merchant Ship*, which is mainly written for reactors using pressurised-water reactor technologies. Many of the risks that were identified may require additional preventive and mitigating safeguards.

Not all safeguards and recommendations listed in the HAZID registers will be applicable to all vessel types. Some are obviously practical and of benefit, but others may require a further investigation of their merit. However, they are all listed for consideration and may help to inform prescriptive requirements and develop inherently safer designs and arrangements. Importantly, the additional safeguards and recommendations will contribute to a further reduction of the risks.

Nuclear power for almost all types of merchant vessels is new to the maritime industry. However, land-based power generation using nuclear technologies has been in operation for many decades with regulations developed by regulatory authorities such as the NRC, which optimised safety requirements through operating experience accrued over several decades of nuclear power plant fleets operating worldwide Therefore, existing safety practices from the nuclear industry are valuable to adopt and additional risk identification for marine applications may require additional work to increase address risk quantification and accuracy.

Radiation

Splitting atoms in a nuclear-energy plant causes fission fragments that decay to more stable conditions by shedding energy through radioactive decay, which leads to radiation sources. It can be extremely dangerous, so it must be carefully managed. Radiation has varying impacts on living organisms, humans, the degradation of materials and causes long-term environmental issues. At high doses, ionising radiation can cause immediate damage to a person or living organisms' body, including, at very high doses, radiation sickness and death. At lower doses, it can cause health effects such as cardiovascular disease and cataracts, as well as cancer. It causes cancer primarily because it damages the DNA, which can lead to cancer-causing gene mutations. In case the radiation is released in the environment it has very long-lasting impact and may disturb ecosystem.

Radiation Leakage

To minimise radiation leakage risk proper radiation shielding suitable for marine environment is to be provided. Radiation shields attenuate and, depending on materials and shield thickness, entirely stop radiation by converting it into heat. Radiation control and monitoring will have to be provided on all areas of the vessel involved in the operations of the reactor.

Nuclear Reactor and Reactor Space

The reactor location in the context of vessel structures is to provide the highest protection against marine risk/incident. Marine risks that need to be considered are collision, grounding, flooding, sinking, capsizing etc. The reactor room should have appropriate firefighting protection.

Reactors and systems are to be designed to meet the typical design life of a vessel (i.e., 30 years or more). Most SMR and microreactor technologies fuel lifecycle is between 2 to 10 years. Typically, the vessel goes to dry-docking every 5 years and it is necessary to align fuel replacement cycle with dry-docking cycle.

Current reactors are designed for land-based applications. These designs will need to be adjusted to accommodate the restrictions and challenges brought by operation in a marine environment.

Special consideration should be given to the survival of the vessel and reactor from natural catastrophes (typhoons, hurricanes, etc.) while in transit, during construction in the shipyard (earthquakes), and during dry-docking.

Material Selection

High-energy radiation involving neutrons, ions, and electromagnetic waves can alter the microstructure and properties of metallic materials in a variety of ways. It is of enormous importance to understand these effects due to many reasons. Any material which is exposed is to be selected properly, tested and approved. Materials used should be selected in a way that any element impurity within the material, which can be activated e.g. upon exposure to neutrons interacting with the material with a certain energy, should not be allowed. For example, a steel alloy containing cobalt shall not be used in the proximity of the core as irradiated cobalt becomes Cobalt-60 which emits gamma radiation (utilised for industrial and medical applications). Similarly, the components of paints and coatings should also be thoroughly investigated.

Accommodation

The general arrangements for the accommodation should be a primary concern. Each arrangement should be studied separately when reactor rooms and systems are located close to crew or passenger accommodation; clearly, the safest location will be away from the crew accommodation or passenger cabins.

Nuclear Fuel Supply, Storage & Waste Disposal

Technology developers will need to design reactors and their fuel to meet non-proliferation treaty aspect to limit spread of nuclear weapons and make it impossible to access them or use them in a harmful manner.

TRISO particle fuel could be considered, but its supply-chain and long-term availability would need to be further studied in case the maritime industry proves to be interested in adopting it.

Studies will have to be conducted on the storage of radioactive waste onboard; additional end-of-life assessments will need to examine disposal procedures for the reactor, vessel equipment such as the hull-reactor core, piping, heat exchangers, pumps, and other materials that may have been exposed.

Maintenance & Dry-docking

Inspection and maintenance plans need to be developed to verify the integrity of the reactor’s foundation and the radiation shielding during maintenance or dry-docking.

It is critical to establish the time that will be required for the reactor to cool down and reach a safe condition before maintenance or dry-docking activities can be conducted. Depending on the reactor technology used, the time to reach a safe level for maintenance vary and needs to be established during design and testing. As an example, for VHTR/HTGR there is a possibility that activated Argon in air can be present in the reactor compartment or reactor container. Typically, it requires 2-3 hours waiting time for Argon to come back to its original safe state.

Ventilation

HVAC loads must be established for reactor compartments to maintain the temperatures within the acceptable range.

The surrounding spaces for machinery or other components will need to be provided with independent ventilation to minimise the possibility of radiation ingress.

All ventilation inlets and outlets will need to have enough separation to avoid mixing and interfering with other ventilation openings. In addition, high efficiency filtration that is capable of capturing radiation and continuous monitoring of air exhaust will need to be provided in all HVAC inlet ducting potentially interacting with the air vented from the reactor compartment.

The reactor compartment ventilation outlet location is to be selected so that it does not pose risk to crew or passengers.

Vents

Some technologies have vent system possibility or radiation discharge exist and such vent lines should be designed as double ducted with annular space pressurised. Discharge location to be decided after dispersion analysis.

Electrical equipment and installation

Safety and support system need to be able to survive partial flooding and able to maintain the reactor in a safe condition after flooding, grounding or collisions.

The minimum auxiliary/supplemental power needs to be identified for each vessel, as well as alternative ways to ensure the reactor core is maintained in safe condition.

Electrical cables will have to be certified according to the requirements of the nuclear regulator, be able to operate in radioactive environment and survive submerged conditions. They also will have to follow the optimum route and distance from the reactors to the motors.

Any penetration in the reactor or system which has the potential to leak radiation is to be certified, tested and approved.

Safety & Security

The location of the muster stations -- and their proximity to the radiation zones and other high-risk areas -- is critical and should be dictated by the findings of a radiation-dispersion analysis.

All crew should have security-clearance certifications.

Terrorist threats such as hijacking, piracy, terror or attacks from flying objects (missiles, planes, etc.) will have to be addressed and mitigation measures put in place to protect the vessel.

A protocol to address an '*emergency shut down*' from a cyber-attack will need to be developed based on current utilised provisions for similar attacks to nuclear power plant installations.

Emergency

Dedicated spaces and properly equipped facilities must be provided for the medical treatment of crew members or passengers following exposure to radiation.

An Emergency Shut Down philosophy for the reactors will need to depict: (i) motion of the ship; (ii) normal operations; (iii) emergency and (iv) conditions beyond emergency.

Emergency protocols will need to be developed, including the location of the nearest shelter/port of refuge in the event of an accident related to the vessel's nuclear system.

Salvage operations based on the vessel's design and radioactivity dose rates will need to be investigated; procedures and training instructions for the salvage crew also will need to be developed.

If refloating the vessel is considered after grounding, risk-control processes need to be in place.

The design of the reactor needs to account for any port regulations that will require the vessel to depart within one hour in the event of an emergency.

Propelled lifeboats should be considered for the vessel to decrease escape times from the radiation zone.

Personal Protective Equipment (PPE)

Onboard PPE designed to protect against radiation exposure will need to be provided for each mariner.

Certified lifesaving appliances will need to be provided to ensure survival and escape if radiation is released into the atmosphere; a related study is advised.

Fire & Firefighting Systems

Analyses of a fire's impact and load will need to be conducted for the worst-case conditions related to nuclear-power plants and their support systems.

If a fire breaks out, the normally accepted best mitigation strategy is to spray water on the surrounding equipment area to protect it from heat, and to isolate the equipment/system and minimise the fuel/inventory that is feeding fire.

Fire related to cargo spaces, accommodation etc. is to be considered and proper fire risk analysis is to be conducted. The fire load on reactor compartment is to be determined and appropriate mitigating firefighting arrangement is to be provided to protect the reactor and reactor compartment.

Bilge System

The bilge system from any room with potential for radiation exposure/leakage must be independent; dedicated bilge storage should be provided to contain radioactive materials. Further study is needed to identify the associated risks and any effective mitigation measures.

A further study will be needed on the safe storage and disposal of bilge water in the event of contamination.

The bilge systems from the reactor room are to be designed to consider the potential for radiation and contaminated water; they should be independent from other systems.

Environmental Issues

An environmental impact study will need to be conducted to assess the potential for radiation leakage from flooding, sinking or capsizing events or total loss of vessel.

Crew Training

Any crew will have to be trained to operate in a nuclear-reactor environment.

A dedicated study will be needed to set allowable levels of radiation and the maximum period crew members can be allowed to stay on these types of vessels.

In accordance with the rules and guidance set by the regulatory authorities and the technology providers, there will be specialised training required to operate vessel-optimised nuclear power plants; special accreditation will be needed. A special training programme in cooperation with both parties is to be developed and the certification requirement determined.

Salvage Operation

From design stage salvage risks are to be evaluated and design needs to accommodate salvage operation considering radiation. The design needs to consider the possibility of removing the reactor during salvage operation from any depth. Proper salvage procedure and training are to be developed. A salvage plan needs to be approved by the local authority.

Table 17 below summarises the main hazards and causes form the HAZID studies.

Table 17. Summary of main hazards and causes from HAZID studies.

System/Area/Regulation/Operation	Hazards	Causes
Impact on Human, marine life, environment	Radiation	- Nuclear incident - Sinking - Uncontrolled reactivity
Nuclear Reactor	Radiation Leak	- Uncontrolled Reaction - Material degradation due to radiation - Marine accidents (flooding, grounding, collision, capsizing etc.) - Failure of radiation shielding - Reactor fuel removal, refuelling or entire module removal. - Fatigue failure - Thermal load variation - Vibration - Sloshing - Dynamic load and motion - Flooding - External pressure collapse of reactor core due to sinking
	Power availability	- Reliability not established yet – new technology.
	Fuel unavailable	- Availability of TRISCO fuel
Technology	Technology readiness	- Technology yet not qualified
Reactor refuelling/fuel removal	Radiation	- Radiation from reactor – spent fuel
	Dropped Object	- Handling, dropping reactor
	Approved Shipyard	- Licensing - Skill - Facility to handle Radioactive material. - Local Regulation - Security issue - Non-proliferation issue
	Vessel Design – Unable to remove/refuel etc.	- Vessel design
Radioactive west handling/storage	Radiation	- Wast generated during operation. - Spent fuel. - Activated materiel due to exposure to neutron/radiation

System/Area/Regulation/Operation	Hazards	Causes
	Unauthorised access/ Security	- Lack of security
Vent from reactor compartment	Radiation	- Ionizing radiation - Neutron escaping - Proximity to occupied spaces
Accommodation	Radiation	- Proximity to reactor compartment - Radiation leakage from reactors - Proximity of vents/ventilation lines - Vent line/ducting from reactor/machinery compartment. - Explosion in reactor compartment - Handling and removal for radioactive waste, fuel (spent/new), removal of reactor module etc.
	Emergency escape and evacuation	- Unable to protect crew in case of radiation leakage
Cargo on ship	Cargo fire	- Flammable cargo damaging reactors, system and structure leading to radiation leak
Dropped object	Reactor handling during construction, installation, removing	- Dropped reactor leading to core damage
	Dropped load on reactor/reactor compartment	- Dropped load
	Overhead lifting above reactor and system	- Dropped load
Operational Risk	Loss of control of vessel reactor	- Hijacking, piracy, terror
	Unauthorised access	- Lack of security
	Cyber Security	- Unauthorised access to electronic system
	Kinetic Energy Impact	- Flying object (missile, plane attack etc.) attack
	Crew Availability	- Availability of skilled operator for Nuclear - Security clearance requirement - Nationality
	Training	- Programme not established
Marine risk	Grounding	- Navigation - Human error
	Collision	- Navigation - Marine traffic - Narrow channel - Human error

System/Area/Regulation/Operation	Hazards	Causes
	Sinking/ Capsizing	- Marine incident - Vessel design - Operational issue - Human error - Storm - Wave
	Flooding (reactor compartment)	- Grounding, collision, sinking, capsizing, - Structural failure
	Vessel Motion	- Wind - Wave - Stability
	Environmental risk	- Sinking and radiation leak under water
Regulation	Uncertainty/project delay	- Lack of regulation

4.5.1 Main Gaps Identified in the Regulatory Framework

Nuclear-powered vessels need appropriate technical guidelines to trade safely and protect life, environment and assets from radiological hazards throughout all the phases of the vessel's life cycle, i.e., design, construction, commissioning, operation and decommissioning.

Based on the risk assessment studies conducted, the list below includes the most important design and operation related issues that need to be addressed by the regulatory framework:

- Safety and risk acceptance principles need to be developed considering various nuclear technologies.
- Vessel's basic design criteria and safety functions requirements need to be developed.
- Vessels are currently designed to meet IMO/SOLAS/Class requirements for damage penetration and stability; this needs to be reconsidered from the perspective of the additional safety measures (e.g. higher damage penetration, etc.) required due to the presence of nuclear systems and radiation risk.
- Requirements related to radiation shielding, allowable dosage limits for crew, passenger, and the environment leveraging the existing knowledge base accrued through operational experience from stationary nuclear power plants needs to be developed for applications to vessel/marine-environment.
- Regulatory criteria for the NPP and its system factory acceptance, integration, sea trial and functional testing need to be developed with the original-equipment manufacturer, shipyard, owner and regulator.
- Emergency-shelter related regulation need to be developed, including any port restrictions. International legislation needs to be in place.
- Based on operational experience from NPP, manning, training, qualification, updating of knowledge, drills and musters related requirements need to be developed for vessel-specific applications.
- Leveraging, the large body of knowledge on training personnel supporting stationary NPP operation, a special training programme in cooperation with regulators and technology providers needs to be developed, as well as a certification requirement for crews and operators.
- Legislation requirements need to be developed for external threats and risks such as cyber threats, hijacking, piracy, terrorism and attacks involving flying objects (missiles, planes, drones, etc.).
- The material requirements for use in nuclear technology, in particular, material characterisation, testing, inspection and periodic inspection criteria in the context of marine applications needs to be developed

factoring irradiation-induced radioactivity of materials utilised in the context of vessels operating in a marine environment.

- NPP technology and the refuelling, maintenance and inspection intervals, the NPP requirements in the context of dry-docking operations need to be developed.
- Vessel accident criteria and NPP safety requirements need to be developed.
- Marine salvage operations related requirements need to be developed. The reactor designer needs to consider the safe reactor's removal during salvage operation.
- Detailed operational procedures need to be developed for salvage companies to follow to protect the environment, crew/people from potential radiation exposure etc.
- Salvage operations based on vessel designs and potential for radiation exposure need to be further investigated and proper procedures and training instructions need to be developed for the salvage crew.
- Decommissioning and end of life related requirements to safely remove all radioactive materials and dispose them safely need to be developed.
- Requirements need to be developed related to emergency and auxiliary/support power needs and its operational requirements for normal, emergency and accidental situations (e.g. marine accident, hull listing, sinking etc.).
- Security requirements for NPP require additional measure on vessels due to higher risk. This will be applied to all phases of vessel design life (i.e., while in operation, sailing, construction, maintenance, dry-dock, salvage, decommissioning).

The great majority of '*need to be developed*' aspects addressed above can leverage the vast knowledgebase available through nuclear regulatory authorities and nuclear safety agencies as all of the aspects listed represent activities conducted during handling, transporting and managing fresh and especially spent (radioactive) nuclear fuels via truck, rail, vessels and in some cases aircraft. Provisions for safely handling equipment and protect crews, the general public and the environment developed for these activities can be leveraged to address similar activities conducted within the context of NPPs applied to merchant vessels.

5. Overall Conclusions of Nuclear Power Study

The maritime industry is responsible for about 3% of the global CO_2 emissions caused by human activities and it is currently facing challenges that are mostly driven by increasingly strict legislation on air emissions and climate-related matters. Innovative technologies and new fuels are growing in maturity to help the industry meet the IMO and regional targets for reaching net-zero GHG emissions. With most alternative fuels having low energy density and given their limited availability worldwide, nuclear power has been investigated as an alternative for the coming decades since it produces zero emissions during operation.

Nuclear power has been used in navies for decades, but the concept is still new for merchant vessels; as such, the technology readiness varies among the various types. Moreover, issues related to nuclear fuel availability and infrastructure for commercial use remain to be solved. Therefore, a collaborative effort will be needed to develop reliable and cost-effective solutions and a solid regulatory framework covering safety, environment protection and liability standards.

The specific requirements of merchant vessels - such as load variations and limitations in weight and volume – will need to be carefully considered. However, the comparative benefits (to emerging alternative fuels) of nuclear power range from high energy output to no or infrequent requirements for re-fuelling. Among the available options, some Gen IV technologies, namely PWR, VHTR/HTGR, MSR, and LFR, have been identified as the most promising, each of them presenting unique characteristics.

In terms of emissions, nuclear propulsion presents a unique advantage in that its use produces almost no well-to-wake emissions, in addition both NO_X, SO_X and particulate matters are eliminated which provide significantly health improvement. Its energy-generating process is based on fission and does not involve combustion; indirectly, the emissions produced during the transportation, extraction and processing of required uranium are minimal. The overall WTW emissions are considered comparatively low. Also, in the future, the use of renewable energy needs to be considered for these activities to minimise the resulting emissions.

In this study, the total cost of ownership (TCO) for nuclear-powered vessels is estimated to be lower than that of comparable vessels running on conventional fuel oils. Based on the assumptions presented in this study, case examples of container ships, bulk carriers, liquefied gas carriers and oil tankers have demonstrated that the TCO for nuclear-powered and VLSFO-fuelled vessels are similar during the initial years of operation. However, over time, the operating expenses for VLSFO-fuelled vessels are expected to increase, given the anticipated rises in carbon costs and higher fuel prices; this is not the case for nuclear-powered vessels. At the same time, as technology matures, a reduction in the capital expenditure for nuclear-powered marine applications could make this option more attractive. It is important to note that nuclear fuel prices vary depending on the type of fuel so a more detailed evaluation of the TCO and vessel speed needs to be investigated on a case by case. Also, it is important to note that decommissioning cost, which can be rather high, has not been considered in this study.

The business case, together with shifts in public opinion as social pressures grow to reduce GHG emissions, may increase investors' interest. In summary, as the sector continues to evolve on, the integration of nuclear technology on merchant vessels may provide competitive advantages.

At the same time, the regulatory framework has been relatively well developed in the land-based commercial nuclear industry. However, to ensure robust safety practices, environmental protection and the integration of technologies, additional regulatory work will be required before nuclear power could be widely adopted on merchant vessels. Also, there are nations which do not currently accept any nuclear infrastructure; this poses additional challenges for an international industry where vessels sail globally. Therefore, co-ordinated efforts and partnerships will be needed to identify the risks and demonstrate the safety of these novel arrangements. It is also noted that due to the risks involved, it may be difficult for nuclear-powered vessels to be insured, or the premium may be significantly increased.

The analyses in this study highlighted a list of major concerns related to use of nuclear-powered system for ships: radioactivity/radiation leaks and control; vessels sinking; collision; grounding; capsizing, flooding, manning and training; technology licensing; compliance with requirements of non-proliferation treaties; external risks (such as piracy, hijacking, terrorist attacks, etc.); shipyard licensing and technical capabilities; dry-docking, refuelling, nuclear waste handling/disposal, and regulatory requirements. These issues will require more detailed studies to better understand the risks and additional safeguards that will be needed to address major hazards. The HAZID cases identified numerous preventive and mitigative safeguards and recommendations for the vessel types that were studied. These may help to develop prescriptive requirements, inherently safer designs and arrangements, and could contribute to additional risk-reduction studies.

Table 18. Summary of the observations.

Subject	Observation/Mitigations/Suggestions
Nuclear Power Plants	**Observations:** • Nuclear power produced zero-emission during operation and low carbon during its lifecycle. Therefore, it is worth exploring it for shipping decarbonizing. • Various technologies are under development. • Public perception may be a barrier to the adoption. **Mitigations and Suggestions:** • Invest in next-generation reactors such as SMRs and Gen IV designs, which are more efficient, safer, and produce less waste, while also reducing construction costs and lead times. • Enhance nuclear waste management practices by developing long-term, secure storage solutions (such as deep geological repositories) and advancing research into fuel reprocessing to reduce the volume of high-level waste. • Strengthen global regulatory frameworks to ensure that all countries operating nuclear power plants adhere to the highest safety and operational standards, preventing accidents and fostering public confidence. • Expand public education and engagement programmes to improve understanding of nuclear energy's benefits and safety measures, which can help alleviate public concerns about nuclear energy. • Explore hybrid energy systems where nuclear plants complement renewable energy sources, helping to stabilise grids and ensure consistent, clean energy output while optimizing the overall sustainability of energy production.
Suitability	**Observations:** • Nuclear power plants are well-suited for large-scale, continuous power generation, making them ideal for base-load energy production. Vessels have variable load needs. • The scalability of nuclear plants is limited by high upfront costs, long construction timelines, and stringent regulatory approvals, which may hinder their suitability for smaller markets or regions with fluctuating energy needs. • The long operational life of nuclear power plants (often 40+ years) means they provide long-term energy stability, but they may not be as flexible as renewable energy technologies in terms of quick scalability or adaptability to market changes. • Nuclear fuel for merchant vessels is not as readily available as traditional marine fuels. • Infrastructure for enrichment and fuel cycle management are still underdeveloped for merchant use. **Mitigations and Suggestions:** • The vessel lifetime can be matched with the reactor project lifetime. • Adopt flexible licensing and regulatory processes for emerging nuclear technologies, enabling quicker deployment of nuclear solutions in regions where rapid energy development is needed. • Expand nuclear fuel supply chains, ensuring reactors on merchant vessels have access to fuel similar to military nuclear programmes. • International collaboration could facilitate shared infrastructure for fuel enrichment, reprocessing, and waste disposal. • Consider government-backed supply guarantees for nuclear fuel.

Subject	Observation/Mitigations/Suggestions
Sustainability and Availability	**Observations:** • Nuclear-powered vessels produce near-zero GHG emissions during operation, significantly reducing CO_2 emissions compared to traditional fossil fuel-powered vessels. • Lifecycle emissions from uranium mining, fuel processing, and decommissioning must be considered. • ·Despite their environmental benefits during operation, the construction, maintenance, decommissioning, and waste management involve challenges such as high costs, long lead times, and public safety concerns. • ·Nuclear waste management, particularly high-level radioactive waste, remains a significant issue due to its long-term environmental impact and the lack of universally accepted disposal solutions. • Public perception and acceptance of nuclear energy remain mixed, with concerns about accidents (e.g., Fukushima, Chernobyl) and long-term safety. **Mitigations and Suggestions:** • Develop comprehensive lifecycle assessments to minimise emissions during uranium mining, fuel processing, reactor operation, and decommissioning. This will ensure that the entire nuclear fuel cycle, from extraction to waste disposal, is optimised for low environmental impact. • Implement best practices for nuclear waste management, particularly focusing on high-level nuclear waste and spent fuel storage, to reduce long-term environmental risks and build public trust in the sustainability of nuclear-powered vessels. • Invest in research on recycling nuclear fuel, such as reprocessing spent fuel to extend its usability and further reduce the environmental footprint of nuclear propulsion systems. • Promote international collaboration on sustainable nuclear fuel supply chains, ensuring that countries adopt environmentally responsible practices for mining, enrichment, and waste disposal. • Encourage the integration of renewable energy sources to power non-propulsion systems onboard nuclear-powered vessels, further reducing overall energy consumption and reliance on fossil fuels. • Emphasise the long-term cost benefits of nuclear propulsion in merchant shipping, particularly in meeting global GHG reduction targets, to strengthen the economic argument for its sustainability. • Continue improving the public perception of nuclear energy's environmental benefits.
Techno-economical	**Observations:** • Nuclear-powered vessels have a high initial capital cost (CAPEX) compared to conventional vessels. • They can offer long-term operational cost savings due to lower fuel costs and elimination of carbon taxes. • High CAPEX and decommissioning costs are major barriers. • Lack of data and uncertainties related to the TCO model. • Decommissioning costs for nuclear-powered vessels and VLSFO-fuelled vessels residual value have not been considered. **Mitigations and Suggestions:** • Encourage policy incentives like GHG reduction targets, carbon taxes, and government subsidies to make nuclear propulsion economically viable. • Consider advancements in SMRs and LFRs to reduce CAPEX. • Develop shipyards capable of handling reactor installation and retrofits. • Include decommissioning costs, residual values, as well as the use of TRISO fuel, could enhance the accuracy of TCO comparisons in future analyses.

<table>
<tr><th>Subject</th><th>Observation/Mitigations/Suggestions</th></tr>
<tr><td></td><td></td></tr>
<tr><td>Rules and Regulation</td><td>Observation
The land-based commercial nuclear industry operates under a well-developed regulatory regime with international oversight that includes standards for design, operations, and nuclear waste and spent nuclear fuel handling and disposal. Although nuclear power has decades of operating experience in Navies, the regulatory regimes are not able to be transferred or modified for merchant marine use.
Integrating nuclear technology for merchant vessel propulsion will require complex assessment and considerations to either update existing codes and standards or create new regulatory mechanisms.
It may be expected that regional cargo or service vessels with nuclear propulsion will be commissioned before international alignment to establish an appropriate set of Codes for the widespread use of nuclear propulsion for merchant shipping.
Mitigations and Suggestions:
Regulatory involvement is essential at an early stage in the design of a merchant vessel integrating nuclear propulsion systems.
Merchant vessels using nuclear propulsion should execute thorough risk assessment design iterations to integrate and operate innovative technology and promote decarbonised solutions safely.</td></tr>
<tr><td>Risk & Safety</td><td>Observation:
The major safety concerns related to nuclear-powered vessels are the ionising radiation and the impact of radiation on humans, living organisms and the environment.
SMR and microreactor technologies are not yet fully qualified for marine applications.
Each SMR technology has individual/specific risks and these need to be further analysed.
Material suitability for use in radioactive service under high temperature, fatigue loading, and marine environment requires additional study and material characterisation.
Radiation shielding for marine applications need to be developed.
Marine loads such as vessel motion, structural flexibility and extreme condition impact on the reactor.
Marine incidents such as grounding, collision, sinking, capsizing, reactor compartment flooding have a major impact on safety of the reactor and possibility of radiation release
Storage, handling and disposal of radioactive waste, spent fuel etc.
The disposal of the reactor and any other exposed component/machinery is to be planned.
Availability of crew should be considered since personnel should be properly trained and qualified.
Emergency protocols need to be developed for crew, ports and local state / authority / country.
There are no clear regulatory requirements established related to vessel design, operation, licensing, security, reactor design for marine application.
Mitigations and Suggestions:
Regulatory requirements are to be developed for safe marine operation of nuclear-powered vessels.
Training and manning requirements are to be developed for safe marine operation.
Risks are to be identified and addressed. As a minimum the following should be required:
Risk assessment plan is to be developed.
Risk management plans are to be developed and implemented.
Qualitative and quantitative risk assessments are to be conducted.</td></tr>
</table>

Subject	Observation/Mitigations/Suggestions
	- The key safety studies required by regulators include deterministic safety analysis (DSA) and/or probabilistic safety analysis (PSA). - Verification of compliance with existing nuclear regulation and safety assessments. - Safe operation of nuclear reactors requires the potential for human error to be reduced as much as possible, so a detailed human-factor engineering study will be needed. - A detailed environmental-impact study needs to be conducted for scenarios involving a total loss of containment, release of radiation. • SMR and microreactor Technologies will need to be certified for use in a marine environment. The maritime industry will have to develop functional lifecycle requirements for reactors to operate in marine environments. • Detailed test plan for reactors, system and equipment from manufacturing to installation, operation and in-service is to be developed. • Radiation shielding and exposure prevention need to be further investigated; the proximity of crews in permanently manned spaces is much closer than those of typical land-based applications. • Material selection and qualification plan for material exposed to radioactivity and radiation for marine application to be developed. • Atmosphere and radiation control inside reactor compartment is to be further studied considering marine application. • Vessel routes and traffic in port and channels should be studied to minimise the probability of grounding, striking rock formations, collisions, etc. • Marine salvage operations should be considered from the design stage. Detailed operational procedures and emergency plans are to be developed for salvage companies to protect the environment and people from exposure to radiation. • The support system and its requirements are to be further developed. • External fire risk (cargo, accommodation, other machinery space, etc.) to be further analyzed and fire risk assessment to be conducted to determine impact on reactor compartment. • Considering radioactivity, end of life disposal is to be considered from the beginning of the vessel design to facilitate safe handling, removal and disposal of any parts such as equipment and material that might be contaminated with radioactive material. • Refuelling of reactors is to be considered from initial design and proper procedure plan including handling, storage and transportation is to be developed. • The strength requirements for the reactor compartment(s) against explosion or other structural accident have yet to be determined; further research is needed to examine the regulatory requirements. • Location of the nuclear reactor and support system should be provided with the highest possible protection levels against external risks (e.g. collision, flooding, grounding, dropped object, capsizing etc.). Reactor compartment protection against marine incidents is to be further studied and additional requirements are to be developed. • Vessel design and construction should consider the procedures of installing a nuclear reactor, fuelling /refuelling it (if applicable) and removing the reactor module (during partial refuelling, maintenance, or replacement). • Security protocol and regulation for sailing routes, port and crew are to be developed. • Regulation and protocols are to be developed regarding licensing requirements and authorisation to operate a nuclear reactor onboard.

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Appendix I – Symbols, Abbreviations and Acronyms

ABS	American Bureau of Shipping
AIP	Approval In Principle
ALARP	As Low As Reasonably Practical
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing of Materials
BPVC	Boiler and Pressure Vessel Code
BV	Bureau Veritas
BWR	Boiling Water Reactor
CAPEX	Capital Expenditure
cbm	Cubic metre
CCC	Carriage of Cargoes and Containers Sub-Committee (IMO)
C_F	Fuel-Conversion Factor (IMO - EEDI)
CFR	Code of Federal Regulations
CII	Carbon Intensity Indicator (IMO)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CNSC	Canadian Nuclear Safety Commission (Canada)
DCS	Data Collection System (IMO)
DNV	Det Norske Veritas
DOT	Department of Transport
DSA	Deterministic Safety Analysis
DWT	Deadweight Tonnage
D_2O	Deuterium oxide (heavy water)
EEDI	Energy Efficiency Design Index (IMO)
EEXI	Energy Efficiency Existing Ship Index (IMO)
EMSA	European Maritime Safety Agency
EN	European Standards (European Norm)
EPA	Environmental Protection Agency
ESD	Emergency Shutdown
EU	European Union
FAT	Factory Acceptance Test
FGSS	Fuel Gas Supply System
FMECA	Failure Mode, Effects and Criticality Analysis
FNR	Fast Neutron Reactor
FOC	Fuel Oil Consumption
FSS	Fuel Supply System
FT	Fischer-Tropsch
GCR	Gas-Cooled Reactor
GFR	Gas-cooled Fast Reactor
GMR	Graphite Moderated Reactor
GHG	Green House Gas

GIF	Generation IV International Forum
GSR	General Safety Requirements (IAEA)
GWP	Global Warming Potential
HALEU	High Assay Low Enriched Uranium
HAZID	Hazard Identification Studies
HAZOP	Hazard and Operability Study
He	Helium
HEU	Highly Enriched Uranium
HFO	Heavy Fuel Oil
HLW	High-Level Waste (HLW)
HTGR	High-Temperature Gas-cooled Reactor
HWR	Heavy Water Reactor
H_2O	Ordinary (light) water
IACS	International Association of Classification Societies
IAEA	International Atomic Energy Agency
IAPPC	International Air Pollution Prevention Certificate (IMO)
IBC Code	International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IMO)
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ILW	Intermediate-Level Waste
IMDG Code	International Maritime Dangerous Goods Code (IMO)
IMO	International Maritime Organisation
INF	International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on board ships (IMO)
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISM	International Safety Management Code (IMO)
ISO	International Organisation for Standardisation
ISPS	International Ship and Port Facility Security Code (IMO)
LEU	Low Enriched Uranium
LFR	Lead-cooled Fast Reactor
LLW	Low-level waste
LMCR	Liquid Metal Cooled Reactors

LMFBR	Liquid Metal Fast Breeder Reactor
LNG	Liquefied Natural Gas
LNGC	Liquefied Natural Gas Carrier
LPG	Liquefied Petroleum Gas
LR	Lloyd's Register
LWR	Light Water Reactor
MARPOL	Marine Pollution (IMO)
MCR	Maximum Continuous Rating
MEPC	Marine Environment Protection Committee (IMO)
MIE	Minimum Ignition Energy
MGO	Marine Gas Oil
MOX	Mixed Oxide
MR	Medium Range
MRV	Monitoring Reporting Verification (EU)
MSC	Maritime Safety Committee (IMO)
MSR	Molten Salt Reactor
MWe	Megawatts of Electricity
MWt	Megawatts of Thermal Energy
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Association
NGO	Non-Governmental Organisation
NH_3	Ammonia
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
NRC	Nuclear Regulatory Commission (US)
NSSC	Nuclear Safety and Security Commission (South Korea)
N_2O	Nitrous Oxide
NUMO	Nuclear Waste Management Organisation
OECD	Organisation for Economic Co-operation and Development
ONR	Office of Nuclear Regulation (UK)
OPEX	Operating Expenditure
PAH	Polycyclic Aromatic Hydrocarbons
PEM	Proton Exchange Membrane
PM	Particulate Matter
PPE	Personal Protective Equipment
PPM	Parts Per Million
PPR	Pollution Prevention and Response Sub-Committee (IMO)
POB	Persons on Board
PRV	Pressure Relief Valve
PSA	Probabilistic Safety Analysis
PSC	Port State Control
Pu	Plutonium

Pu-239	Plutonium-239
PWR	Pressurised Water Reactor
RA	Risk Assessment
RAM	Reliability, Availability and Maintainability
RED	Renewable Energy Directive (EU)
RINA	Registro Italiano Navale
RS	Russian Maritime Register of Shipping
SCR	Selective Catalytic Reduction
SCWR	Supercritical Water Reactor
SFR	Sodium-cooled Fast Reactor
SIGTTO	Society of International Tanker and Terminal Operators
SIMOPS	Simultaneous Operations
SOLAS	International Convention for the Safety of Life at Sea, 1974, as amended (IMO)
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxides
SSR	Specific Safety Requirements (IAEA)
STCW	Standards of Training, Certification and Watchkeeping for seafarers
TCO	Total Cost of Ownership
TCS	Tank Connection Space
TEU	Twenty Foot Equivalent (Container)
Th	Thorium
Th-232	Thorium-232
TNR	Thermal Neutron Reactor
TRL	Technology Readiness Level
TTW	Tank To Wake
U	Uranium
UI	Unified Interpretation
UO_2	Uranium Oxide
UR	Unified Requirement
USCG	United States Coast Guard
U-235	Uranium-235
VHTR	Very High-Temperature Reactor
VLCC	Very Large Crude Carrier
VLSFO	Very Low Sulphur Fuel Oil
VOC	Volatile Organic Compound
WinGD	Winterthur Gas & Diesel
WNA	World Nuclear Association
WNTI	World Nuclear Transport Institute

Appendix II – HAZID Risk Matrix

Category	Consequence Severity				
Asset	No shutdown, costs less than $10,000 to repair	No shutdown, costs less than $100,000 to repair	Operations shutdown, loss of day rate for 1-7 days and/or repair costs of up to $1,000,000	Operations shutdown, loss of day rate for 7-28 days and/or repair costs of up to $10,000,000	Operations shutdown, loss of day rate for more than 28 days and/or repair more than $10,000,000
Environmental Effects	No lasting effect. Low level impacts on biological or physical environment. Limited damage to minimal area of low significance.	Minor effects on biological or physical environment. Minor short-term damage to small area of limited significance.	Moderate effects on biological or physical environment but not affecting ecosystem function. Moderate short-medium-term widespread impacts e.g., oil spill causing impacts on shoreline.	Serious environmental effects with some impairment of ecosystem function e.g., displacement of species. Relatively widespread medium-long term impacts.	Very serious effects with impairment of ecosystem function. Long term widespread effects on significant environment e.g., unique habitat, national park.
Community/ Government/ Media/ Reputation	Public concern restricted to local complaints. Ongoing scrutiny/ attention from regulator.	Minor, adverse local public or media attention and complaints. Significant hardship from regulator. Reputation is adversely affected with a small number of site-focused people.	Attention from media and/or heightened concern by local community. Criticism by NGOs. Significant difficulties in gaining approvals. Environmental credentials moderately affected.	Significant adverse national media/public/ NGO attention. May lose licence to operate or not gain approval. Environment/ management credentials are significantly tarnished.	Serious public or media outcry (international coverage). Damaging NGO campaign. Licence to operate threatened. Reputation severely tarnished. Share price may be affected.
Injury and Disease	Low level short-term subjective inconvenience or symptoms. No measurable physical effects. No medical treatment required.	Objective but reversible disability/impairment and/or medical treatment, injuries requiring hospitalisation.	Moderate irreversible disability or impairment (<30%) to one or more persons.	Single fatality and/or severe irreversible disability or impairment (>30%) to one or more persons.	Short- or long-term health effects leading to multiple fatalities, or significant irreversible health effects to >50 persons.
	Low	**Minor**	**Moderate**	**Major**	**Critical**

Category			Consequence Severity				
			1	2	3	4	5
Likelihood	Almost Certain - Occurs 1 or more times a year	E	High	High	Extreme	Extreme	Extreme
	Likely - Occurs once every 1-10 years	D	Moderate	High	High	Extreme	Extreme
	Possible - Occurs once every 10-100 years	C	Low	Moderate	High	Extreme	Extreme
	Unlikely - Occurs once every 100-1,000 years	B	Low	Low	Moderate	High	Extreme
	Rare - Occurs once every 1,000-10,000 years	A	Low	Low	Moderate	High	High
Action Key	Low		No action is required, unless change in circumstances				
	Moderate		No additional controls are required, monitoring is required to ensure no changes in circumstances				
	High		Risk is high and additional control is required to manage risk				
	Extreme		Intolerable risk, mitigation is required				

Appendix III – List of Recommendations – Cruise Ship with LFR

No.	References	Action
1	1.1 General Comments – General Vessel Arrangement 4.2 Vessel Motion – Global Hazards 4.6 Vessel Capsizing – Global Hazards	Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc.
2	1.1 General Comments – General Vessel Arrangement	Considering radioactivity, end of life disposal is to be considered from beginning of the ship design to facilitate safe handling, removal and disposal of any parts, equipment's, material that might be contaminated with radioactive material.
3	1.1 General Comments – General Vessel Arrangement	Considering possibility of fire inside reactor compartment and considering radiation possibility, design principle should include minimizing fire possibility by using appropriate material and appropriate means are to be provided to fight fire in reactor and machinery compartment and structural design to consider fire load in design.
4	1.1 General Comments – General Vessel Arrangement 3.1 General Recommendation – Ship Construction 13.3 Fuel Charging & Refuelling – Nuclear Technology Hazards 14.2 Fuel Loading, Unloading, Storage – Nuclear Technology Hazards - Lead Fast Reactor	Ship design and construction are to consider nuclear reactor installation sequence and fuelling/refuelling sequence due to technology provider restriction, Shipyard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place. This may require special provision in mid-ship section to facilitate construction sequence and may pose challenge for construction.
5	1.1 General Comments – General Vessel Arrangement 3.1 General Recommendation – Ship Construction 10.1 General Comments – System Hazards - Dry Docking	Considering very specialised design and construction requirement for nuclear power plant related system and licensing requirement from OEM and regulatory agency capability of shipyard to construct or service such specialised ship are to be further investigated.
6	1.1 General Comments – General Vessel Arrangement	Reactor and its systems are to be designed to meet the design life of the cruise ship (typically 45 years) with refuelling on board.
7	1.1 General Comments – General Vessel Arrangement	Considering NPP application for passenger ship reliability and availability are most important aspect to supply power for marine system and hotel loads. Proper study is to be conducted to meet those target and appropriate design/system mitigation to be incorporated from beginning of such cruise ship.
8	1.1 General Comments – General Vessel Arrangement	Radiation control and its monitoring are to be provided on all area of ship where such risk exist considering passenger and staff in large number exist on ship.
9	1.1 General Comments – General Vessel Arrangement 4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards 4.6 Vessel Capsizing – Global Hazards	Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage.
10	1.1 General Comments – General Vessel Arrangement 8.1 Ventilation Air – System Hazards - Vent & Ventilation 8.2 Reactive material on passenger deck – System Hazards - Vent & Ventilation 8.3 Other Machinery Spaces – System Hazards - Vent & Ventilation	Considering where ventilation funnel is located and surrounding passenger area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height.

No.	References	Action
11	1.1 General Comments – General Vessel Arrangement	Investigate if it is appropriate to add reactor safety and radiation containment to the SRtP rules - or if reactor safety and radiation containment requirements post any single (or double) failure are to be managed by any nuclear passenger ship regulation.
12	1.1 General Comments – General Vessel Arrangement	Since there is workshop located near the nuclear reactor room, consider avoiding any equipment/system which can have potential stored energy, flammable/explosive material etc. A study to be conducted to minimise impact on surrounding and nuclear system due to incident/risk in workshop.
13	1.1 General Comments – General Vessel Arrangement	Considering nuclear room and machinery space is located at tank top level and there are various machinery below nuclear room deck level need to consider any potential for fire, explosion and proper mitigation to be provided e.g. Sewage plant has potential to release methane /sewer has which is fire/explosion hazards, any hydraulic system can also pose fire hazards, any rotating machinery may pose flying object hazards, etc. etc.
14	1.1 General Comments – General Vessel Arrangement 4.5 Collision – Global Hazards	Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design.
15	1.2 Hospital Area – General Vessel Arrangement	Further study to be done on medical oxygen leakage and explosion possibility and impact on nuclear reactor and control room.
16	1.2 Hospital Area – General Vessel Arrangement 8.5 Ventilation Philosophy – System Hazards - Vent & Ventilation	Further study is to be done for the ventilation philosophy of all surrounding areas to the nuclear reactor, e.g., positive or negative pressure areas to avoid possible contamination.
17	1.3 Safe Return to Port – General Vessel Arrangement	At early design stage considering safe return to port regulation and nuclear regulation, a design study to be done for the separation, redundancy, availability, back-up power requirement tec. to meet safe return to port criteria.
18	1.3 Safe Return to Port – General Vessel Arrangement	Considering nuclear ship propulsion regulations are not developed yet, but under consideration at IMO and nuclear agency, recommendation is to participate in such activities.
19	2.1 General Comments – Licensing & Approval Process	Nuclear-Powered vessels will travel to various countries and there is existing regulation related to export/licensing etc. a legislation is to be developed so ships can travel between various countries or legislation between countries and owner/technology OEM is to be developed to facilitate trade.
20	2.1 General Comments – Licensing & Approval Process 13.2 Security & External Threat – Nuclear Technology Hazards	Legislation and requirements are to be developed for external threat/risk such as hijacking, piracy, terror, flying object (missile, plane etc.) attack, etc. Ship designer and Technology developer need to consider such threat based on regulation
21	2.1 General Comments – Licensing & Approval Process	For Nuclear-Powered vessel liability related legislation is to be developed at international level for operation of such ship
22	2.1 General Comments – Licensing & Approval Process	Considering that licensing legislation/requirement to construct, operate and maintain nuclear power plant on ship does not exist and may force cost escalation, industry has to develop requirements to eliminate uncertainty. Participation in such activity is recommended.
23	2.1 General Comments – Licensing & Approval Process	Ports do not have any regulation at moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues.
24	2.1 General Comments – Licensing & Approval Process	Per nuclear regulation and technology provider there will be specialised training needed to operate NPP. A special training programme in cooperation with regulator and technology provider is to be developed and certification requirements are to be determined.
25	2.1 General Comments – Licensing & Approval Process 13.6 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Vessel design is to consider proper nuclear waste storage, handling and disposal as per nuclear regulation requirements generated during normal operation, maintenance, refuelling, etc. prior to proper disposal for life of ship. Proper monitoring is to be considered onboard for waste storage.
26	3.1 General Recommendation – Ship Construction 11.1 Dry Docking Hazards – System Hazards - Dropped Object & Energy Release	Study to be performed for risks anticipated during construction, installation process, maintenance and dry docking (e.g., dropped object) to prevent any damage to reactor and its system.

No.	References	Action
27	3.1 General Recommendation – Ship Construction 14.2 Fuel Loading, Unloading, Storage – Nuclear Technology Hazards - Lead Fast Reactor	Considering nuclear technology/industry has numerous existing regulations, which may require special licensing and training for shipyard and its supplier, selection of shipyard is to be further studied to meet all licensing and construction requirements.
28	3.1 General Recommendation – Ship Construction	Considering commercial maritime industry has limited to no knowledge on nuclear technology and its construction requirement, further training/cooperation is to be developed between shipyards, nuclear technology/equipment provider and nuclear regulator.
29	4.1 General Comments – Global Hazards 13.2 Security & External Threat – Nuclear Technology Hazards	Investigate proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them.
30	4.1 General Comments – Global Hazards	Further study is to be done on geo-political issues that may affect routes and destinations.
31	4.1 General Comments – Global Hazards	Impact of Non-Proliferation Treaty is to be further investigated and should be considered in design and operation of nuclear-powered vessels
32	4.1 General Comments – Global Hazards	Most SMR technology like LFR proposes to use TRISO particle fuel and availability of such fuel needs to be further studied for long term availability, licensing etc.
33	4.2 Vessel Motion – Global Hazards	Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactor, its component for life of design. In addition, considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered.
34	4.2 Vessel Motion – Global Hazards 4.3 Vessel Vibration – Global Hazards	Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such.
35	4.2 Vessel Motion – Global Hazards 4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards 4.6 Vessel Capsizing – Global Hazards	Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel.
36	4.3 Vessel Vibration – Global Hazards	Detailed vibration study is to be conducted and during commissioning and sea trial, vibrations are to be measured and calibrated with analysis. During operation and maintenance, vibration needs to be monitored to verify that vibration levels are within an acceptable design range.
37	4.3 Vessel Vibration – Global Hazards	Any area where radioactive material can spill or possibility of radiation leak are to be provided with biological shield to control radiation per applicable nuclear regulations
38	4.4 Grounding – Global Hazards	There is possibility of reactor compartment flooding due to grounding, collision, submergence etc. Design needs to consider such event. A study is to be performed into whether the existing IMO/SOLAS/Class requirements for damage penetration and stability are sufficient for nuclear-powered passenger ships.
39	4.4 Grounding – Global Hazards	Radiation shielding and insulation of reactor and reactor compartment to consider total flooding of compartment or alternate justification to be provided.
40	4.4 Grounding – Global Hazards	In case of flooding and depending on which systems are impacted, lead solidification may happen (loss of circulation, heating etc.). Design needs to consider such event in design and appropriate mitigation to be provided.
41	4.4 Grounding – Global Hazards	Grounding/collision/submergence etc. can lead to reactor's essential and auxiliary system damage and its impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship.
42	4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards 4.6 Vessel Capsizing – Global Hazards	A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety.
43	4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards 4.6 Vessel Capsizing – Global Hazards	A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety.

No.	References	Action
44	4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards 4.6 Vessel Capsizing – Global Hazards 4.7 Hull splitting (shallow water) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
45	4.7 Hull splitting (shallow water) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Salvage operations based ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew.
46	4.7 Hull splitting (shallow water) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Further study to be done on the submergence conditions of reactor and its system for the capability of the design to withstand external pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent any radiation leakage due to collapse of reactor and other system, including all penetrations into the reactor and system.
47	4.7 Hull splitting (shallow water) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Further study is to be done on the impact on the surroundings of any case of radiation leakage.
48	4.7 Hull splitting (shallow water) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Further study to be done on the Emergency Shut Down (ESD) philosophy of the reactor considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency.
49	4.9 Seismic Event – Global Hazards	Further study to be done on the process of choosing a shipyard considering nuclear regulation and proliferation matters.
50	4.9 Seismic Event – Global Hazards	Reactor and its system are to consider seismic event, tsunami, etc. probability, in design while in dry dock, port, channel etc.
51	4.10 Typhoon – Global Hazards	Identify a necessary study with flag, classification, yard and insurers for developing upper limits for the survivable environment of the cruise ship (separate from operational limits).
52	5.1 General Comments – Global Hazards - Ship Operation	Further study is to be done on the availability of having a one-hour readiness of the ship to leave the port (e.g., nuclear power for propulsion). Further study is to be done to ensure sufficient emergency and back-up power is available for necessary period of time taking into account the nuclear power plant, especially possible emergency cooling needs.
53	5.1 General Comments – Global Hazards - Ship Operation	Emergency protocol in case of accident related to nuclear system are to be developed considering nuclear exposure hazards.
54	5.1 General Comments – Global Hazards - Ship Operation	Due to radiation exposure risk in emergency situations, radiation medication and other primary care on site are to be provided.
55	5.1 General Comments – Global Hazards - Ship Operation	Radiation dispersion analysis for escaped radiation in case of accident are to be conducted and how it will affect lifesaving appliances and other passenger area are to be analyzed.
56	5.1 General Comments – Global Hazards - Ship Operation	Location of muster stations and their proximity to radiation zone and other high-risk area to be further studied based on radiation dispersion analysis.
57	5.1 General Comments – Global Hazards - Ship Operation	High efficiency filtration to capture radiation and minimise its impact is to be provided in all HVAC ducting where probability of radiation exists.
58	5.1 General Comments – Global Hazards - Ship Operation	Considering radiation exposure to passenger and crew consideration for propelled lifeboats to decrease escape time from ship and radiation zone around ship.
59	5.1 General Comments – Global Hazards - Ship Operation	In case of radiation detection on weather deck or any other contaminated area is to be closed and appropriate security, evacuation procedures are to be developed.
60	5.1 General Comments – Global Hazards - Ship Operation	Considering steam power plant is not the favourable option for commercial marine applications in the last decade, further study is to be done on the integration with nuclear plant manufacturer.
61	6.2 Bilge System – System Hazards	Considering radiation bilge system from any room which has potential for radiation is to be independent and bilge storage are to be provided to contain radioactive material, further study to be done to identify risk and proper mitigation measures are to be considered.

No.	References	Action
62	6.2 Bilge System – System Hazards	Further study to be done on potentially safely storing and disposal of bilged water in case of radioactivity.
63	6.2 Bilge System – System Hazards	Further study to be done on sizing of bilge system and Fire Fighting System (FFS) for reactor compartment and other reactor spaces.
64	6.2 Bilge System – System Hazards	Further study to be done on the ability of the bilge system to drain both the nuclear reactor room water and the Fire Fighting System (FFS) water quantity.
65	6.3 Emergency Response – System Hazards	Emergency and evacuation procedures are to be developed in addition to existing ones. In accordance with nuclear and maritime regulators.
66	6.3 Emergency Response – System Hazards	Personal Protection Equipment (PPE) quantity, location and disposal in case of exposure to radiation are to be considered based on dispersion analysis, radiation zone and nuclear regulations.
67	6.3 Emergency Response – System Hazards	Lab/Facility (radioactive laboratory) to be provided on ship to track exposure limit for crew and for management to limit radiation exposure.
68	6.3 Emergency Response – System Hazards	Emergency plan and Firefighting plan is to include location of Personal Protection Equipment (PPE) for radioactive exposure spaces. PPE requirement for radiation exposure to be further studied and need to meet nuclear regulator requirements.
69	7.1 Steam Release – System Hazards - Power & Propulsion 8.1 Ventilation Air – System Hazards - Vent & Ventilation	Materials used in nuclear applications are to be suitable for use in radioactive environment as per nuclear regulator and codes and standards requirements. Also, these materials are to be checked for application in marine environment as per classification/SOLAS/IMO rules.
70	7.1 Steam Release – System Hazards - Power & Propulsion	Detail shielding study to be performed at design stage to ensure radiation level is spaces are within acceptable limits per regulation requirements.
71	7.1 Steam Release – System Hazards - Power & Propulsion	Loss of steam pipe or any other piping consequence to be further studied and the impact on the reactor.
72	7.1 Steam Release – System Hazards - Power & Propulsion	Auxiliary and emergency backup power requirement need to be further studied per nuclear technology requirement and nuclear regulation to maintain nuclear reactor in safe condition in all conditions including emergency. Location on ship of auxiliary/emergency power is to be further studied for its availability considering all accidental conditions of ship and nuclear reactor.
73	7.2 Battery (Auxiliary) – System Hazards - Power & Propulsion	Further study to be done on the impact from battery fire on the reactor compartment.
74	7.2 Battery (Auxiliary) – System Hazards - Power & Propulsion	Further study to be done due to possibility of battery room explosion on reactor compartment.
75	7.2 Battery (Auxiliary) – System Hazards - Power & Propulsion	Consider providing blow out panel to minimise explosion consequences.
76	8.1 Ventilation Air – System Hazards - Vent & Ventilation	Further study to be done on all the failure causes from malfunction to the air inlet system.
77	8.1 Ventilation Air – System Hazards - Vent & Ventilation	Further study is to be done on ventilation requirements and mitigation measures in case of contaminated vent lines during incident or normal operation.
78	8.1 Ventilation Air – System Hazards - Vent & Ventilation	Further study is to be done on the criticality of the ventilation system and redundancy requirements.
79	8.1 Ventilation Air – System Hazards - Vent & Ventilation	Further study is to be done on radiation monitoring in case of back flow.
80	8.1 Ventilation Air – System Hazards - Vent & Ventilation 8.3 Other Machinery Spaces – System Hazards - Vent & Ventilation	Further study is to be done on the necessary air changes per hour.
81	8.1 Ventilation Air – System Hazards - Vent & Ventilation	Further study is to be done on additional fire structural/radiation barriers provided.
82	8.1 Ventilation Air – System Hazards - Vent & Ventilation	Further study is to be done on the dispersion of radioactive air from the exhaust system.
83	8.1 Ventilation Air – System Hazards - Vent & Ventilation	Study is to be conducted for air quality requirement for ventilation of reactor room and machinery/steam room considering marine air has high salinity and moisture.
84	8.2 Reactive material on passenger deck – System Hazards - Vent & Ventilation	Port operation procedures and emergency plan are to be developed considering radiation risk to host a vessel following a radioactive release.

No.	References	Action
	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	
85	8.2 Reactive material on passenger deck – System Hazards - Vent & Ventilation	Further study to be done on how to contain radioactive release within the compartment.
86	8.2 Reactive material on passenger deck – System Hazards - Vent & Ventilation	Mustering and evacuation plans are to be developed considering reactor emergency/accident. Location of muster stations and necessary air circulation for the muster area are to be further studied considering radiation leakage.
87	8.2 Reactive material on passenger deck – System Hazards - Vent & Ventilation	Further study to be done on other machinery space outside reactor room and ventilation in order to minimise radioactive exposure on deck.
88	8.3 Other Machinery Spaces – System Hazards - Vent & Ventilation	Further study to be done on ventilation ducts to avoid ventilation with nuclear compartment.
89	8.4 Condenser / Exhaust from Steam Cycle – System Hazards - Vent & Ventilation	Further study to be done on any system having a potential for radiation leakage on the stream side of the circuit.
90	9.1 Maintenance during operation – Maintenance and Inspection	Daily visual routine inspection requirements are to be further developed and detailed procedures are to be in place.
91	9.1 Maintenance during operation – Maintenance and Inspection	Access to certain areas e.g., reactor area compartments are to be restricted and only trained authorised personnel are to be permitted.
92	9.1 Maintenance during operation – Maintenance and Inspection	Total radiation exposure for each crew member is to be monitored and radiation exposure limits are to be established by nuclear regulator and to be followed to protect crew.
93	9.1 Maintenance during operation – Maintenance and Inspection	Detailed crew training and education plans are to be developed.
94	9.2 Shutdown – Maintenance and Inspection	Further study is to be done on the development of maintenance plans defining responsibilities between general and specialised crew considering the regulatory requirements.
95	9.2 Shutdown – Maintenance and Inspection	In case steam condenser or other contaminated machinery requires drainage, proper maintenance is to be provided.
96	10.1 General Comments – System Hazards - Dry Docking	Further study is to be done on procedure for dry docking security measures.
97	10.1 General Comments – System Hazards - Dry Docking	Further study to be done on dry docking survey and maintenance requirements from typical existing procedures to accommodate for nuclear power needs.
98	10.1 General Comments – System Hazards - Dry Docking 13.3 Fuel Charging & Refuelling – Nuclear Technology Hazards 14.2 Fuel Loading, Unloading, Storage – Nuclear Technology Hazards - Lead Fast Reactor	Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies are to be done.
99	10.1 General Comments – System Hazards - Dry Docking	Further study to be done on special licensing needed from nuclear regulator for dry docking.
100	10.1 General Comments – System Hazards - Dry Docking	Further study to be done on the possibility of earthquake, mainly when the ship is at construction and/or dry-dock supported from bottom (as per IAEA/NRC this is one of the assessments as part of PRA), and coordination with reactor manufacturer.
101	10.1 General Comments – System Hazards - Dry Docking	Total loss of SY power to be further studied for impact on reactor safety and requirement for all support system to maintain reactor safety to be developed and provided while in SY.
102	10.1 General Comments – System Hazards - Dry Docking	Security protocol and access control to be implemented
103	10.1 General Comments – System Hazards - Dry Docking 12.1 Fire on Passenger Area – System Hazards - Fire Fighting System (FFS)	Further studies are to be done on the provision of heat source to maintain liquid condition of the Molten Salt medium.
104	11.2 Kinetic/stored energy release – System Hazards - Dropped Object & Energy Release	Consider further foreign object study and strength of hull, specific to each ship as General Arrangement may be different, in way of reactor.
105	11.2 Kinetic/stored energy release – System Hazards - Dropped Object & Energy Release	Further study is to be done on potential energy impact and appropriate mitigation measures defined.

No.	References	Action
106	11.2 Kinetic/stored energy release – System Hazards - Dropped Object & Energy Release	Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
107	12.1 Fire on Passenger Area – System Hazards - Fire Fighting System (FFS)	Fire analysis is to be conducted, and appropriate active/passive firefighting mitigation measures are to be provided.
108	12.1 Fire on Passenger Area – System Hazards - Fire Fighting System (FFS)	Fire and smoke detector location study to be conducted considering reactor
109	12.1 Fire on Passenger Area – System Hazards - Fire Fighting System (FFS)	To enhance fire safety, additional class notations are to be considered related to fire and firefighting.
110	12.1 Fire on Passenger Area – System Hazards - Fire Fighting System (FFS)	Consider increased risk due to nuclear reactor on board. Additional requirements may come from IMO/Regulator or Flag regarding the development of enhanced safety for firefighting, fire protection, insulation, structure, etc.
111	12.1 Fire on Passenger Area – System Hazards - Fire Fighting System (FFS)	Further studies to be done on location of firefighting pumps.
112	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Number of Crew needed to operate nuclear reactor and its system are to be studied considering nuclear regulatory and technology provider requirement to operate.
113	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Considering nuclear regulation crew qualification, training, requirements for certification, background check etc. are required and detailed programme need to be developed.
114	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Investigate whether nuclear regulator is required on board ships all the time or not.
115	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Training programme considering existing regulation is to be developed.
116	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Port personnel to be trained in emergency and risk.
117	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements.
118	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Human Factor Engineering (HFE) analysis is to be conducted for operation as it is required under nuclear regulatory requirements.
119	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Regulatory requirements are to be checked for citizenship and security clearance requirement.
120	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards 13.2 Security & External Threat – Nuclear Technology Hazards	Further study to be done on the presence of a radiation officer on board.
121	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Appropriate drills for nuclear emergencies and or loss of containment of radiation should be developed with the regulator and/or flag.
122	13.2 Security & External Threat – Nuclear Technology Hazards	Proper security measures are to be developed in communication with regulator.
123	13.2 Security & External Threat – Nuclear Technology Hazards	Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.
124	13.2 Security & External Threat – Nuclear Technology Hazards	Access control measures are to be provided.
125	13.2 Security & External Threat – Nuclear Technology Hazards	Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber-attack. Transponder to be programmed to provide location of the reactor/vessel.
126	13.3 Fuel Charging & Refuelling – Nuclear Technology Hazards 14.2 Fuel Loading, Unloading, Storage – Nuclear Technology Hazards - Lead Fast Reactor	Further study to be done on refuelling process of the vessel and on how the reactor as a complete system would be removed as a complete system would be removed at the end of vessel's lifetime, or alternatively at the end of the reactor's lifetime (e.g., total loss incident of the reactor), whichever comes first.
127	13.4 Supporting Systems – Nuclear Technology Hazards	Further study is to be done on how lead will be maintained in liquid state during all operational and emergency situation.
128	13.4 Supporting Systems – Nuclear Technology Hazards	In emergency situation considering longer time required to maintain reactor safety the auxiliary and emergency generator are to be further studied.

No.	References	Action
129	13.4 Supporting Systems – Nuclear Technology Hazards	Control and monitoring systems in case of emergency may require more monitoring time than normal marine practices and are to be further studied with the regulators and the technology providers.
130	13.4 Supporting Systems – Nuclear Technology Hazards	Emergency systems are to be operated at a much higher angle of inclination and need to be considered for the system availability of equipment design.
131	13.4 Supporting Systems – Nuclear Technology Hazards	It is expected the control room needs to be accessible in case of emergency such as marine incidents (collision, grounding, heavy listing etc.). For such a condition further analysis is to be conducted for the crew's safety and operability.
132	13.4 Supporting Systems – Nuclear Technology Hazards	The requirements for crew/salvors to manually interact with the reactor safety & control systems during or after any abandonment should be considered
133	13.5 Heat Removal & Cooling – Nuclear Technology Hazards 14.1 General – Nuclear Technology Hazards - Lead Fast Reactor 14.3 Operation, Normal – Nuclear Technology Hazards - Lead Fast Reactor 14.5 Port Maneuvering – Nuclear Technology Hazards - Lead Fast Reactor 14.6 Harbour Operation – Nuclear Technology Hazards - Lead Fast Reactor	Considering ship power needs vary depending on operation and typically nuclear reactor operates on constant heat generation mode, a detailed study for the reactor design is to be conducted to accommodate ship load variation requirements to meet operational needs e.g., managing of excess extra heat due to low power requirements. Load variation may produce higher fatigue load and is to be considered in design. Capability to provide full power in short time is to be considered e.g., emergency departure in port.
134	13.5 Heat Removal & Cooling – Nuclear Technology Hazards	Further study to be done on HVAC of reactor compartment and exhaust from reactor compartment.
135	13.5 Heat Removal & Cooling – Nuclear Technology Hazards	Further study to be done on cooling of reactor and need to meet regulatory requirement.
136	13.6 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Further study to be done on detailed plan of handling of radioactive material at the end of ship life, before end of ship lifetime, or normal operation, maintenance e.g., hull, reactor core, piping, heat exchangers, pumps, any other exposed material.
137	13.6 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Further study to be done on disposal procedures.
138	14.1 General – Nuclear Technology Hazards - Lead Fast Reactor	Considering Lead corrosivity and marine environment, appropriate material are to be selected and detail testing to be conducted
139	14.2 Fuel Loading, Unloading, Storage – Nuclear Technology Hazards - Lead Fast Reactor	Ship design to consider nuclear fuel loading and removal in a safe manner per regulatory requirements.
140	14.3 Operation, Normal – Nuclear Technology Hazards - Lead Fast Reactor 14.6 Harbour Operation – Nuclear Technology Hazards - Lead Fast Reactor	Further study to be done on partial load operation of the reactor considering normal ship operation. there is a testing requirement for internal combustion engines for 110% load and it should be checked if such a testing approach is necessary for nuclear reactors and steam plants, particularly given specific testing requirements for nuclear reactors which will apply.
141	14.4 Radiation Shielding, Barrier – Nuclear Technology Hazards - Lead Fast Reactor	Further study to be done on the material and thickness of reactor biological shielding, cooling arrangement and ventilation with reactor technology provider and to comply with regulatory requirement.
142	14.5 Port Maneuvering – Nuclear Technology Hazards - Lead Fast Reactor 14.6 Harbor Operation – Nuclear Technology Hazards - Lead Fast Reactor	Further study is to be done if reactors run on partial load for extended period in port and large amount of heat have to be dissipated and the impact in marine environment e.g., increase in water temperature. All systems are to be designed to operate globally considering atmospheric and sea water temperature variation
143	15.1 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	Port of Refuge and Shelter law is to be further study as in emergency port of refuge can be questionable.
144	15.1 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	Further study is to be done on the potential of contamination in a port environment and the consequences for the local community.
145	15.1 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	Further study is to be done on the development of a protocol between port authorities and ship.
146	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	End of life Recycling and salvage to be further studied considering radiation hazards and procedures are to be developed
147	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Disposal of radioactive materials is to be further studied and proper procedure to be developed in accordance with local regulation for radioactive west.

No.	References	Action
148	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Considering reactor may be design for longer life compared to ship life, possibility of reactor transferred to another ship/location is to be considered from the initial stage of design.
149	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Further study is to be done on how the reactor will stay in place in case of the salvage process and radiation is contained.
150	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Further study is to be done on risk control options in place of active safety management during the salvage process.
151	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Salvage crews are to be specially trained to operate nuclear reactors.
152	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Port of safe refuge is to be considered and appropriate permission to enter is to be given.
153	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Further study is to be done on salvage scenarios and appropriate mitigating measures.
154	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Radiation survey on SSC prior to vessel dismantling.
155	16.1 New – Nuclear Technology Hazards - Ship Recycling & Salvage	Further study to be done on the dismantling of the reactor.
156	17.1 General Comments – Finance Risk & Liability	P&I Club and insurance entities are to be involved.
157	17.1 General Comments – Finance Risk & Liability	Regulations are to be developed so that liability can be defined.
158	17.1 General Comments – Finance Risk & Liability	Technology readiness and replacement are to be further studied.
159	17.1 General Comments – Finance Risk & Liability	Reactor replacement timing is to be further investigated.
160	17.1 General Comments – Finance Risk & Liability	Considering the availability of nuclear technology and availability of spare parts, further study is to be done.
161	17.1 General Comments – Finance Risk & Liability	Any accident or nuclear related incident is to be further included in the financial analysis.

Appendix IV – HAZID Register – Cruise Ship with LFR

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 1	**Name:** General Vessel Arrangement	
Design Intent:		
Description: General Vessel Arrangement		
Associated Drawings:		

No.: 1 **Name:** General Vessel Arrangement

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
1.1	General Comments		1.1.1. General Recommendation							Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc.

No.: 1	Name: General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 2. Considering radioactivity, end of life disposal is to be considered from beginning of the ship design to facilitate safe handling, removal and disposal of any parts, equipment's, material that might be contaminated with radioactive material. Rec 3. Considering possibility of fire inside reactor compartment and considering radiation possibility, design principle should include minimizing fire possibility by using appropriate material and appropriate means are to be provided to fight fire in reactor and machinery compartment and structural design to consider fire load in design. Rec 4. Ship design and construction are to consider nuclear reactor installation sequence and fuelling/refuelling sequence due to technology provider restriction, Shipyard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place. This may require special provision in mid-ship section to facilitate construction sequence and may pose challenge for construction. Rec 5. Considering very specialised design and construction requirement for nuclear power plant related system and licensing requirement from OEM and regulatory agency capability of shipyard to construct or service such specialised ship are to be further investigated.

No.: 1	**Name:** General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 6. Reactor and its systems are to be designed to meet the design life of the cruise ship (typically 45 years) with refuelling on board. Rec 7. Considering NPP application for passenger ship reliability and availability are most important aspect to supply power for marine system and hotel loads. Proper study is to be conducted to meet those target and appropriate design/system mitigation to be incorporated from beginning of such cruise ship. Rec 8. Radiation control and its monitoring are to be provided on all area of ship where such risk exist considering passenger and staff in large number exist on ship. Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 10. Considering where ventilation funnel is located and surrounding passenger area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height. Rec 11. Investigate if it is appropriate to add reactor safety and radiation containment to the SRtP rules - or if reactor safety and radiation containment requirements post any single (or double) failure are to be managed by any nuclear passenger ship regulation.

No.: 1	**Name:** General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 12. Since there is workshop located near the nuclear reactor room, consider avoiding any equipment/system which can have potential stored energy, flammable/explosive material etc. A study to be conducted to minimise impact on surrounding and nuclear system due to incident/risk in workshop. Rec 13. Considering nuclear room and machinery space is located at tank top level and there are various machinery below nuclear room deck level need to consider any potential for fire, explosion and proper mitigation to be provided e.g. Sewage plant has potential to release methane /sewer has which is fire/explosion hazards, any hydraulic system can also pose fire hazards, any rotating machinery may pose flying object hazards, etc. etc. Rec 14. Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design.
1.2	Hospital Area	Negative ventilation	1.2.1. Medical oxygen Leak **Comment:** Hospital is located next to reactor room	1.2.1. Explosion	Asset	Unlikely	Moderate	Moderate (6)	1.2.1. Medical oxygen inventory of hospital is kept to minimum quantity.	Rec 15. Further study to be done on medical oxygen leakage and explosion possibility and impact on nuclear reactor and control room.

No.: 1	**Name:** General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									1.2.2. Storage of medical oxygen is on aft mooring deck.	
				1.2.2. Damage to the reactor room/reactor	Overall	Rare	Major	High (4)		
			1.2.2. Radiation leakage inside hospital **Comment:** Depending on ventilation design	1.2.3. Human exposure to radiation	Injury	Possible	Moderate	High (9)		Rec 16. Further study is to be done for the ventilation philosophy of all surrounding areas to the nuclear reactor, e.g., positive or negative pressure areas to avoid possible contamination.
1.3	Safe Return to Port	Current regulations do not cover nuclear propulsion.	1.3.1. Single point of failure	1.3.1. Inability to return to port	Overall	Possible	Moderate	High (9)	1.3.1. Current design meets regulation having main control room and bridge control facility. 1.3.2. Two nuclear reactors and DG support	Rec 17. At early design stage considering safe return to port regulation and nuclear regulation, a design study to be done for the separation, redundancy, availability, back-up power requirement tec. to meet safe return to port criteria. Rec 18. Considering nuclear ship propulsion regulations are not developed yet, but under consideration at IMO and nuclear agency, recommendation is to participate in such activities.

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 2	**Name:** Licensing & Approval Process	
Design Intent:		
Description: Licensing & Approval Process		
Associated Drawings:		

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
2.1	General Comments		2.1.1. General Recommendation	2.1.1. General Comments - Finance Risk & Liability (see 17.1)						Rec 19. Nuclear-Powered vessels will travel to various countries and there is existing regulation related to export/licensing etc. a legislation is to be developed so ships can travel between various countries or legislation between countries and owner/technology OEM is to be developed to facilitate trade. Rec 20. Legislation and requirements are to be developed for external threat/risk such as hijacking, piracy, terror, flying object (missile, plane etc.) attack, etc. Ship designer and Technology developer need to consider such threat based on regulation Rec 21. For Nuclear-Powered vessel liability related legislation is to be developed at international level for operation of such ship Rec 22. Considering that licensing legislation/requirement to construct, operate and maintain nuclear power plant on ship does not exist and may force cost escalation, industry has to develop requirements to eliminate uncertainty. Participation in such activity is recommended.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 23. Ports do not have any regulation at moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues. Rec 24. Per nuclear regulation and technology provider there will be specialised training needed to operate NPP. A special training programme in cooperation with regulator and technology provider is to be developed and certification requirements are to be determined. Rec 25. Vessel design is to consider proper nuclear waste storage, handling and disposal as per nuclear regulation requirements generated during normal operation, maintenance, refuelling, etc. prior to proper disposal for life of ship. Proper monitoring is to be considered onboard for waste storage.

Title: Cruise Ship		**Company:**	**Method:** HAZID
No.: 3	**Name:** Ship Construction		
Design Intent:			
Description: Ship Construction			
Associated Drawings:			

No.: 3	**Name:** Ship Construction									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
3.1	General Recommendation	Nuclear ships are expected to require less time than shore power plants due to more efficient processes and on site assembly of technologies	3.1.1. General recommendation							Rec 4. Ship design and construction are to consider nuclear reactor installation sequence and fuelling/refuelling sequence due to technology provider restriction, Shipyard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place. This may require special provision in mid-ship section to facilitate construction sequence and may pose challenge for construction. Rec 5. Considering very specialised design and construction requirement for nuclear power plant related system and licensing requirement from OEM and regulatory agency capability of shipyard to construct or service such specialised ship are to be further investigated. Rec 26. Study to be performed for risks anticipated during construction, installation process, maintenance and dry docking (e.g., dropped object) to prevent any damage to reactor and its system.

No.: 3	**Name:** Ship Construction									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 27. Considering nuclear technology/industry has numerous existing regulations, which may require special licensing and training for shipyard and its supplier, selection of shipyard is to be further studied to meet all licensing and construction requirements. Rec 28. Considering commercial maritime industry has limited to no knowledge on nuclear technology and its construction requirement, further training/cooperation is to be developed between shipyards, nuclear technology/equipment provider and nuclear regulator.

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 4	**Name:** Global Hazards	
Design Intent:		
Description: Global Hazards		
Associated Drawings:		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.1	General Comments		4.1.1. General							Rec 29. Investigate proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them. Rec 30. Further study is to be done on geo-political issues that may affect routes and destinations. Rec 31. Impact of Non-Proliferation Treaty is to be further investigated and should be considered in design and operation of nuclear-powered vessel. Rec 32. Most SMR technology like LFR proposes to use TRISO particle fuel and availability of such fuel needs to be further studied for long term availability, licensing etc.
			4.1.2. Incident Liability							Rec 29. Investigate proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them. Rec 30. Further study is to be done on geo-political issues that may affect routes and destinations. Rec 31. Impact of Non-Proliferation Treaty is to be further investigated and should be considered in design and operation of nuclear-powered vessels.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 32. Most SMR technology like LFR proposes to use TRISO particle fuel and availability of such fuel needs to be further studied for long term availability, licensing etc.
4.2	Vessel Motion	SOLAS requirements define tolerance to 30 ° static and 45° dynamic inclination.	4.2.1. Marine environment	4.2.1. Rocking motion leading to reactor lead sloshing damaging internal parts	Overall	Possible	Major	Extreme (12)	4.2.1. Proper machinery support.	Rec 33. Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design need to consider such load and impact on reactor, its component for life of design. In addition considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered. Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel.
				4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)		
				4.2.4. Unable to control reaction etc. due to internal damage	Overall	Possible	Major	Extreme (12)		
				4.2.5. Impact on reactor operability	Overall	Possible	Major	Extreme (12)		

No.: 4 **Name:** Global Hazards

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
			4.2.2. Vessel motion	4.2.1. Rocking motion leading to reactor lead sloshing damaging internal parts	Overall	Possible	Major	Extreme (12)	4.2.1. Proper machinery support.	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc. Rec 33. Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design need to consider such load and impact on reactor, its component for life of design. In addition considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered. Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)		
				4.2.5. Impact on reactor operability	Overall	Possible	Major	Extreme (12)		
				4.2.7. Damage to concrete biological shield due to material brittleness	Asset	Unlikely	Major	High (8)		
			4.2.3. Bottom slamming	4.2.2. High acceleration of reactor/machinery foundations leading to foundation damage	Asset	Possible	Moderate	High (9)	4.2.1. Proper machinery support.	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 33. Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design need to consider such load and impact on reactor, its component for life of design. In addition considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered. Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such.
				4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)		

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.2.4. Vessel acceleration.	4.2.1. Rocking motion leading to reactor lead sloshing damaging internal parts	Overall	Possible	Major	Extreme (12)	4.2.1. Proper machinery support.	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc. Rec 33. Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design need to consider such load and impact on reactor, its component for life of design. In addition considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered. Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such.

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.2.2. High acceleration of reactor/machinery foundations leading to foundation damage	Asset	Possible	Moderate	High (9)		
				4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)		
				4.2.4. Unable to control reaction etc. due to internal damage	Overall	Possible	Major	Extreme (12)		
				4.2.5. Impact on reactor operability	Overall	Possible	Major	Extreme (12)		
				4.2.6. Weight shift leading to loss of vessel stability.	Overall	Possible	Moderate	High (9)		
				4.2.7. Damage to concrete biological shield due to material brittleness	Asset	Unlikely	Major	High (8)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.2.5. Freak wave hitting ship.	4.2.1. Rocking motion leading to reactor lead sloshing damaging internal parts	Overall	Possible	Major	Extreme (12)	4.2.1. Proper machinery support.	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc. Rec 33. Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design need to consider such load and impact on reactor, its component for life of design. In addition considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered. Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such.

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.2.2. High acceleration of reactor/machinery foundations leading to foundation damage	Asset	Possible	Moderate	High (9)		
				4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)		
				4.2.4. Unable to control reaction etc. due to internal damage	Overall	Possible	Major	Extreme (12)		
				4.2.5. Impact on reactor operability	Overall	Possible	Major	Extreme (12)		
				4.2.6. Weight shift leading to loss of vessel stability.	Overall	Possible	Moderate	High (9)		
				4.2.7. Damage to concrete biological shield due to material brittleness	Asset	Unlikely	Major	High (8)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.2.6. Resonance from shaft.	4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)	4.2.1. Proper machinery support.	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc. Rec 33. Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design need to consider such load and impact on reactor, its component for life of design. In addition considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered. Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.2.4. Unable to control reaction etc. due to internal damage	Overall	Possible	Major	Extreme (12)		
				4.2.5. Impact on reactor operability	Overall	Possible	Major	Extreme (12)		
				4.2.7. Damage to concrete biological shield due to material brittleness	Asset	Unlikely	Major	High (8)		
			4.2.7. Gyroscopic effect **Comment:** The gyroscopic effect is the resistance to the change of the axis of rotation of a spinning object. When a spinning object is subjected to a torque that tries to tilt or rotate its axis, the object will rotate about a third axis perpendicular to both the original axis and the torque axis.	4.2.1. Rocking motion leading to reactor lead sloshing damaging internal parts	Overall	Possible	Major	Extreme (12)	4.2.1. Proper machinery support.	Rec 33. Considering ship motion, liquid lead can produce extremely high sloshing load and may have potential to damage reactor and its internal components and machinery. Reactor design need to consider such load and impact on reactor, its component for life of design. In addition considering it has high impact on safety detailed inspection/maintenance/monitoring to be considered. Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such.
				4.2.2. High acceleration of reactor/machinery foundations leading to foundation damage	Asset	Possible	Moderate	High (9)		
				4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)		

No.: 4	Name: Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.2.4. Unable to control reaction etc. due to internal damage	Overall	Possible	Major	Extreme (12)		
				4.2.5. Impact on reactor operability	Overall	Possible	Major	Extreme (12)		
				4.2.6. Weight shift leading to loss of vessel stability.	Overall	Possible	Moderate	High (9)		
				4.2.7. Damage to concrete biological shield due to material brittleness	Asset	Unlikely	Major	High (8)		
			4.2.8. Vessel Vibration (see 4.3)	4.2.3. Damage to machinery	Asset	Possible	Minor	Moderate (6)		
4.3	Vessel Vibration		4.3.1. Component induced vibration - propeller, rotating machinery, bow slamming, wave, ship motion etc.	4.3.1. Damage to the foundations of the reactor	Asset	Possible	Moderate	High (9)		Rec 34. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such. Rec 36. Detailed vibration study is to be conducted and during commissioning and sea trial, vibrations are to be measured and calibrated with analysis. During operation and maintenance, vibration needs to be monitored to verify that vibration levels are within an acceptable design range. Rec 37. Any area where radioactive material can spill or possibility of radiation leak are to be provided with biological shield to control radiation per applicable nuclear regulations
				4.3.2. Damage to component, piping, connections etc.	Asset	Likely	Moderate	High (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.3.3. Radioactive material leakage/spill	Environmental	Possible	Moderate	High (9)		
				4.3.4. Potential for radiation exposure	Injury	Possible	Moderate	High (9)		
				4.3.5. Vessel Motion (see 4.2)						
4.4	Grounding		4.4.1. Grounding	4.4.1. Damage to the hull structure.	Asset	Possible	Moderate	High (9)	4.4.1. Adequate design of ship. B/20 standard margin 4.4.2. Compartmentalisation 4.4.3. Thermal Management 4.4.4. Radioactivity management. **Comment:** Active/Passive control rod lifting 4.4.5. Emergency Shut Down (ESD) **Comment:** Further study to be done on the compartment flooding. 4.4.6. Monitoring of water ingress in critical compartments. 4.4.7. Release mechanism to avoid overpressure in reactor compartment 4.4.8. All essential supporting equipment is to be positioned outside flooding zone. **Comment:** Heating & Cooling system.	Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel. Rec 38. There is possibility of reactor compartment flooding due to grounding, collision, submergence etc. design need to consider such event. A study is to be performed into whether the existing IMO/SOLAS/Class requirements for damage penetration and stability are sufficient for nuclear-powered passenger ships. Rec 39. Radiation shielding and insulation of reactor and reactor compartment to consider total flooding of compartment or alternate justification to be provided.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 40. In case of flooding and depending on which systems are impacted lead solidification may happen (loss of circulation, heating etc.). Design needs to consider such event in design and appropriate mitigation to be provided. Rec 41. Grounding/collision/submergence etc. can lead to reactor essential and auxiliary system damage and its impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship. Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
				4.4.2. Flooding of reactor compartment	Overall	Possible	Major	Extreme (12)		
				4.4.3. Steam generation from contact of flooding water with the reactor walls	Asset	Possible	Moderate	High (9)		
				4.4.4. Over pressurisation of reactor compartment due to steam generation	Overall	Possible	Moderate	High (9)		
				4.4.5. Solidification of lead due to cool down/system loss	Asset	Possible	Major	Extreme (12)		
				4.4.6. Damage to the reactor.	Overall	Unlikely	Major	High (8)		
				4.4.7. Damage of auxiliary machinery spaces (cooling water circuit, cooling water tank)	Asset	Unlikely	Moderate	Moderate (6)		
				4.4.8. Progressive flooding, loss of stability.	Asset	Unlikely	Major	High (8)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.4.9. Human exposure to radiation	Injury	Possible	Moderate	High (9)		
				4.4.10. Bilge System - System Hazards (see 6.2)						
				4.4.11. New - Nuclear Technology Hazards - Ship Recycling & Salvage (see 16.1)						
			4.4.3. Collision (see 4.5)							
			4.4.4. Vessel Capsizing (see 4.6)							
4.5	Collision		4.5.1. Collision	4.5.1. Damage to the hull	Asset	Possible	Moderate	High (9)	4.5.1. Design has a separate control room on the bridge. 4.5.2. Position of reactor in safe position away from damage penetration zone 4.5.3. Conformity with B/5 regulations prerequisite 4.5.4. Good seafarer practice, training, pilotage in channel port area etc.	Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 14. Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
				4.5.2. Flooding	Overall	Possible	Major	Extreme (12)		
				4.5.3. Damage to steam generator plant	Asset	Unlikely	Moderate	Moderate (6)		
				4.5.4. Damage to gas turbine plant	Asset	Possible	Moderate	High (9)		
				4.5.5. Damage to the reactor compartment	Overall	Unlikely	Major	High (8)		

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.5.6. Damage to control room **Comment:** Located in Deck 3.	Asset	Possible	Minor	Moderate (6)		
				4.5.7. Loss of vessel stability	Overall	Possible	Major	Extreme (12)		
				4.5.8. Grounding (see 4.4)						
				4.5.9. Vessel Capsizing (see 4.6)						
				4.5.10. Bilge System - System Hazards (see 6.2)						
				4.5.11. New - Nuclear Technology Hazards - Ship Recycling & Salvage (see 16.1)						

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.6	Vessel Capsizing		4.6.1. Extreme wave	4.6.1. Partial flooding	Overall	Possible	Moderate	High (9)	4.6.1. Vessel design to IMO/SOLAS and class rules 4.6.2. Safe navigation practices 4.6.3. Emergency Shut Down (ESD)	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc. Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel.

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Vessel capsizing	Overall	Unlikely	Major	High (8)		
				4.6.4. Grounding (see 4.4)						

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.6.2. Extreme roll and motion	4.6.1. Partial flooding	Overall	Possible	Moderate	High (9)	4.6.1. Vessel design to IMO/SOLAS and class rules 4.6.2. Safe navigation practices 4.6.3. Emergency Shut Down (ESD)	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc. Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Vessel capsizing	Overall	Unlikely	Major	High (8)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.6.3. Soft Grounding	4.6.1. Partial flooding	Overall	Possible	Moderate	High (9)	4.6.1. Vessel design to IMO/SOLAS and class rules 4.6.2. Safe navigation practices 4.6.3. Emergency Shut Down (ESD)	Rec 1. Various additional loads and operational conditions exist in marine application for use of nuclear technology, which is typically certified for land-based application, such condition/loads for its machinery, system (primary, secondary, auxiliary) are to be considered. Ship operation in normal, upset, emergency, shutdown operation and accidental condition are to be considered for reactor design. Additional loads on reactor design to consider are due to ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earth quack load during dry docking, Typhoon, etc. Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Vessel capsizing	Overall	Unlikely	Major	High (8)		
			4.6.4. Mistake - maintenance/operation of ballast water system	4.6.1. Partial flooding	Overall	Possible	Moderate	High (9)	4.6.1. Vessel design to IMO/SOLAS and class rules 4.6.2. Safe navigation practices 4.6.3. Emergency Shut Down (ESD)	Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel. Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Vessel capsizing	Overall	Unlikely	Major	High (8)		

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.6.5. Partial flooding	4.6.1. Partial flooding	Overall	Possible	Moderate	High (9)	4.6.1. Vessel design to IMO/SOLAS and class rules 4.6.2. Safe navigation practices 4.6.3. Emergency Shut Down (ESD)	Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel. Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Vessel capsizing	Overall	Unlikely	Major	High (8)		
			4.6.6. Gravity will not allow safety systems e.g., drainage system to function	4.6.1. Partial flooding	Overall	Possible	Moderate	High (9)	4.6.1. Vessel design to IMO/SOLAS and class rules 4.6.2. Safe navigation practices 4.6.3. Emergency Shut Down (ESD)	Rec 9. Environmental impact study in case of flooding, sinking or capsizing event is to be conducted considering radioactive material leakage. Rec 35. Reactor support and structure are to be designed to stay in place considering various dynamic loads, sinking of vessel, flooding of reactor room etc. consideration should be to provide support to the floatation and structure of the vessel. Rec 42. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 43. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Vessel capsizing	Overall	Unlikely	Major	High (8)		
			4.6.7. Collision (see 4.5)							
			4.6.8. Hull splitting (shallow water) (see 4.7)							
4.7	Hull splitting (shallow water)		4.7.1. Weather loading.	4.7.1. Hull split	Asset	Possible	Major	Extreme (12)	4.7.1. Creation of operational processes. 4.7.2. Sufficient hull design. 4.7.3. Emergency Shut Down (ESD) of reactor	Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Rec 45. Salvage operations based ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew.

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 46. Further study to be done on the submergence conditions of reactor and its system for the capability of the design to withstand external pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent any radiation leakage due to collapse of reactor and other system, including all penetrations into the reactor and system. Rec 47. Further study is to be done on the impact on the surroundings of any case of radiation leakage. Rec 48. Further study to be done on the Emergency Shut Down (ESD) philosophy of the reactor considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency.
				4.7.2. Reactor compartment flooding	Overall	Possible	Moderate	High (9)		
				4.7.3. Equipment damage	Asset	Possible	Major	Extreme (12)		
				4.7.4. Radiation leakage (Environmental)	Environmental	Possible	Major	Extreme (12)		
				4.7.5. Radiation leakage (Perceptions - Reputation)	Reputation	Possible	Major	Extreme (12)		
				4.7.6. Radiation leakage (Human Exposure to the Surroundings)	Injury	Possible	Major	Extreme (12)		
				4.7.7. Radiation leakage (Asset)	Environmental	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.7.2. Hull degradation and fatigue.	4.7.1. Hull split	Asset	Possible	Major	Extreme (12)	4.7.1. Creation of operational processes. 4.7.2. Sufficient hull design. 4.7.3. Emergency Shut Down (ESD) of reactor	Rec 45. Salvage operations based ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Rec 46. Further study to be done on the submergence conditions of reactor and its system for the capability of the design to withstand external pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent any radiation leakage due to collapse of reactor and other system, including all penetrations into the reactor and system. Rec 47. Further study is to be done on the impact on the surroundings of any case of radiation leakage. Rec 48. Further study to be done on the Emergency Shut Down (ESD) philosophy of the reactor considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency.
				4.7.2. Reactor compartment flooding	Overall	Possible	Moderate	High (9)		
				4.7.3. Equipment damage	Asset	Possible	Major	Extreme (12)		
				4.7.4. Radiation leakage (Environmental)	Environmental	Possible	Major	Extreme (12)		
				4.7.5. Radiation leakage (Perceptions - Reputation)	Reputation	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.7.6. Radiation leakage (Human Exposure to the Surroundings)	Injury	Possible	Major	Extreme (12)		
				4.7.7. Radiation leakage (Asset)	Environmental	Possible	Major	Extreme (12)		
4.8	Hull splitting and sinking		4.8.1. Weather loading.	4.8.1. Hull split	Asset	Possible	Major	Extreme (12)	4.8.1. Creation of operational processes. 4.8.2. Sufficient hull design. 4.8.3. Emergency Shut Down (ESD) of reactor	Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Rec 45. Salvage operations based ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Rec 46. Further study to be done on the submergence conditions of reactor and its system for the capability of the design to withstand external pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent any radiation leakage due to collapse of reactor and other system, including all penetrations into the reactor and system. Rec 47. Further study is to be done on the impact on the surroundings of any case of radiation leakage.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 48. Further study to be done on the Emergency Shut Down (ESD) philosophy of the reactor considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency.
				4.8.2. Reactor compartment flooding	Overall	Possible	Moderate	High (9)		
				4.8.3. Equipment damage	Asset	Possible	Major	Extreme (12)		
				4.8.4. Radiation leakage (Environmental)	Environmental	Possible	Major	Extreme (12)		
				4.8.5. Radiation leakage (Perceptions - Reputation)	Reputation	Possible	Major	Extreme (12)		
				4.8.6. Radiation leakage (Human Exposure to the Surroundings)	Injury	Possible	Major	Extreme (12)		
				4.8.7. Radiation leakage (Asset)	Environmental	Possible	Major	Extreme (12)		
				4.8.8. Sinking	Asset	Possible	Critical	Extreme (15)		
			4.8.2. Hull degradation and fatigue.	4.8.1. Hull split	Asset	Possible	Major	Extreme (12)	4.8.1. Creation of operational processes. 4.8.2. Sufficient hull design. 4.8.3. Emergency Shut Down (ESD) of reactor	Rec 44. Marine salvage and refloating operation with risk control option is to be considered from initial stage of design and detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc.

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 45. Salvage operations based ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Rec 46. Further study to be done on the submergence conditions of reactor and its system for the capability of the design to withstand external pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent any radiation leakage due to collapse of reactor and other system, including all penetrations into the reactor and system. Rec 47. Further study is to be done on the impact on the surroundings of any case of radiation leakage. Rec 48. Further study to be done on the Emergency Shut Down (ESD) philosophy of the reactor considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency.
				4.8.2. Reactor compartment flooding	Overall	Possible	Moderate	High (9)		
				4.8.3. Equipment damage	Asset	Possible	Major	Extreme (12)		
				4.8.4. Radiation leakage (Environmental)	Environmental	Possible	Major	Extreme (12)		
				4.8.5. Radiation leakage (Perceptions - Reputation)	Reputation	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.8.6. Radiation leakage (Human Exposure to the Surroundings)	Injury	Possible	Major	Extreme (12)		
				4.8.7. Radiation leakage (Asset)	Environmental	Possible	Major	Extreme (12)		
				4.8.8. Sinking	Asset	Possible	Critical	Extreme (15)		
4.9	Seismic Event		4.9.1. Earthquake while at shipyard.	4.9.1. Tsunami leading to damage to ship/reactor	Asset	Possible	Major	Extreme (12)		Rec 49. Further study to be done on the process of choosing a shipyard considering nuclear regulation and proliferation matters. Rec 50. Reactor and its system are to consider seismic event, tsunami, etc. probability, in design while in dry dock, port, channel etc.
				4.9.2. Damage to Biological Shield	Environmental	Possible	Moderate	High (9)		
				4.9.3. Damage on the reactor couplers.	Asset	Possible	Moderate	High (9)		
				4.9.4. Damage to the reactor	Asset	Possible	Major	Extreme (12)		
			4.9.2. Earthquake while at dry docking	4.9.2. Damage to Biological Shield	Environmental	Possible	Moderate	High (9)		Rec 49. Further study to be done on the process of choosing a shipyard considering nuclear regulation and proliferation matters. Rec 50. Reactor and its system are to consider seismic event, tsunami, etc. probability, in design while in dry dock, port, channel etc.
				4.9.3. Damage on the reactor couplers.	Asset	Possible	Moderate	High (9)		
				4.9.4. Damage to the reactor	Asset	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.9.3. Tsunami	4.9.1. Tsunami leading to damage to ship/reactor	Asset	Possible	Major	Extreme (12)		Rec 49. Further study to be done on the process of choosing a shipyard considering nuclear regulation and proliferation matters. Rec 50. Reactor and its system are to consider seismic event, tsunami, etc. probability, in design while in dry dock, port, channel etc.
				4.9.2. Damage to Biological Shield	Environmental	Possible	Moderate	High (9)		
				4.9.3. Damage on the reactor couplers.	Asset	Possible	Moderate	High (9)		
				4.9.4. Damage to the reactor	Asset	Possible	Major	Extreme (12)		
			4.9.5.	4.9.2. Damage to Biological Shield	Environmental	Possible	Moderate	High (9)		
			4.9.6. General Comments - System Hazards - Dry Docking (see 10.1)							
4.10	Typhoon		4.10.1. Typhoon	4.10.1. Damage of the vessel	Asset	Possible	Major	Extreme (12)	4.10.1. Weather monitoring and routing	Rec 51. Identify a necessary study with flag, classification, yard and insurers for developing upper limits for the survivable environment of the cruise ship (separate from operational limits).
				4.10.2. Damage to the reactor	Asset	Possible	Critical	Extreme (15)		
			4.10.2. General Comments - System Hazards - Dry Docking (see 10.1)							

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 5	**Name:** Global Hazards - Ship Operation	
Design Intent:		
Description: Global Hazards - Ship Operation		
Associated Drawings:		

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
5.1	General Comments		5.1.1. General Recommendation **Comment:** No additional item identified relative to nuclear propulsion						5.1.1. Instructions on how to assemble in a muster station 5.1.2. Metering devices/detectors in the muster area	Rec 52. Further study is to be done on the availability of having a one hour readiness of the ship to leave the port (e.g., nuclear power for propulsion). Further study is to be done to ensure sufficient emergency and back-up power is available for necessary period of time taking into account the nuclear power plant, especially possible emergency cooling needs. Rec 53. Emergency protocol in case of accident related to nuclear system are to be developed considering nuclear exposure hazards. Rec 54. Due to radiation exposure risk in emergency situations, radiation medication and other primary care on site are to be provided.

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 55. Radiation dispersion analysis for escaped radiation in case of accident are to be conducted and how it will affect life saving appliances and other passenger area are to be analyzed. Rec 56. Location of muster stations and their proximity to radiation zone and other high risk area to be further studied based on radiation dispersion analysis. Rec 57. High efficiency filtration to capture radiation and minimise its impact is to be provided in all HVAC ducting where probability of radiation exists. Rec 58. Considering radiation exposure to passenger and crew consideration for propelled lifeboats to decrease escape time from ship and radiation zone around ship.

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 59. In case of radiation detection on weather deck or any other contaminated area is to be closed and appropriate security, evacuation procedures are to be developed.

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 6	**Name:** System Hazards	
Design Intent:		
Description: System Hazards		
Associated Drawings:		

No.: 6 **Name:** System Hazards

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
6.1	Piping, Material and Supporting Material		6.1.1. High temperature - Thermal stress.	6.1.1. Pipe failure.	Asset	Possible	Major	Extreme (12)	6.1.3. Design considers thermal stress and fatigue.	
			6.1.2. Corrosion.	6.1.1. Pipe failure.	Asset	Possible	Major	Extreme (12)	6.1.1. Proper material characterisation and selection. 6.1.2. Follow existing nuclear regulation for qualification.	
				6.1.2. High pressure steam leakage.	Overall	Possible	Moderate	High (9)		
			6.1.3. Bubble creation.	6.1.1. Pipe failure.	Asset	Possible	Major	Extreme (12)	6.1.1. Proper material characterisation and selection. 6.1.2. Follow existing nuclear regulation for qualification. 6.1.3. Design considers thermal stress and fatigue.	

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
6.2	Bilge System		6.2.1. Water ingress	6.2.1. Flooding	Asset	Possible	Moderate	High (9)	6.2.1. Bilge system inside reactor compartment	Rec 61. Considering radiation bilge system from any room which has potential for radiation is to be independent and bilge storage are to be provided to contain radio active material, further study to be done to identify risk and proper mitigation measures are to be considered. Rec 62. Further study to be done on potentially safely storing and disposal of bilged water in case of radioactivity. Rec 63. Further study to be done on sizing of bilge system and Fire Fighting System (FFS) for reactor compartment and other reactor spaces.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 64. Further study to be done on the ability of the bilge system to drain both the nuclear reactor room water and the Fire Fighting System (FFS) water quantity.
				6.2.2. Contamination	Overall	Possible	Major	Extreme (12)		
			6.2.2. Grounding - Global Hazards (see 4.4)							
			6.2.3. Collision - Global Hazards (see 4.5)							
6.3	Emergency Response		6.3.1. General Recommendation						6.3.1. Personal Protection Equipment (PPE)	Rec 65. Emergency and evacuation procedures are to be developed in addition to existing ones. In accordance with nuclear and maritime regulators. Rec 66. Personal Protection Equipment (PPE) quantity, location and disposal in case of exposure to radiation are to be considered based on dispersion analysis, radiation zone and nuclear regulations.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 67. Lab/Facility (radioactive laboratory) to be provided on ship to track exposure limit for crew and for management to limit radiation exposure. Rec 68. Emergency plan and Fire fighting plan is to include location of Personal Protection Equipment (PPE) for radioactive exposure spaces. PPE requirement for radiation exposure to be further studied and need to meet nuclear regulator requirements.

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 7	**Name:** System Hazards - Power & Propulsion	
Design Intent:		
Description: System Hazards - Power & Propulsion		
Associated Drawings:		

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
7.1	Steam Release	Majority of incidents are concerned with the steam plant rather than the nuclear reactor.	7.1.1. Pipe degradation inside reactor room **Comment:** vibration, corrosion, fatigue, overloading	7.1.1. Release of super heated Steam upon pipe break.	Asset	Possible	Moderate	High (9)	7.1.1. Radiation Shield 7.1.2. Design according to nuclear regulations. 7.1.3. Full redundancy of reactors 7.1.4. Inherently safe design 7.1.5. Solidification of lead leads to safe condition for reactor	Rec 69. Materials used in nuclear application are to be suitable for use in radioactive environment as per nuclear regulator and codes and standards requirements. Also, these materials are to be checked for application in marine environment as per classification/SOLAS/IMO rules. Rec 70. Detail shielding study to be performed at design stage to ensure radiation level is spaces are within acceptable limits per regulation requirements. Rec 71. Loss of steam pipe or any other piping consequence to be further studied and the impact on the reactor.
				7.1.2. Release of radiation inside reactor room due to radioactive steam **Comment:** Steam may be radiated	Environmental	Possible	Moderate	High (9)		
				7.1.4. Inability to extract heat from the reactor	Overall	Possible	Major	Extreme (12)		
				7.1.5. Solidification of lead	Asset	Unlikely	Major	High (8)		

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				7.1.6. Potential for reactor explosion if heat is not removed	Overall	Unlikely	Critical	Extreme (10)		
				7.1.7. Reactor not available, loss of power generation						
			7.1.2. Pipe Degradation outside of reactor room	7.1.1. Release of super heated Steam upon pipe break.	Asset	Possible	Moderate	High (9)	7.1.1. Radiation Shield 7.1.2. Design according to nuclear regulations. 7.1.3. Full redundancy of reactors	Rec 70. Detail shielding study to be performed at design stage to ensure radiation level is spaces are within acceptable limits per regulation requirements.
				7.1.2. Release of radiation inside reactor room due to radioactive steam **Comment:** Steam may be radiated	Environmental	Possible	Moderate	High (9)		
				7.1.3. Human exposure and injury	Injury	Unlikely	Moderate	Moderate (6)		
				7.1.4. Inability to extract heat from the reactor	Overall	Possible	Major	Extreme (12)		
				7.1.5. Solidification of lead	Asset	Unlikely	Major	High (8)		
				7.1.6. Potential for reactor explosion if heat is not removed	Overall	Unlikely	Critical	Extreme (10)		
				7.1.7. Reactor not available, loss of power generation						

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			7.1.3. Loss of back-up power/heat.	7.1.5. Solidification of lead	Asset	Unlikely	Major	High (8)	7.1.2. Design according to nuclear regulations. 7.1.4. Inherently safe design 7.1.5. Solidification of lead leads to safe condition for reactor	Rec 72. Auxiliary and emergency backup power requirement need to be further studied per nuclear technology requirement and nuclear regulation to maintain nuclear reactor in safe condition in all conditions including emergency. Location on ship of auxiliary/emergency power is to be further studied for its availability considering all accidental condition of ship and nuclear reactor.
				7.1.6. Potential for reactor explosion if heat is not removed	Overall	Unlikely	Critical	Extreme (10)		
7.2	Battery (Auxiliary)	In case Battery is provided for back-up power or starting need	7.2.1. Battery explosion **Comment:** Li-Ion Battery	7.2.1. Damage to reactor component	Asset	Possible	Major	Extreme (12)	7.2.1. Reinforced Cofferdam 7.2.2. Battery certified by class and independent laboratory 7.2.3. Battery system meets class and IEC requirements	Rec 73. Further study to be done on impact on reactor compartment from battery fire. Rec 74. Further study to be done due to possibility of battery room explosion on reactor compartment. Rec 75. Consider providing blow out panel to minimise explosion consequences.
				7.2.2. Reactor compartment damage due to high heat load	Asset	Possible	Major	Extreme (12)		
			7.2.2. Battery Fire	7.2.1. Damage to reactor component	Asset	Possible	Major	Extreme (12)	7.2.1. Reinforced Cofferdam	Rec 73. Further study to be done on impact on reactor compartment from battery fire. Rec 74. Further study to be done due to possibility of battery room explosion on reactor compartment.

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				7.2.2. Reactor compartment damage due to high heat load	Asset	Possible	Major	Extreme (12)		
				7.2.3. Kinetic/stored energy release - System Hazards - Dropped Object & Energy Release (see 11.2)						

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 8	**Name:** System Hazards - Vent & Ventilation	
Design Intent:		
Description: System Hazards - Vent & Ventilation		
Associated Drawings:		

No.: 8 **Name:** System Hazards - Vent & Ventilation

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
8.1	Ventilation Air	Inlet from Deck 6 from the side.	8.1.1. Moisture and salinity in air	8.1.1. Corrosion	Asset	Likely	Moderate	High (12)		Rec 69. Materials used in nuclear application are to be suitable for use in radioactive environment as per nuclear regulator and codes and standards requirements. Also, these materials are to be checked for application in marine environment as per classification/SOLAS/IMO rules. Rec 83. Study is to be conducted for air quality requirement for ventilation of reactor room and machinery/steam room considering marine air has high salinity and moisture.
				8.1.5. Steam/Lead leak	Overall	Possible	Moderate	High (9)		
			8.1.2. Radiation inside reactor compartment	8.1.2. Release of radioactive gaseous material inside reactor/machinery space.	Overall	Unlikely	Moderate	Moderate (6)	8.1.1. Inlet dumpers to stop air leaving from reactor compartment	Rec 10. Considering where ventilation funnel is located and surrounding passenger area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									8.1.2. Reactor and piping provided with radiation shield to minimise radiation inside compartment to acceptable level per nuclear regulation 8.1.3. Radiation monitoring 8.1.4. Filters 8.1.5. Dumpers at ventilation exhaust inlet 8.1.6. Gas tight design of vent duct **Comment:** To the highest possible degree.	Rec 69. Materials used in nuclear application are to be suitable for use in radioactive environment as per nuclear regulator and codes and standards requirements. Also, these materials are to be checked for application in marine environment as per classification/SOLAS/IMO rules. Rec 76. Further study to be done on all failure causes from malfunction to the air inlet system. Rec 77. Further study is to be done on ventilation requirements and mitigation measures in case of contaminated vent lines during incident or normal operation. Rec 78. Further study is to be done on criticality of ventilation system and redundancy requirements. Rec 79. Further study is to be done on radiation monitoring in case of back flow. Rec 80. Further study is to be done on necessary air changes per hour. Rec 81. Further study is to be done on additional fire structural/radiation barriers provided. Rec 82. Further study is to be done on dispersion of radio active air from the exhaust system.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				8.1.3. Contamination of air inside reactor/machinery space.	Overall	Unlikely	Moderate	Moderate (6)		
				8.1.4. Radioactive leakage to atmosphere at outlet	Overall	Possible	Moderate	High (9)		
				8.1.6. Human exposure on deck	Injury	Possible	Moderate	High (9)		
			8.1.3. Damage to piping due to radiation reactivity. **Comment:** TO BE CHECKED WITH NUCLEAR EXPERT	8.1.5. Steam/Lead leak	Overall	Possible	Moderate	High (9)		
8.2	Reactive material on passenger deck		8.2.1. Damage to existing piping.	8.2.1. Release of radioactive air.	Environmental	Unlikely	Moderate	Moderate (6)	8.2.1. Filters 8.2.2. Dumpers at ventilation exhaust inlet 8.2.3. Radioactive monitoring in the inlet of the vent stack. 8.2.4. Radiation monitoring 8.2.5. Gas tight design of vent duct **Comment:** To the highest possible degree.	Rec 10. Considering where ventilation funnel is located and surrounding passenger area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height. Rec 84. Port operation procedures and emergency plan are to be developed considering radiation risk to host a vessel following a radioactive release. Rec 85. Further study to be done on how to contain radioactive release within the compartment.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 86. Mustering and evacuation plans are to be developed considering reactor emergency/accident. Location of muster stations and necessary air circulation for the muster area are to be further studied considering radiation leakage. Rec 87. Further study to be done on other machinery space outside reactor room and ventilation in order to minimise radioactive exposure on deck.
				8.2.2. Exposure of passenger.	Injury	Unlikely	Major	High (8)		
				8.2.3. Exposure of people in port or port facilities.	Injury	Unlikely	Moderate	Moderate (6)		
				8.2.4. Exposure of people on bridge or bridge itself.	Injury	Unlikely	Moderate	Moderate (6)		
			8.2.2. Ventilation Air (see 8.1)							
8.3	Other Machinery Spaces		8.3.1. General Recommendation							Rec 10. Considering where ventilation funnel is located and surrounding passenger area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height. Rec 80. Further study is to be done on necessary air changes per hour.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 88. Further study to be done on ventilation ducts to avoid ventilation with nuclear compartment.
8.4	Condenser / Exhaust from Steam Cycle		8.4.1. Potential radiation leakage.	8.4.1. Contamination in the water feed system	Environmental	Unlikely	Moderate	Moderate (6)		Rec 89. Further study to be done on any system having a potential for radiation leakage on the stream side of the circuit.
				8.4.2. Contamination of exhaust line	Environmental	Unlikely	Moderate	Moderate (6)		
				8.4.3. Exposure to people.	Injury	Unlikely	Moderate	Moderate (6)		
8.5	Ventilation Philosophy	Normally nuclear reactor negative pressure hospital negative control room positive other areas to be defined	8.5.1. General Recommendation							Rec 16. Further study is to be done for the ventilation philosophy of all surrounding areas to the nuclear reactor, e.g., positive or negative pressure areas to avoid possible contamination.

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 9	**Name:** Maintenance and Inspection	
Design Intent:		
Description: Maintenance and Inspection		
Associated Drawings:		

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
9.1	Maintenance during operation		9.1.1. Entering Reactor Compartment. **Comment:** Require entry in to reactor compartment.	9.1.1. Personnel exposure.	Injury	Possible	Critical	Extreme (15)	9.1.1. Radiation detectors. 9.1.2. Personal Protection Equipment (PPE). 9.1.3. Recording of the exposure time inside the reactor compartment. 9.1.4. Special training and education of crew. 9.1.5. Systems check prior to reactor start up.	Rec 90. Daily visual routine inspection requirements are to be further developed and detailed procedures are to be in place. Rec 91. Access to certain areas e.g., reactor area compartments are to be restricted and only trained authorised personnel are to be permitted. Rec 92. Total radiation exposure for each crew member is to be monitored and radiation exposure limits are to be established by nuclear regulator and to be followed to protect crew. Rec 93. Detailed crew training and education plans are to be developed.

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			9.1.2. Shutdown maintenance.							Rec 91. Access to certain areas e.g., reactor area compartments are to be restricted and only trained authorised personnel are to be permitted. Rec 92. Total radiation exposure for each crew member is to be monitored and radiation exposure limits are to be established by nuclear regulator and to be followed to protect crew. Rec 93. Detailed crew training and education plans are to be developed.
9.2	Shutdown		9.2.1. Shutdown maintenance	9.2.1. Personnel exposure.	Injury	Possible	Critical	Extreme (15)	9.2.1. Systems check prior to reactor start up.	Rec 94. Further study is to be done on development of maintenance plans defining responsibilities between general and specialised crew considering the regulatory requirements. Rec 95. In case steam condenser or other contaminated machinery requires drainage, proper maintenance is to be provided.

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 10	**Name:** System Hazards - Dry Docking	
Design Intent:		
Description: System Hazards - Dry Docking		
Associated Drawings:		

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
10.1	General Comments		10.1.1. General recommendation							Rec 5. Considering very specialised design and construction requirement for nuclear power plant related system and licensing requirement from OEM and regulatory agency capability of shipyard to construct or service such specialised ship are to be further investigated. Rec 98. Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies are to be done.

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 99. Further study to be done on special licensing needed from nuclear regulator for dry docking.
			10.1.2. Black out at shipyard	10.1.1. Loss of circulation pump	Asset	Possible	Moderate	High (9)	10.1.1. Back up power	Rec 97. Further study to be done on dry docking survey and maintenance requirements from typical existing procedures to accommodate for nuclear power needs. Rec 101. Total loss of SY power to be further studied for impact on reactor safety and requirement for all support system to maintain reactor safety to be developed and provided while in SY. Rec 103. Further studies are to be done on provision of heat source to maintain liquid condition of the Molten Salt medium.
				10.1.2. Loss of core cooling **Comment:** If needed	Asset	Possible	Moderate	High (9)		
				10.1.3. Solidification of lead	Asset	Unlikely	Major	High (8)		

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				10.1.4. Core temperature rise	Asset	Possible	Moderate	High (9)		
			10.1.3. Loss of cooling water supply	10.1.2. Loss of core cooling **Comment:** If needed	Asset	Possible	Moderate	High (9)		Rec 98. Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies are to be done. Rec 101. Total loss of SY power to be further studied for impact on reactor safety and requirement for all support system to maintain reactor safety to be developed and provided while in SY.
				10.1.4. Core temperature rise	Asset	Possible	Moderate	High (9)		
			10.1.4. Earthquake	10.1.5. Damage to the ship	Asset	Possible	Moderate	High (9)	10.1.1. Back up power	Rec 97. Further study to be done on dry docking survey and maintenance requirements from typical existing procedures to accommodate for nuclear power needs.

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 100. Further study to be done on possibility of earthquake, mainly when the ship is at construction and/or dry-dock supported from bottom (as per IAEA/NRC this is one of the assessments as part of PRA), and coordination with reactor manufacturer.
				10.1.7. Damage to reactor, its support or internal component	Overall	Possible	Major	Extreme (12)		
				10.1.8. Seismic Event - Global Hazards (see 4.9)						
			10.1.5. Hurricanes	10.1.1. Loss of circulation pump	Asset	Possible	Moderate	High (9)		Rec 100. Further study to be done on possibility of earthquake, mainly when the ship is at construction and/or dry-dock supported from bottom (as per IAEA/NRC this is one of the assessments as part of PRA), and coordination with reactor manufacturer.
				10.1.2. Loss of core cooling **Comment:** If needed	Asset	Possible	Moderate	High (9)		
				10.1.3. Solidification of lead	Asset	Unlikely	Major	High (8)		

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				10.1.4. Core temperature rise	Asset	Possible	Moderate	High (9)		
				10.1.5. Damage to the ship	Asset	Possible	Moderate	High (9)		
				10.1.6. Loss of reactor support system	Overall	Possible	Moderate	High (9)		
				10.1.7. Damage to reactor, its support or internal component	Overall	Possible	Major	Extreme (12)		
				10.1.9. Typhoon - Global Hazards (see 4.10)						
			10.1.6. Security breach							Rec 96. Further study is to be done on procedure for dry docking security measures. Rec 102. Security protocol and access control to be implemented

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 11	**Name:** System Hazards - Dropped Object & Energy Release	
Design Intent:		
Description: Dropped Object/stored energy/kinetic energy		
Associated Drawings:		

No.: 11	**Name:** System Hazards - Dropped Object & Energy Release									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
11.1	Dry Docking Hazards		11.1.1. Dropped object from crane (reactor maintenance)							Rec 26. Study to be performed for risks anticipated during construction, installation process, maintenance and dry docking (e.g., dropped object) to prevent any damage to reactor and its system.
11.2	Kinetic/stored energy release		11.2.1. Steam turbine broken blade	11.2.1. Breach of reactor barrier or damage to reactor due to kinetic energy of the blade	Overall	Possible	Major	Extreme (12)	11.2.1. Reactor compartment protected by coffer dam	Rec 105. Further study is to be done on potential energy impact and appropriate mitigation measures defined. Rec 106. Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
				11.2.2. Release of fragment	Asset	Possible	Moderate	High (9)		
				11.2.3. Leakage of lead or steam	Overall	Unlikely	Major	High (8)		

No.: 11	**Name:** System Hazards - Dropped Object & Energy Release									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			11.2.2. Steam pipe failure	11.2.2. Release of fragment	Asset	Possible	Moderate	High (9)	11.2.1. Reactor compartment protected by coffer dam	Rec 104. Consider further foreign object study and strength of hull, specific to each ship as General Arrangement may be different, in way of reactor. Rec 105. Further study is to be done on potential energy impact and appropriate mitigation measures defined. Rec 106. Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
				11.2.3. Leakage of lead or steam	Overall	Unlikely	Major	High (8)		
			11.2.3. Battery explosion (see 7.2)							

Title: Cruise Ship		**Company:**	**Method:** HAZID
No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)		
Design Intent:			
Description: Fire in passenger area			
Associated Drawings:			

No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
12.1	Fire on Passenger Area		12.1.1. Fire in the passenger area/close to reactor system	12.1.1. Elevated temperatures inside reactor room **Comment:** Boiling of shielding water	Asset	Possible	Moderate	High (9)	12.1.1. FFS 12.1.2. Water spray system 12.1.3. Reactor emergency shut down 12.1.4. Cofferdam to protect reactor compartment 12.1.5. Adequate vessel structure design	Rec 103. Further studies are to be done on provision of heat source to maintain liquid condition of the Molten Salt medium. Rec 107. Fire analysis is to be conducted and appropriate active/passive firefighting mitigation measures are to be provided. Rec 108. Fire and smoke detector location study to be conducted considering reactor Rec 109. To enhance fire safety, additional class notations are to be considered related to fire and fire fighting.

No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 110. Consider increased risk due to nuclear reactor on board. Additional requirements may come from IMO/Regulator or Flag regarding the development of enhanced safety for firefighting, fire protection, insulation, structure, etc. Rec 111. Further studies to be done on location of fire fighting pumps.
				12.1.2. Collapse of structure reactor compartment	Overall	Unlikely	Major	High (8)		
				12.1.3. Loss of control instrumentation due to heat gain	Asset	Possible	Moderate	High (9)		

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 13	**Name:** Nuclear Technology Hazards	
Design Intent:		
Description: Nuclear Technology Hazards		
Associated Drawings:		

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.1	Crew, Training, Human Factor		13.1.1. General Recommendations							Rec 84. Port operation procedures and emergency plan are to be developed considering radiation risk to host a vessel following a radioactive release. Rec 112. Number of Crew needed to operate nuclear reactor and its system are to be studied considering nuclear regulatory and technology provider requirement to operate. Rec 113. Considering nuclear regulation crew qualification, training, requirements for certification, back ground check etc. are required and detailed programme need to be developed.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 114. Investigate whether nuclear regulator is required on board ships all the time or not. Rec 115. Training programme considering existing regulation is to be developed. Rec 116. Port personnel to be trained in emergency and risk. Rec 117. Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements. Rec 118. Human Factor Engineering (HFE) analysis is to be conducted for operation as it is required under nuclear regulatory requirements. Rec 119. Regulatory requirements are to be checked for citizenship and security clearance requirement.

No.: 13 **Name:** Nuclear Technology Hazards

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
										Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 121. Appropriate drills for nuclear emergencies and or loss of containment of radiation should be developed with the regulator and/or flag.
			13.1.2. Availability of personnel due to citizenship requirement	13.1.1. Unavailability of seafarers	Overall	Likely	Moderate	High (12)	13.1.1. SOLAS requirements 13.1.2. STCW convention	Rec 113. Considering nuclear regulation crew qualification, training, requirements for certification, back ground check etc. are required and detailed programme need to be developed. Rec 115. Training programme considering existing regulation is to be developed.

No.: 13	**Name:** Nuclear Technology Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 117. Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements. Rec 118. Human Factor Engineering (HFE) analysis is to be conducted for operation as it is required under nuclear regulatory requirements. Rec 119. Regulatory requirements are to be checked for citizenship and security clearance requirement.
				13.1.2. Higher cost of crew	Overall	Likely	Moderate	High (12)		
				13.1.3. Crew injury	Injury	Possible	Major	Extreme (12)		

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.1.3. Human error	13.1.4. Unsafe reactor operation	Environmental	Possible	Moderate	High (9)	13.1.1. SOLAS requirements 13.1.2. STCW convention	Rec 113. Considering nuclear regulation crew qualification, training, requirements for certification, back ground check etc. are required and detailed programme need to be developed. Rec 115. Training programme considering existing regulation is to be developed. Rec 117. Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements. Rec 118. Human Factor Engineering (HFE) analysis is to be conducted for operation as it is required under nuclear regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.2	Security & External Threat		13.2.1. High jacking/piracy/terrorist	13.2.1. Control of reactor/radioactive material	Overall	Possible	Critical	Extreme (15)	13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 20. Legislation and requirements are to be developed for external threat/risk such as hijacking, piracy, terror, flying object (missile, plane etc.) attack, etc. Ship designer and Technology developer need to consider such threat based on regulation Rec 29. Investigate proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them. Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 124. Access control measures are to be provided. Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
				13.2.2. Damage to the Reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.3. Breach of reactor barrier or damage to the reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.4. Leakage of fuel	Overall	Possible	Critical	Extreme (15)		
			13.2.2. Ship attack	13.2.1. Control of reactor/radioactive material	Overall	Possible	Critical	Extreme (15)	13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 124. Access control measures are to be provided. Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
				13.2.2. Damage to the Reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.3. Breach of reactor barrier or damage to the reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.4. Leakage of fuel	Overall	Possible	Critical	Extreme (15)		
			13.2.3. Plane/drone attack	13.2.1. Control of reactor/radioactive material	Overall	Possible	Critical	Extreme (15)	13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 124. Access control measures are to be provided. Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
				13.2.2. Damage to the Reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.3. Breach of reactor barrier or damage to the reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.4. Leakage of fuel	Overall	Possible	Critical	Extreme (15)		
			13.2.4. Cyber attack	13.2.1. Control of reactor/radioactive material	Overall	Possible	Critical	Extreme (15)	13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 124. Access control measures are to be provided. Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
				13.2.2. Damage to the Reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.3. Breach of reactor barrier or damage to the reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.4. Leakage of fuel	Overall	Possible	Critical	Extreme (15)		
			13.2.5. Unauthorised access	13.2.1. Control of reactor/radioactive material	Overall	Possible	Critical	Extreme (15)	13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	Name: Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 124. Access control measures are to be provided. Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
				13.2.2. Damage to the Reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.3. Breach of reactor barrier or damage to the reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.4. Leakage of fuel	Overall	Possible	Critical	Extreme (15)		
			13.2.6. Torpedo attack	13.2.1. Control of reactor/radioactive material	Overall	Possible	Critical	Extreme (15)	13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 124. Access control measures are to be provided. Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
				13.2.2. Damage to the Reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.3. Breach of reactor barrier or damage to the reactor	Asset	Possible	Critical	Extreme (15)		
				13.2.4. Leakage of fuel	Overall	Possible	Critical	Extreme (15)		
			13.2.7. High jacking/piracy/terrorist						13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 124. Access control measures are to be provided. Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
			13.2.8. Ship attack						13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements. Rec 124. Access control measures are to be provided.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
			13.2.9. Plane/drone attack						13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements. Rec 124. Access control measures are to be provided.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
			13.2.10. Caber attack						13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements. Rec 124. Access control measures are to be provided.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
			13.2.11. Unauthorised access						13.2.1. Security measures on access to all critical machinery spaces. 13.2.2. High freeboard 13.2.3. Restricted area of operation 13.2.4. Guarded personnel 13.2.5. Reactor room is secured 13.2.6. Emergency Shut Down (ESD)	Rec 120. Further study to be done on the presence of a radiation officer on board. Rec 122. Proper security measures are to be developed in communication with regulator. Rec 123. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements. Rec 124. Access control measures are to be provided.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 125. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to cyber attack. Transponder to be programmed to provide location of the reactor/vessel.
13.3	Fuel Charging & Refuelling		13.3.1. Inability to load fuel							Rec 4. Ship design and construction are to consider nuclear reactor installation sequence and fuelling/refuelling sequence due to technology provider restriction, Shipyard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place. This may require special provision in mid-ship section to facilitate construction sequence and may pose challenge for construction.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 98. Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies are to be done. Rec 126. Further study to be done on refuelling process of the vessel and on how the reactor as a complete system would be removed as a complete system would be removed at the end of vessel's lifetime, or alternatively at the end of the reactor's lifetime (e.g., total loss incident of the reactor), whichever comes first.
13.4	Supporting Systems		13.4.1. Black out **Comment:** Back up power needed to maintain reactor in safe condition provided by redundant emergency generator.	13.4.1. Lead solidification	Asset	Possible	Major	Extreme (12)	13.4.1. Emergency Shut Down (ESD)	Rec 127. Further study is to be done on how lead will be maintained in liquid state during all operational and emergency situation.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 128. In emergency situation considering longer time required to maintain reactor safety the auxiliary and emergency generator are to be further studied. Rec 129. Control and monitoring systems in case of emergency may require more monitoring time than normal marine practices and are to be further studied with the regulators and the technology providers. Rec 130. Emergency systems are to be operated on a much higher angle of inclination and need to be considered for the system availability of equipment design.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 131. It is expected the control room needs to be accessible in case of emergency such as marine incidents (collision, grounding, heavy listing etc.). For such a condition further analysis is to be conducted for the crew's safety and operability. Rec 132. The requirements for crew/salvors to manually interact with the reactor safety & control systems during or after any abandonment should be considered
				13.4.2. Support system not available	Overall	Possible	Moderate	High (9)		
			13.4.2. Automation failures	13.4.1. Lead solidification	Asset	Possible	Major	Extreme (12)	13.4.1. Emergency Shut Down (ESD) 13.4.2. Redundancy 13.4.3. Certification 13.4.4. Testing 13.4.5. Cyber security 13.4.6. Nuclear Agency Regulations	Rec 128. In emergency situation considering longer time required to maintain reactor safety the auxiliary and emergency generator are to be further studied.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				13.4.2. Support system not available	Overall	Possible	Moderate	High (9)		
13.5	Heat Removal & Cooling		13.5.1. General Recommendations							Rec 133. Considering ship power needs vary depending on operation and typically nuclear reactor operates on constant heat generation mode, a detailed study for the reactor design is to be conducted to accommodate ship load variation requirements to meet operational needs e.g., managing of excess extra heat due to low power requirements. Load variation may produce higher fatigue load and is to be considered in design. Capability to provide full power in short time is to be considered e.g., emergency departure in port. Rec 134. Further study to be done on HVAC of reactor compartment and exhaust from reactor compartment.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 135. Further study to be done on cooling of reactor and need to meet regulatory requirement.
13.6	Nuclear Waste Storage, Handling, & Disposal		13.6.1. Radioactive waste and materials	13.6.1. Exposure of humans	Injury	Possible	Moderate	High (9)		Rec 25. Vessel design is to consider proper nuclear waste storage, handling and disposal as per nuclear regulation requirements generated during normal operation, maintenance, refuelling, etc. prior to proper disposal for life of ship. Proper monitoring is to be considered onboard for waste storage. Rec 136. Further study to be done on detailed plan of handling of radioactive material at the end of ship life, before end of ship lifetime, or normal operation, maintenance e.g., hull, reactor core, piping, heat exchangers, pumps, any other exposed material. Rec 137. Further study to be done on disposal procedures.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				13.6.2. Environmental Damage	Environmental	Possible	Moderate	High (9)		
			13.6.2. Ventilation Air - System Hazards - Vent & Ventilation (see 8.1)							

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 14	**Name:** Nuclear Technology Hazards - Lead Fast Reactor	
Design Intent:		
Description: Nuclear Technology Hazards - Lead Fast Reactor		
Associated Drawings:		

No.: 14 **Name:** Nuclear Technology Hazards - Lead Fast Reactor

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
14.1	General		14.1.1. General Recommendations							Rec 133. Considering ship power needs vary depending on operation and typically nuclear reactor operates on constant heat generation mode, a detailed study for the reactor design is to be conducted to accommodate ship load variation requirements to meet operational needs e.g., managing of excess extra heat due to low power requirements. Load variation may produce higher fatigue load and is to be considered in design. Capability to provide full power in short time is to be considered e.g., emergency departure in port. Rec 138. Considering Lead corrosivity and marine environment, appropriate material are to be selected and detail testing to be conducted

No.: 14	**Name:** Nuclear Technology Hazards - Lead Fast Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
14.2	Fuel Loading, Unloading, Storage	First fuelling is to be followed by a special process (while in shipyard). Fuel is to be loaded last in the reactor.	14.2.1. Fuel loading.	14.2.1. Inability to load fuel.	Asset	Unlikely	Major	High (8)		Rec 4. Ship design and construction are to consider nuclear reactor installation sequence and fuelling/refuelling sequence due to technology provider restriction, Shipyard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place. This may require special provision in mid-ship section to facilitate construction sequence and may pose challenge for construction. Rec 27. Considering nuclear technology/industry has numerous existing regulations, which may require special licensing and training for shipyard and its supplier, selection of shipyard is to be further studied to meet all licensing and construction requirements. Rec 98. Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies are to be done.

No.: 14	Name: Nuclear Technology Hazards - Lead Fast Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 126. Further study to be done on refuelling process of the vessel and on how the reactor as a complete system would be removed as a complete system would be removed at the end of vessel's lifetime, or alternatively at the end of the reactor's lifetime (e.g., total loss incident of the reactor), whichever comes first. Rec 139. Ship design to consider nuclear fuel loading and removal in safe manner per regulatory requirements.
14.3	Operation, Normal	5% LFR per minute power increase Icebreakers: 20% to 100% in one minute (PWR). For this vessel ramp power will be needed twice a day when maneuvering in channels and harbor. Speed will be adjusted to accommodate itinerary 100% electrical power implies 70% reactor power	14.3.1. Load variation **Comment:** Passing through storm, slow down, favourable condition, etc.	14.3.1. Impact on reactor and support system due to load variation	Asset	Almost Certain	Minor	High (10)	14.3.1. Condenser to dump excess heat 14.3.2. Safety valve	Rec 133. Considering ship power needs vary depending on operation and typically nuclear reactor operates on constant heat generation mode, a detailed study for the reactor design is to be conducted to accommodate ship load variation requirements to meet operational needs e.g., managing of excess extra heat due to low power requirements. Load variation may produce higher fatigue load and is to be considered in design. Capability to provide full power in short time is to be considered e.g., emergency departure in port.

No.: 14	**Name:** Nuclear Technology Hazards - Lead Fast Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 140. Further study to be done on partial load operation of the reactor considering normal ship operation. there is a testing requirement for internal combustion engines for 110% load and it should be checked if such a testing approach is necessary for nuclear reactors and steam plants, particularly given specific testing requirements for nuclear reactors which will apply.
14.4	Radiation Shielding, Barrier		14.4.1. Radiation emission	14.4.1. Radiation contamination	Injury	Possible	Major	Extreme (12)		Rec 141. Further study to be done on the material and thickness of reactor biological shielding, cooling arrangement and ventilation with reactor technology provider and to comply with regulatory requirement.

No.: 14	**Name:** Nuclear Technology Hazards - Lead Fast Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
14.5	Port Maneuvering	Sudden power increase may be needed, propulsion load increase 50% in a minute i.e., 10 MW in a minute. Crash stop regulation (from stop to full power	14.5.1. Sudden increase/decrease of power demand. **Comment:** Reactor may not supply sudden increase in power need	14.5.1. Accident, grounding, collision, hit a bridge	Asset	Possible	Major	Extreme (12)	14.5.1. Azipod ability to follow crash stop.	Rec 133. Considering ship power needs vary depending on operation and typically nuclear reactor operates on constant heat generation mode, a detailed study for the reactor design is to be conducted to accommodate ship load variation requirements to meet operational needs e.g., managing of excess extra heat due to low power requirements. Load variation may produce higher fatigue load and is to be considered in design. Capability to provide full power in short time is to be considered e.g., emergency departure in port. Rec 142. Further study is to be done if reactor runs on partial load for extended period in port and large amount of heat have to be dissipated and the impact in marine environment e.g., increase in water temperature. All systems are to be designed to operate globally considering atmospheric and sea water temperature variation
				14.5.2. Black out	Asset	Unlikely	Moderate	Moderate (6)		

No.: 14	**Name:** Nuclear Technology Hazards - Lead Fast Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
14.6	Harbour Operation	In harbor loads are very low	14.6.1. Partial load of reactor							Rec 133. Considering ship power needs vary depending on operation and typically nuclear reactor operates on constant heat generation mode, a detailed study for the reactor design is to be conducted to accommodate ship load variation requirements to meet operational needs e.g., managing of excess extra heat due to low power requirements. Load variation may produce higher fatigue load and is to be considered in design. Capability to provide full power in short time is to be considered e.g., emergency departure in port. Rec 140. Further study to be done on partial load operation of the reactor considering normal ship operation. there is a testing requirement for internal combustion engines for 110% load and it should be checked if such a testing approach is necessary for nuclear reactors and steam plants, particularly given specific testing requirements for nuclear reactors which will apply.

No.: 14	**Name:** Nuclear Technology Hazards - Lead Fast Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 142. Further study is to be done if reactor runs on partial load for extended period in port and large amount of heat have to be dissipated and the impact in marine environment e.g., increase in water temperature. All systems are to be designed to operate globally considering atmospheric and sea water temperature variation
			14.6.2. Emergency Shelter - Nuclear Technology Hazards - Impact on Ports (see 15.1)							

Title: Cruise Ship		**Company:**	**Method:** HAZID
No.: 15	**Name:** Nuclear Technology Hazards - Impact on Ports		
Design Intent:			
Description: Nuclear Technology Hazards - Impact on Ports			
Associated Drawings:			

No.: 15		**Name:** Nuclear Technology Hazards - Impact on Ports								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
15.1	Emergency Shelter	Cruise liner Ships have a self-maneuvering capability	15.1.1. General Recommendation	15.1.1. Harbour Operation - Nuclear Technology Hazards - Lead Fast Reactor (see 14.6)						Rec 143. Port of Refuge and Shelter law is to be further study as in emergency port of refuge can be questionable. Rec 144. Further study is to be done on the potential of contamination in a port environment and the consequences for the local community. Rec 145. Further study is to be done on the development of a protocol between port authorities and ship.

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 16	**Name:** Nuclear Technology Hazards - Ship Recycling & Salvage	
Design Intent:		
Description: Nuclear Technology Hazards - Ship Recycling & Salvage		
Associated Drawings:		

No.: 16 — **Name:** Nuclear Technology Hazards - Ship Recycling & Salvage

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
16.1	New		16.1.1. General Recommendation						16.1.1. Inventory of Hazardous Materials (IHM)	Rec 146. End of life Recycling and salvage to be further studied considering radiation hazards and procedures are to be developed Rec 147. Disposal of radioactive materials is to be further studied and proper procedure to be developed in accordance with local regulation for radioactive west. Rec 148. Considering reactor may be design for longer life compared to ship life, possibility of reactor transferred to another ship/location is to be considered from the initial stage of design. Rec 149. Further study is to be done on how the reactor will stay in place in case of salvage process and radiation is contained.

No.: 16 **Name:** Nuclear Technology Hazards - Ship Recycling & Salvage

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
										Rec 150. Further study is to be done on risk control options in place of active safety management during salvage process. Rec 151. Salvage crews are to be specially trained to operate nuclear reactors. Rec 152. Port of safe refuge is to be considered and appropriate permission to enter is to be given. Rec 153. Further study is to be done on salvage scenarios and appropriate mitigating measures. Rec 154. Radiation survey on SSC prior to vessel dismantling. Rec 155. Further study to be done on the dismantling of the reactor.
			16.1.2. Hull splitting (shallow water) - Global Hazards (see 4.7)							
			16.1.3. Grounding - Global Hazards (see 4.4)							
			16.1.4. Collision - Global Hazards (see 4.5)							

Title: Cruise Ship	**Company:**	**Method:** HAZID
No.: 17	**Name:** Finance Risk & Liability	
Design Intent:		
Description: Finance Risk & Liability		
Associated Drawings:		

No.: 17 **Name:** Finance Risk & Liability

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
17.1	General Comments		17.1.1. General							Rec 156. P&I Club and insurance entities are to be involved. Rec 157. Regulations are to be developed so that liability can be defined. Rec 158. Technology readiness and replacement are to be further studied. Rec 159. Reactor replacement timing is to be further investigated. Rec 160. Considering availability of nuclear technology and availability of spare parts, further study is to be done. Rec 161. Any accident or nuclear related incident is to be further included in the financial analysis.
			17.1.2. General Comments - Licensing & Approval Process (see 2.1)							

Appendix V – List of Recommendations – Bulk Carrier with VHTR/HTGR

No.	References	Action
1	1.1 General Recommendation – General Comments & Notes 4.1 General Global Hazard Comments – Global Hazards 5.2 Reactor Availability – Global Hazards - Ship Operation	Current reactors are designed for land-based applications for four design conditions - Normal Operation, Anticipated Operational occurrence, design basis accident and design extension condition. Which lacks additional loads and functional requirement needed for marine application. The maritime industry must develop functional requirements for the reactors to operate effectively in a marine environment throughout its life on the ship. Nuclear technology is to be approved by the nuclear regulatory and has to go through a complete technology qualification process to get approved for marine us.
2	1.1 General Recommendation – General Comments & Notes 4.1 General Global Hazard Comments – Global Hazards 10.1 General Recommendation – System Hazards - Dry Docking	Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc.
3	1.1 General Recommendation – General Comments & Notes 6.4 Power Need (Auxiliary & Back up) – System Hazards	Further study to be done on the location of the nuclear reactor to provide the highest protection against any external risk (Ed.GA. collision, flooding, grounding, dropped objects etc.). Possibility to be moved to the middle of the vessel.
4	1.1 General Recommendation – General Comments & Notes 6.2 Bilge System Inside Reactor Compartment – System Hazards	There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event.
5	1.1 General Recommendation – General Comments & Notes 2.1 General Licensing & Approval Comment – Licensing & Approval Process 3.1 General Ship Construction Comments – Ship Construction 4.10 Seismic event – Global Hazards	"Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship
6	1.1 General Recommendation – General Comments & Notes	Considering radioactivity, end of life disposal is to be considered from beginning of the ship design to facilitate safe handling, removal and disposal of any parts, equipment and material that might be contaminated with radioactive material.
7	1.1 General Recommendation – General Comments & Notes 12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Considering possibility of fire internal/external outside of reactor compartment and considering radiation leakage possibility, design principle should include following: 1. Consider arranging each reactor in separate compartments and providing enough isolation to prevent fire migration and protection against fire incident. 2. Minimize fire possibility by using appropriate material. 3. Appropriate means are to be provided to fight fire in reactor and machinery compartment. 4. Structural design to consider fire load in design and its survivability.

No.	References	Action
8	1.1 General Recommendation – General Comments & Notes 3.1 General Ship Construction Comments – Ship Construction 13.4 Fuel Charging & Refuelling – Nuclear Technology Hazards	Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 years), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design.
9	1.1 General Recommendation – General Comments & Notes 9.1 Maintenance, Live – Maintenance and Inspection 13.9 Radiological Leakage – Nuclear Technology Hazards	Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied.
10	1.1 General Recommendation – General Comments & Notes 2.1 General Licensing & Approval Comment – Licensing & Approval Process 3.1 General Ship Construction Comments – Ship Construction 10.1 General Recommendation – System Hazards - Dry Docking	Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship.
11	1.1 General Recommendation – General Comments & Notes	The Reactor and its systems are to be designed to meet the design life of the ship (typically 30 years), considering the possibility to install/reuse for another project are to be further investigated to improve economics.
12	1.1 General Recommendation – General Comments & Notes 4.1 General Global Hazard Comments – Global Hazards 4.7 Capsizing – Global Hazards	Environmental impact study in case of flooding, sinking or capsizing events are to be conducted.
13	1.1 General Recommendation – General Comments & Notes	Vessel's general arrangement is to be further studied for radiation hazards to other surrounding spaces next to reactor room
14	1.1 General Recommendation – General Comments & Notes	Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design.
15	2.1 General Licensing & Approval Comment – Licensing & Approval Process 4.5 Grounding – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process.
16	2.1 General Licensing & Approval Comment – Licensing & Approval Process 13.12 Liability – Nuclear Technology Hazards 17.1 General Financing Hazard – Finance Risk & Liability	Considering that regulations framework and classification requirements are still in development for nuclear power marine application, regulation development framework is to be developed and work with appropriate regulatory agency for development of requirements from design, licensing, operation, and liability related issues.

No.	References	Action
17	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Nuclear-Powered vessels will travel to various countries and there are existing regulations related to export/licensing, nonproliferation treaty etc. a legislation need to be developed so ship can travel between various country or legislation between country and owner/technology OEM to be developed to facilitate trade and trading route. Legislation to do trade across countries is to be developed.
18	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Further study is to be done on geo-political issues that may affect routes and destinations.
19	2.1 General Licensing & Approval Comment – Licensing & Approval Process	OEM proposed to use Tri-Structural Isotopic (TRISO) particle fuel and availability of such fuel needs to be further studied for long term availability, licensing etc.
20	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Export control legislation needs to be further investigated for the trading routes and ownership by the shipowner.
21	2.1 General Licensing & Approval Comment – Licensing & Approval Process 15.1 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	Operation in port areas or traditional water is to be considered in any licensing process. Ports do not have any regulations at the moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues in future regulations development.
22	2.1 General Licensing & Approval Comment – Licensing & Approval Process 3.1 General Ship Construction Comments – Ship Construction	Considering maritime industry has limited to no knowledge on nuclear technology and its construction requirements, further training/cooperation is to be developed between shipyards, nuclear technology/equipment providers and nuclear regulators.
23	2.1 General Licensing & Approval Comment – Licensing & Approval Process 13.3 Security & External Threat – Nuclear Technology Hazards	Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation.
24	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Considering that licensing legislation/requirements to construct, operate and maintain nuclear power plants on ships does not exist and may lead to cost escalation, industry is to develop requirements to eliminate uncertainty. Participation of shipping companies in such an activity is recommended.
25	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Per nuclear regulations and technology provider there will be specialised training needed to operate NPP, and special accreditation needed by regulators. A special training programme in cooperation with regulators and technology provider are to be developed and certification requirement to be determine.
26	3.1 General Ship Construction Comments – Ship Construction 4.10 Seismic event – Global Hazards	The reactors and their systems are to consider seismic events, tsunami, etc. probability, in design while in shipyard, dry dock, port, channel etc.
27	3.1 General Ship Construction Comments – Ship Construction	Detail procedure for sea trial and reactor trial are to be developed with OEM, SY, Owner and regulator
28	3.1 General Ship Construction Comments – Ship Construction 13.4 Fuel Charging & Refuelling – Nuclear Technology Hazards	Vessel modification including engine removal, structural modification etc. are to be further investigated to accommodate nuclear power plant.
29	3.1 General Ship Construction Comments – Ship Construction	Installation and removal of NPP while it is loaded with fuel are to be further studied for all possible case during design and for construction and proper procedure are to be developed.
30	3.1 General Ship Construction Comments – Ship Construction 10.1 General Recommendation – System Hazards - Dry Docking 11.1 General Dry-Docking Hazards – System Hazards - Dropped Object & Energy Release	Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane, other load etc.).

No.	References	Action
31	3.1 General Ship Construction Comments – Ship Construction 6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards 8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation 8.3 Contamination & Pollution – System Hazards - Vent & Ventilation 8.4 HVAC Air – System Hazards - Vent & Ventilation 8.5 Reactivity in the Air – System Hazards - Vent & Ventilation	Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.
32	4.1 General Global Hazard Comments – Global Hazards 13.4 Fuel Charging & Refuelling – Nuclear Technology Hazards	Considering treaty on the nonproliferation of nuclear weapons and risk of ship trading worldwide, technology developers are to design proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them or use them in a harmful manner. Further, the impact of treaty on design and operation is to be further studied.
33	4.1 General Global Hazard Comments – Global Hazards	Further study is to be done on geo-political issues that may affect routes and destinations.
34	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards 4.4 Sloshing – Global Hazards	Vessel specific motion study is to be conducted to determine acceleration values for vessel to be used in design for nuclear power plants and systems. Class society and IMO regulations are to be followed for these values with appropriate safety margin.
35	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards 4.4 Sloshing – Global Hazards	Further study to be done on the optimum orientation and position of the reactors to minimize the impact of marine loads.
36	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards 4.7 Capsizing – Global Hazards	Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure.
37	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards	Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has high impact on safety detailed inspection/maintenance/monitoring is to be considered.
38	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards	Magnetic bearing design and selection is to consider all ship loads.
39	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards 13.9 Radiological Leakage – Nuclear Technology Hazards	Inspection and maintenance plans need to be developed to verify the integrity or the reactors foundation and radiation biological shielding.
40	4.3 Vibration – Global Hazards	Detailed vibration study to be conducted and during commissioning and sea trial vibration to be measured and calibrated with analysis. During operation and maintenance vibrations need to be monitored to verify that they are in design acceptable range. Considering marine-machinery induced vibration (propeller, engine etc.), bow slamming is to be considered.
41	4.5 Grounding – Global Hazards 4.6 Collision – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling).

No.	References	Action
42	4.5 Grounding – Global Hazards	There is a possibility of reactors compartment flooding due to grounding, collision, submergence etc. therefore design is to consider such an event. Ships are currently designed per IMO/SOLAS/Class requirements for damage penetration, and this is to be investigated considering nuclear system safety and additional measures are to be implemented.
43	4.5 Grounding – Global Hazards	Radiation shielding and insulation of reactors and reactors compartment to consider total flooding of compartment in shielding design or alternate justification to be provided.
44	4.5 Grounding – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.
45	4.5 Grounding – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Further study is to be done on the impact to the surrounding environment of any case of radiation leakage.
46	4.5 Grounding – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills.
47	4.5 Grounding – Global Hazards 15.1 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	Emergency shelter/port of refuge plan is to be considered and whether there is a port available in case of emergency considering nuclear technology on board.
48	4.5 Grounding – Global Hazards	Further study is to be done on reactors safety considering various accidental scenarios and loads. The proper safety shutdown system is to be developed and provided (active and passive).
49	4.5 Grounding – Global Hazards 4.6 Collision – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation.
50	4.5 Grounding – Global Hazards	Consider increasing double bottom height to provide additional protection to reactors' compartment.
51	4.5 Grounding – Global Hazards 4.6 Collision – Global Hazards 4.7 Capsizing – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc.
52	4.5 Grounding – Global Hazards 4.6 Collision – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards	In flooding condition electrical equipment can be damaged due to exposure to salt water and the support system will not be available etc. A study is to be conducted considering such a situation to identify the risk to reactors safety and consider appropriate electrical equipment e.g., IP rating.
53	4.5 Grounding – Global Hazards 4.6 Collision – Global Hazards 13.6 Supporting Systems – Nuclear Technology Hazards	Grounding/collision/submergence etc. can lead to reactors' essential and auxiliary systems damage and their impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship.
54	4.5 Grounding – Global Hazards 4.6 Collision – Global Hazards	In case of damage due to grounding/collision etc., progressive flooding may be possibility and needs to be investigated to prevent such an event.
55	4.5 Grounding – Global Hazards	Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety and appropriate measures are to be in place.
56	4.5 Grounding – Global Hazards 4.6 Collision – Global Hazards	The reactors and their systems design need to consider steam formation; appropriate mitigation measures are to be provided to prevent radiation leakage or damage to reactors.

No.	References	Action
57	4.6 Collision – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Further study is to be done on collision assessment considering nuclear reactors compartment.
58	4.6 Collision – Global Hazards	Any extra loads created during a collision incident are to be considered in the reactors design.
59	4.6 Collision – Global Hazards 4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Further study is to be done on the creation of an automatic passive water flooding system of the reactors to equalize pressure and prevent radiation leakage.
60	4.6 Collision – Global Hazards	Further study is to be done on the inclusion of additional protection bulkheads, possible to the extra available volume due to the removal of the piston engine.
61	4.6 Collision – Global Hazards	The position of the reactors ais at a higher level from the level the piston engine was positioned. Stability of Vessel needs to be rechecked
62	4.6 Collision – Global Hazards	Further study is to be done on the use of non-flammable foam on the sides of the ship.
63	4.6 Collision – Global Hazards	A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.
64	4.6 Collision – Global Hazards 5.2 Reactor Availability – Global Hazards - Ship Operation	Further study is to be done on the minimum necessary power needs of the vessel considering the regulations and the maximum power needed in case of collision avoidance. Battery use (larger size) is to be investigated as an alternative to thermal power damping in case the reactors are kept warm continuously.
65	4.7 Capsizing – Global Hazards	Further study is to be done on reactors support systems that will have to maintain reactors in place in any accident.
66	4.7 Capsizing – Global Hazards	Further study is to be done on the ability of the reactors to continue operating in an inverted position. Investigate the possibility of water coming in from flipped funnel.
67	4.7 Capsizing – Global Hazards	Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety.
68	4.8 Hull splitting (shallow water) – Global Hazards 4.9 Hull splitting and sinking – Global Hazards	Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.
69	4.10 Seismic event – Global Hazards 5.2 Reactor Availability – Global Hazards - Ship Operation 7.1 Power Availability – System Hazards - Power & Propulsion	Normally port regulations require that in an emergency the ship must depart from port within one hour or less. Reactor designers are to consider such requirement in design for power availability to depart port on short notice.
70	4.11 Typhoon – Global Hazards	Typhoon events are to be included during design of vessel and appropriate load is to be considered in reactors design.
71	4.12 Cargo Fire – Global Hazards 12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Fire impact and fire load analysis is to be conducted depending on the cargo transported for worst case fire condition on nuclear power plants and its support system.
72	5.1 General Recommendation – Global Hazards - Ship Operation	Considering nuclear ship propulsion regulations are not developed yet, but under consideration at IMO and nuclear agencies, suggest participating in such activity.
73	5.1 General Recommendation – Global Hazards - Ship Operation	Emergency protocol in case of accident related to nuclear systems are to be developed considering nuclear exposure hazards.
74	5.1 General Recommendation – Global Hazards - Ship Operation	Due to radiation exposure risk, in emergency radiation medication and other primary care on site are to be provided.
75	5.1 General Recommendation – Global Hazards - Ship Operation	Radiation dispersion analysis for escaped radiation in case of accident are to be conducted and how it will affect lifesaving appliances and crew area are to be analyzed.

No.	References	Action
76	5.1 General Recommendation – Global Hazards - Ship Operation	Location of the muster stations and their proximity to radiation zone and other high-risk areas are to be further studied based on radiation dispersion analysis.
77	5.1 General Recommendation – Global Hazards - Ship Operation	High efficiency filtration to capture radiation and minimize its impact is to be provided in all HVAC ducting where probability of radiation exists.
78	5.1 General Recommendation – Global Hazards - Ship Operation	Considering radiation exposure possibility to crew in accidental situation consideration for propelled lifeboats to decrease escape time from ship and radiation zone around ship.
79	5.1 General Recommendation – Global Hazards - Ship Operation	In case of radiation detection in safe area appropriate security, evacuation procedures are to be developed.
80	5.2 Reactor Availability – Global Hazards - Ship Operation 7.2 Battery – System Hazards - Power & Propulsion	Further study is to be done on the availability of reserve power.
81	5.2 Reactor Availability – Global Hazards - Ship Operation	Further study is to be done on the possibility of keeping the helium in hot conditions so that the emergency start up period can be reduced.
82	5.2 Reactor Availability – Global Hazards - Ship Operation	Further study is to be done for the thermal stress impact on the materials in case of a rapid start up, which creates large thermal gradient.
83	5.2 Reactor Availability – Global Hazards - Ship Operation 7.1 Power Availability – System Hazards - Power & Propulsion	Loss of power due to reactors' unavailability is to be further studied and appropriate mitigation measures and procedures are to be developed.
84	5.3 Bunkering – Global Hazards - Ship Operation 13.2 Public Perception – Nuclear Technology Hazards	Licensing, security protocols and docking agreements with ports are to be developed.
85	5.3 Bunkering – Global Hazards - Ship Operation	Bunkering operations to take the fuel for the need for the electricity are to be considered and further analyzed.
86	6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards 8.6 Reactive Material on Deck – System Hazards - Vent & Ventilation	Further study is to be done on the choice of coating on deck to protect materials from contamination in case of Argon 41 dust particle deposition.
87	6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards	Cooling water piping is to be designed considering high temperature, corrosion, thermal loads and vibrations.
88	6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards	Consider providing a redundant water cooling system with a redundant water pump.
89	6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards	Providing 2 x 100% propulsion motors.
90	6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards	Considering supporting components to be installed away from reactors (more than 20 meters) to protect against radiation (neutron) and to provide protection against accident.
91	6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards	Material selection strategy to include marine environment and appropriate materials are to be selected to eliminate failure due to material degradation.
92	6.1 Piping, Pumps, Material and Supporting Equipment – System Hazards	Piping, component, equipment are to be designed considering high temperature fatigue, creep etc.
93	6.2 Bilge System Inside Reactor Compartment – System Hazards	Further study is needed to evaluate the bilge system's ability to drain water from both the nuclear reactors room and the Fire Fighting System (FFS), as well as its water quantity and storage capacity.
94	6.2 Bilge System Inside Reactor Compartment – System Hazards	Considering the radiation risk, the bilge system from any room with potential for radiation must be independent, and dedicated bilge storage should be provided to contain radioactive material. Further study is needed to identify risks, and appropriate mitigation measures are to be considered.
95	6.2 Bilge System Inside Reactor Compartment – System Hazards	Further study is needed on the safe storage and disposal of bilged water in the event of radioactivity.

No.	References	Action
96	6.3 Electrical Cables – System Hazards	Further study is to be done on how electrical cables meet and be certified according to nuclear regulatory requirement to operate in radioactive environment.
97	6.3 Electrical Cables – System Hazards	Cables are to be designed to withstand submerged conditions.
98	6.3 Electrical Cables – System Hazards 6.4 Power Need (Auxiliary & Back up) – System Hazards	Further study is to be done on the optimum routing and distance of cables from the nuclear reactors to the motors.
99	6.4 Power Need (Auxiliary & Back up) – System Hazards 13.6 Supporting Systems – Nuclear Technology Hazards 13.11 Power Availability – Nuclear Technology Hazards	Further study is to be done on the necessary auxiliary and emergency generators, backup power (e.g., UPS) and the availability and duration for how long they need to operate.
100	6.5 Emergency Response – System Hazards	Emergency and evacuation procedures are to be developed in addition to existing ones in accordance with nuclear and maritime regulators.
101	6.5 Emergency Response – System Hazards	Emergency plan and firefighting plan, consider dispersion analysis, radiation zones and nuclear regulation, is to include quantity, location, and disposal of Personal Protection Equipment (PPE).
102	6.5 Emergency Response – System Hazards	Lab/Facility (radioactive laboratory) is to be provided on ship to track exposure limit for crew and for management to limit radiation exposure.
103	7.1 Power Availability – System Hazards - Power & Propulsion	Requirement for load testing on reactors is to be further studied considering marine engine testing in practice.
104	7.2 Battery – System Hazards - Power & Propulsion	Impact on reactors compartment due to fire and explosion from battery is to be further investigated.
105	8.1 General Recommendation – System Hazards - Vent & Ventilation 13.9 Radiological Leakage – Nuclear Technology Hazards	A detailed radiation leakage and shielding study to be conducted per nuclear regulatory requirement and appropriate radiation shielding is to be provided to maintain radiation within allowable limits by regulators and dispersion study for all condition of operations - normal, upset, emergency, accidental etc. are to be conducted to determine radiation zone/dispersion.
106	8.1 General Recommendation – System Hazards - Vent & Ventilation	Detailed radiation dispersion study for all conditions of operations - normal, upset, emergency, accidental etc. is to be conducted to determine radiation zone/dispersion around vent and ventilation outlets and to be considered in the general arrangement of ship to protect accommodation and other areas.
107	8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation 8.6 Reactive Material on Deck – System Hazards - Vent & Ventilation	Radiation dispersion study is to be done for all normal, upset, accident and emergency modes of operation to determine chimney height considering radiation leakage (e.g., ionised Argon, Helium, and other radiation), to avoid any ingress of radiation/contaminated Argon 41 inside the accommodation area and deposition on the deck area.
108	8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation	Considering air gap allowed and route chimney height is to be further studied for any risk.
109	8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation 13.9 Radiological Leakage – Nuclear Technology Hazards	Further study is to be done on allowable radiation exposure levels and consequent maximum allowable period of crew stay on such a type of vessel; appropriate mitigation measures are to be provided.
110	8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation	Considering reactors compartment vent system location and possibility of radiation may exist, all openings and air inlet are to be further studied and appropriate distance/separation to be provided.
111	8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation	Vent lines from reactors modules are to be further studied as they have higher probability of radiation presence. Consider vent lines ducting from reactor modules to be jacketed with annular space maintained at positive pressure to minimize any possibility or leakage from vent lines ducting to other spaces.

No.	References	Action
112	8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation 8.4 HVAC Air – System Hazards - Vent & Ventilation 8.5 Reactivity in the Air – System Hazards - Vent & Ventilation 8.8 Ventilation Philosophy – System Hazards - Vent & Ventilation 13.5 Reactor Barrier(s) – Nuclear Technology Hazards	Further study is to be done on the reactors' room ventilation requirements and the air changes per hour etc. to keep the room temperature within acceptable limits. Ventilation ducting is to be further studied for any possibility of ionizing radiation and its impact. Consider ventilation ducting to be jacketed with annular space maintain at positive pressure to minimize any possibility or leakage from ventilation ducting to other spaces.
113	8.2 Ionised Argon and Ionize Radiation – System Hazards - Vent & Ventilation	Any radiation leakage between reactors pressure boundary and secondary low-pressure boundary is to be further studied and disposal of such radiation is to be further considered during a detailed design.
114	8.4 HVAC Air – System Hazards - Vent & Ventilation	Bilge systems from reactors rooms are to be properly designed considering radiation and contaminated water and are to be independent of other systems.
115	8.4 HVAC Air – System Hazards - Vent & Ventilation	Further study is to be done on the monitoring of air exhaust.
116	8.4 HVAC Air – System Hazards - Vent & Ventilation	Further study is to be done on nuclear waste storage and disposal.
117	8.4 HVAC Air – System Hazards - Vent & Ventilation	Further study is to be done on procedures and monitoring of storage of contaminated material.
118	8.4 HVAC Air – System Hazards - Vent & Ventilation	Water leakage monitoring inside reactors room.
119	8.4 HVAC Air – System Hazards - Vent & Ventilation	Further study is to be done on HVAC to minimize dust carry overhead.
120	8.4 HVAC Air – System Hazards - Vent & Ventilation	Further study is to be done on how to avoid ingress of condensation.
121	8.4 HVAC Air – System Hazards - Vent & Ventilation	Further study to be done on traps to catch radionuclides is to be implemented.
122	8.4 HVAC Air – System Hazards - Vent & Ventilation 8.8 Ventilation Philosophy – System Hazards - Vent & Ventilation	Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height and emergency procedure to protect crew.
123	8.4 HVAC Air – System Hazards - Vent & Ventilation	Thermodynamic analysis is to be done to determine the HVAC load for the reactors compartment so that the temperature is maintained within the acceptable limits.
124	8.4 HVAC Air – System Hazards - Vent & Ventilation	Reactors modules are to be provided with water leakage detectors and proper coating to contain any leakage.
125	8.4 HVAC Air – System Hazards - Vent & Ventilation 13.6 Supporting Systems – Nuclear Technology Hazards	Consider redundant extraction fan for reactors compartment.
126	8.6 Reactive Material on Deck – System Hazards - Vent & Ventilation	Further study to be done on the maximum contaminant levels allowed, e.g., on open deck surface, which might be deposited in case of leakage through the funnel. Consider the option of installing a scrubber.
127	8.6 Reactive Material on Deck – System Hazards - Vent & Ventilation	Procedures notifying port authorities on nuclear pollutants on board are to be developed.
128	8.7 Other Machinery Spaces – System Hazards - Vent & Ventilation	Surrounding machinery or other space to be provided with independent ventilation to minimize any possibility of radiation entering space or contamination including reverse flow. Ventilation outlet to be separated by distance from reactors compartment and modules ventilation/vent outlets.
129	9.1 Maintenance, Live – Maintenance and Inspection	Further study is to be done on limitations in daily visual routine inspection.
130	9.1 Maintenance, Live – Maintenance and Inspection	Further study is to be done on prohibiting of access to certain reactors area compartments.
131	9.1 Maintenance, Live – Maintenance and Inspection	Further study is to be done on crew training and education.

No.	References	Action
132	10.1 General Recommendation – System Hazards - Dry Docking	Further study is to be done at the required time the reactors need to cool down (boundary C) and reach a safe condition before going to dry dock.
133	10.1 General Recommendation – System Hazards - Dry Docking 11.1 General Dry-Docking Hazards – System Hazards - Dropped Object & Energy Release 11.2 Crane – System Hazards - Dropped Object & Energy Release	Any overhead lifting is to be further investigated and restricted areas are to be further developed.
134	10.1 General Recommendation – System Hazards - Dry Docking	Proper procedure and radiation exposure limits are to be established before anyone entering reactors compartment.
135	10.1 General Recommendation – System Hazards - Dry Docking	For dry docking detailed study is to be done to maintain reactors in safe condition for dry docking period. A study is to be conducted that will include safety monitoring, security of reactors, auxiliary power, and system requirements to maintain reactors in safe condition.
136	10.1 General Recommendation – System Hazards - Dry Docking	Dry docking shipyard selection is to consider earthquake and typhoon risk; reactors design is to consider such threats as well.
137	10.1 General Recommendation – System Hazards - Dry Docking	Security of reactors is to be further studied, and proper arrangement is to be provided to prevent any security issues.
138	11.3 Kinetic or Stored Energy – System Hazards - Dropped Object & Energy Release	Further study is to be done on potential energy impact and appropriate mitigation measures defined.
139	11.3 Kinetic or Stored Energy – System Hazards - Dropped Object & Energy Release	Any kinetic and potential energy release inside or outside or reactors modules is to be identified (pressurised system, rotating system, turbine, dropped object/load etc.) and its impact on reactors or any safety system is to be further studied for risk on nuclear system and appropriate mitigations are to be provided or to eliminate hazards.
140	12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Further studies to be done on fire analysis and appropriate mitigations are to be provided.
141	12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Fire/smoke detectors are to be provided.
142	12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Considering the possibility of fire inside/outside reactors compartment and considering radiation leakage possibility, design principle should include minimizing fire possibility by using appropriate material. General arrangement is to avoid outside fire impact on reactors compartments and appropriate means are to be provided to fight fire in reactors and machinery compartment. Also, detailed fire load analysis is to be conducted during design to improve structural capacity of structure to survive fire load.
143	12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Consider in general arrangement to keep any fire hazards as far as away from reactors compartment.
144	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Further study to be done on the organisations that will be involved in the training and certification (and validation thereof from the regulator) of the personnel.
145	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Detailed training and certification programmes are to be developed considering various regulatory agencies involved.
146	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Human factor studies are to be done for the operation of the ship, for the nuclear reactors.
147	13.1 Crew, Training, Human Factor – Nuclear Technology Hazards	Crew security clearance certificate is to be further investigated.
148	13.2 Public Perception – Nuclear Technology Hazards	Legislation is to be developed for countries and ports involved in secure trade routes.
149	13.3 Security & External Threat – Nuclear Technology Hazards	Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to Cyber-attack. Transponder is to be programmed to provide location of the reactors/vessel.
150	13.3 Security & External Threat – Nuclear Technology Hazards	Terrorist threats are to be addressed.

No.	References	Action
151	13.3 Security & External Threat – Nuclear Technology Hazards	Implement any automation safety features stemming from repositioning of the reactors.
152	13.4 Fuel Charging & Refuelling – Nuclear Technology Hazards	Considering the dry docking period (5 years) and fuel lifetime (7 years) mismatch, further study is to be done on the alignment of them.
153	13.4 Fuel Charging & Refuelling – Nuclear Technology Hazards	Considering HolosGen design is delivering on a continuous basis 10 MWe for a period of eight years and further power consumption may vary, additional studies are to be done with developer to achieve optimum dry docking/recharging cycle.
154	13.4 Fuel Charging & Refuelling – Nuclear Technology Hazards	Further study is to be done on the refuelling process of the vessel and on how the reactor, as a complete system, would be removed.
155	13.4 Fuel Charging & Refuelling – Nuclear Technology Hazards	Reactors replacement timing is to be further investigated.
156	13.5 Reactor Barrier(s) – Nuclear Technology Hazards	Reactors modules' surface temperature is to be maintained within allowable acceptable limits or insulation is to be provided.
157	13.5 Reactor Barrier(s) – Nuclear Technology Hazards	Reactors modules support to consider thermal impact in design.
158	13.5 Reactor Barrier(s) – Nuclear Technology Hazards	Reactor compartment is surrounded by cofferdam and at this point it is not known whether it will be filled with water or concrete or another material to capture neutron. When determined, further risk assessment is to be performed.
159	13.5 Reactor Barrier(s) – Nuclear Technology Hazards	A detailed HAZOP and other risk assessments are to be conducted on the entire reactors systems for further identification of risk.
160	13.5 Reactor Barrier(s) – Nuclear Technology Hazards	Accidental damage analysis for reactors barrier is to be conducted.
161	13.5 Reactor Barrier(s) – Nuclear Technology Hazards	HolosGen is to provide further details and regulators to address such issues for all possible failure.
162	13.6 Supporting Systems – Nuclear Technology Hazards	Water quality requirements are to be further developed, and intermediate cooling type circuits are to be provided with expansion tank.
163	13.6 Supporting Systems – Nuclear Technology Hazards	Automation failure to be considered in detailed risk assessment for control system function FME(C)A.
164	13.7 Heat Removal & Cooling – Nuclear Technology Hazards	Thermal analysis for operational and shutdown conditions and detailed environmental procedural analysis are to be developed.
165	13.8 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Further study to be done on detailed plan of handling of radioactive material at the end of ship life, before end of ship lifetime, or normal operation, maintenance e.g., hull, reactors core, piping, heat exchangers, pumps, any other exposed material.
166	13.8 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Further study to be done on handling waste fuel during ship lifetime.
167	13.8 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Further study to be done on radioactive waste disposal procedures.
168	13.8 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Vessel design is to consider proper arrangement for nuclear waste storage and handling and monitoring on board vessels for radioactive/nuclear waste generated during normal operation, maintenance, accident, upset condition etc. per nuclear regulatory requirements prior to proper disposal.
169	13.9 Radiological Leakage – Nuclear Technology Hazards	Considering possibility of radiation leakage and exposure to crew members a facility/space to be provided next to reactors room for treatment with basic medical equipment per nuclear regulators recommendations.
170	13.10 Magnetic Bearings – Nuclear Technology Hazards	Magnetic bearings design is to be further evaluated for all possible failure modes and have appropriate reliability and availability.
171	14.3 Inspection/Maintenance – Nuclear Technology Hazards - Small Modular Reactor	Further study to be done on sensors calibration.

No.	References	Action
172	14.3 Inspection/Maintenance – Nuclear Technology Hazards - Small Modular Reactor	Further study to be done on pump periodic maintenance plan.
173	14.3 Inspection/Maintenance – Nuclear Technology Hazards - Small Modular Reactor	Detailed inspection maintenance plan for the entire nuclear system and its supporting systems is to be developed considering radiation exposure and risk, and further study such as RAM (Reliability, Availability, Maintainability) analysis is to be considered.
174	14.3 Inspection/Maintenance – Nuclear Technology Hazards - Small Modular Reactor	Detailed training plan for maintenance plan is to be developed.
175	14.3 Inspection/Maintenance – Nuclear Technology Hazards - Small Modular Reactor	Spare part inventory is to be further analyzed, and requirements are to be defined.
176	16.1 General Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	The inventory of Hazardous Materials (IHM) is to be kept.
177	14.6 Escape & Evacuation – Nuclear Technology Hazards - Small Modular Reactor	Further study is to be done on the way a contaminated person can be transported to a hospital.
178	14.6 Escape & Evacuation – Nuclear Technology Hazards - Small Modular Reactor	Spaces on the ship that can treat contaminated persons, including special types of showers.
179	14.6 Escape & Evacuation – Nuclear Technology Hazards - Small Modular Reactor	Further study is to be done on procedures in case of contaminated crew.
180	14.6 Escape & Evacuation – Nuclear Technology Hazards - Small Modular Reactor	Emergency evacuation and escape study to be conducted for all spaces for all modes of operation considering additional risk of radiation exposure as applicable.
181	14.7 Harbor Operation – Nuclear Technology Hazards - Small Modular Reactor	Detailed electrical and power simulation load study to be done for all modes of operation.
182	14.7 Harbor Operation – Nuclear Technology Hazards - Small Modular Reactor	Further study to be done on partial load/low load operation of the reactor considering normal ship operation.
183	15.1 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	Further study is to be done on acceptance of technology from port authorities.
184	16.1 General Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Further study to be done on the dismantling of the reactor.
185	16.1 General Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Plan for disposal of the SSC (System Structure and Components).
186	16.1 General Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Radiation survey on SSC prior to vessel dismantling.
187	17.1 General Financing Hazard – Finance Risk & Liability	P&I Club, and insurance entities are to be involved.
188	17.1 General Financing Hazard – Finance Risk & Liability	Considering the availability of nuclear technology and availability of spare parts, further study is to be done.
189	17.1 General Financing Hazard – Finance Risk & Liability	Any accident or nuclear related incident is to be further included in the financial analysis.

Appendix VI – HAZID Register – Bulk Carrier with VHTR/HTGR

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 1	**Name:** General Comments & Notes	
Design Intent:		
Description: General Comments & Notes		
Associated Drawings:		

No.: 1 **Name:** General Comments & Notes

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
1.1	General Recommendation		1.1.1. General Recommendation. **Comment:** These recommendations are applicable to many nodes therefore been moved to general							Rec 1. Current reactors are designed for land-based applications for four design conditions - Normal Operation, Anticipated Operational occurrence, design basis accident and design extension condition. Which lacks additional loads and functional requirement needed for marine application. The maritime industry must develop functional requirements for the reactors to operate effectively in a marine environment throughout its life on the ship. Nuclear technology is to be approved by the nuclear regulatory and has to go through a complete technology qualification process to get approved for marine us.

No.: 1	**Name:** General Comments & Notes									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 2. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 3. Further study to be done on the location of the nuclear reactor to provide the highest protection against any external risk (Ed.GA. collision, flooding, grounding, dropped objects etc.). Possibility to be moved to the middle of the vessel.

No.: 1	**Name:** General Comments & Notes									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 4. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event. Rec 5. "Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship Rec 6. Considering radioactivity, end of life disposal is to be considered from beginning of the ship design to facilitate safe handling, removal and disposal of any parts, equipment and material that might be contaminated with radioactive material.

No.: 1	**Name:** General Comments & Notes									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 7. Considering possibility of fire internal/external outside of reactor compartment and considering radiation leakage possibility, design principle should include following: 1. Consider arranging each reactor in separate compartments and providing enough isolation to prevent fire migration and protection against fire incident. 2. Minimize fire possibility by using appropriate material. 3. Appropriate means are to be provided to fight fire in reactor and machinery compartment. 4. Structural design to consider fire load in design and its survivability. Rec 8. Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 years), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design.

No.: 1	**Name:** General Comments & Notes									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 9. Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied. Rec 10. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 11. The Reactor and its systems are to be designed to meet the design life of the ship (typically 30 years), considering the possibility to install/reuse for another project are to be further investigated to improve economics. Rec 12. Environmental impact study in case of flooding, sinking or capsizing events are to be conducted.

No.: 1	**Name:** General Comments & Notes									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 13. Vessel's general arrangement is to be further studied for radiation hazards to other surrounding spaces next to reactor room Rec 14. Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 2	**Name:** Licensing & Approval Process	
Design Intent:		
Description: Licensing & Approval Process		
Associated Drawings:		

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
2.1	General Licensing & Approval Comment		2.1.1. General recommendation.							Rec 5. "Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship Rec 10. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 16. Considering that regulations framework and classification requirements are still in development for nuclear power marine application, regulation development framework is to be developed and work with appropriate regulatory agency for development of requirements from design, licensing, operation, and liability related issues.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 17. Nuclear Powered vessels will travel to various countries and there are existing regulations related to export/licensing, nonproliferation treaty etc. a legislation need to be developed so ship can travel between various country or legislation between country and owner/technology OEM to be developed to facilitate trade and trading route. Legislation to do trade across countries is to be developed. Rec 18. Further study is to be done on geo-political issues that may affect routes and destinations. Rec 19. OEM proposed to use Tri-Structural Isotopic (TRISO) particle fuel and availability of such fuel needs to be further studied for long term availability, licensing etc. Rec 20. Export control legislation needs to be further investigated for the trading routes and ownership by the shipowner. Rec 21. Operation in port areas or traditional water is to be considered in any licensing process. Ports do not have any regulations at the moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues in future regulations development.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 22. Considering maritime industry has limited to no knowledge on nuclear technology and its construction requirements, further training/cooperation is to be developed between shipyards, nuclear technology/equipment providers and nuclear regulators. Rec 23. Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation. Rec 24. Considering that licensing legislation/requirements to construct, operate and maintain nuclear power plants on ships does not exist and may lead to cost escalation, industry is to develop requirements to eliminate uncertainty. Participation of shipping companies in such an activity is recommended. Rec 25. Per nuclear regulations and technology provider there will be specialised training needed to operate NPP, and special accreditation needed by regulators. A special training programme in cooperation with regulators and technology provider are to be developed and certification requirement to be determine.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			2.1.2. Incident liability.							Rec 5. "Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 16. Considering that regulations framework and classification requirements are still in development for nuclear power marine application, regulation development framework is to be developed and work with appropriate regulatory agency for development of requirements from design, licensing, operation, and liability related issues. Rec 17. Nuclear-Powered vessels will travel to various countries and there are existing regulations related to export/licensing, nonproliferation treaty etc. a legislation need to be developed so ship can travel between various country or legislation between country and owner/technology OEM to be developed to facilitate trade and trading route. Legislation to do trade across countries is to be developed. Rec 18. Further study is to be done on geo-political issues that may affect routes and destinations. Rec 19. OEM proposed to use Tri-Structural Isotopic (TRISO) particle fuel and availability of such fuel needs to be further studied for long term availability, licensing etc. Rec 20. Export control legislation needs to be further investigated for the trading routes and ownership by the shipowner.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 21. Operation in port areas or traditional water is to be considered in any licensing process. Ports do not have any regulations at the moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues in future regulations development.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 3	**Name:** Ship Construction	
Design Intent:		
Description: Ship Construction		
Associated Drawings:		

No.: 3 **Name:** Ship Construction

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
3.1	General Ship Construction Comments		3.1.1. General recommendation.							Rec 5. "Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship Rec 8. Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 years), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design.

No.: 3	Name: Ship Construction									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 10. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 22. Considering maritime industry has limited to no knowledge on nuclear technology and its construction requirements, further training/cooperation is to be developed between shipyards, nuclear technology/equipment providers and nuclear regulators. Rec 26. The reactors and their systems are to consider seismic events, tsunami, etc. probability, in design while in shipyard, dry dock, port, channel etc. Rec 27. Detail procedure for sea trial and reactor trial are to be developed with OEM, SY, Owner and regulator Rec 28. Vessel modification including engine removal, structural modification etc. are to be further investigated to accommodate nuclear power plant. Rec 29. Installation and removal of NPP while it is loaded with fuel are to be further studied for all possible case during design and for construction and proper procedure are to be developed.

No.: 3	**Name:** Ship Construction									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 30. Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane, other load etc.). Rec 31. Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 4	**Name:** Global Hazards	
Design Intent:		
Description: Global Hazards		
Associated Drawings:		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.1	General Global Hazard Comments		4.1.1. General recommendation.	4.1.1. Loss of control.	Overall	Possible	Major	Extreme (12)		Rec 1. Current reactors are designed for land-based applications for four design conditions - Normal Operation, Anticipated Operational occurrence, design basis accident and design extension condition. Which lacks additional loads and functional requirement needed for marine application. The maritime industry must develop functional requirements for the reactors to operate effectively in a marine environment throughout its life on the ship. Nuclear technology is to be approved by the nuclear regulatory and has to go through a complete technology qualification process to get approved for marine us.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 2. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 12. Environmental impact study in case of flooding, sinking or capsizing events are to be conducted. Rec 32. Considering treaty on the nonproliferation of nuclear weapons and risk of ship trading worldwide, technology developers are to design proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them or use them in a harmful manner. Further, the impact of treaty on design and operation is to be further studied. Rec 33. Further study is to be done on geo-political issues that may affect routes and destinations.

No.: 4	**Name:** Global Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.2	Motion		4.2.1. Marine environment. Vessel motion, acceleration, bow slamming.	4.2.1. Damage on the foundations of the reactor.	Asset	Possible	Moderate	High (9)	4.2.1. Use of radial and thrust active magnetic bearings. **Comment:** Bearings designed for stationary load and for load during transportation (of the reactor). Not affected by vessel location and earth magnetic field. 4.2.2. Catcher bearing in case of failure of magnetic bearings. 4.2.3. Triple redundancy on the magnetic bearings. 4.2.4. Proper reactor shield design. **Comment:** The use of powder graphite powder acts as a shock absorber. 4.2.5. Adequate mounting of reactor on the ship. 4.2.6. Compatibility of magnetic bearings. 4.2.7. Proper magnetic bearing design. 4.2.8. Not monolithic design of concrete shield (puzzle structure). **Comment:** Even if concrete is fractured reactor is not affected. 4.2.9. Use of additives to prevent crack formation.	Rec 34. Vessel specific motion study is to be conducted to determine acceleration values for vessel to be used in design for nuclear power plants and systems. Class society and IMO regulations are to be followed for these values with appropriate safety margin. Rec 35. Further study to be done on the optimum orientation and position of the reactors to minimize the impact of marine loads. Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 37. Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has high impact on safety detailed inspection/maintenance/monitoring is to be considered. Rec 38. Magnetic bearing design and selection is to consider all ship loads. Rec 39. Inspection and maintenance plans need to be developed to verify the integrity or the reactors foundation and radiation biological shielding.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.2.10. Proper cargo storage. 4.2.11. Radiation monitoring.	
				4.2.2. Weight shift leading to loss of vessel stability.	Asset	Unlikely	Moderate	Moderate (6)		
				4.2.3. Damage to magnetic bearings.	Asset	Possible	Major	Extreme (12)		
				4.2.4. Damage to concrete shield due to material brittleness.	Overall	Possible	Moderate	High (9)		
				4.2.5. Impact on reactor operability (graphite).	Overall	Possible	Major	Extreme (12)		
				4.2.6. Radiological Leakage - Nuclear Technology Hazards (see 13.9)	Injury	Possible	Moderate	High (9)		
			4.2.2. Freak wave hitting ship.	4.2.1. Damage on the foundations of the reactor.	Asset	Possible	Moderate	High (9)	4.2.1. Use of radial and thrust active magnetic bearings. **Comment:** Bearings designed for stationary load and for load during transportation (of the reactor). Not affected by vessel location and earth magnetic field. 4.2.2. Catcher bearing in case of failure of magnetic bearings.	Rec 34. Vessel specific motion study is to be conducted to determine acceleration values for vessel to be used in design for nuclear power plants and systems. Class society and IMO regulations are to be followed for these values with appropriate safety margin. Rec 35. Further study to be done on the optimum orientation and position of the reactors to minimize the impact of marine loads.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.2.3. Triple redundancy on the magnetic bearings. 4.2.4. Proper reactor shield design. **Comment:** The use of powder graphite powder acts as a shock absorber. 4.2.5. Adequate mounting of reactor on the ship. 4.2.8. Not monolithic design of concrete shield (puzzle structure). **Comment:** Even if concrete is fractured reactor is not affected. 4.2.9. Use of additives to prevent crack formation.	
				4.2.2. Weight shift leading to loss of vessel stability.	Asset	Unlikely	Moderate	Moderate (6)		
				4.2.3. Damage to magnetic bearings.	Asset	Possible	Major	Extreme (12)		
				4.2.4. Damage to concrete shield due to material brittleness.	Overall	Possible	Moderate	High (9)		
				4.2.5. Impact on reactor operability (graphite).	Overall	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.2.6. Radiological Leakage - Nuclear Technology Hazards (see 13.9)	Injury	Possible	Moderate	High (9)		
			4.2.3. Resonance from shaft.	4.2.1. Damage on the foundations of the reactor.	Asset	Possible	Moderate	High (9)	4.2.6. Compatibility of magnetic bearings. 4.2.7. Proper magnetic bearing design.	
				4.2.2. Weight shift leading to loss of vessel stability.	Asset	Unlikely	Moderate	Moderate (6)		
				4.2.3. Damage to magnetic bearings.	Asset	Possible	Major	Extreme (12)		
				4.2.4. Damage to concrete shield due to material brittleness.	Overall	Possible	Moderate	High (9)		
				4.2.5. Impact on reactor operability (graphite).	Overall	Possible	Major	Extreme (12)		
			4.2.4. Gyroscopic effect.	4.2.1. Damage on the foundations of the reactor.	Asset	Possible	Moderate	High (9)	4.2.7. Proper magnetic bearing design. 4.2.9. Use of additives to prevent crack formation.	
				4.2.2. Weight shift leading to loss of vessel stability.	Asset	Unlikely	Moderate	Moderate (6)		
				4.2.3. Damage to magnetic bearings.	Asset	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.2.4. Damage to concrete shield due to material brittleness.	Overall	Possible	Moderate	High (9)		
			4.2.5. Vibration (see 4.3)							
			4.2.6. Sloshing (see 4.4)							
4.3	Vibration		4.3.1. Fluid induced vibration induced vibration.	4.3.1. Damage on the foundations of the reactor.	Asset	Possible	Moderate	High (9)	4.3.1. Reactor will be certified by nuclear regulator.	Rec 34. Vessel specific motion study is to be conducted to determine acceleration values for vessel to be used in design for nuclear power plants and systems. Class society and IMO regulations are to be followed for these values with appropriate safety margin. Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 37. Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has high impact on safety detailed inspection/maintenance/monitoring is to be considered. Rec 38. Magnetic bearing design and selection is to consider all ship loads.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 39. Inspection and maintenance plans need to be developed to verify the integrity or the reactors foundation and radiation biological shielding. Rec 40. Detailed vibration study to be conducted and during commissioning and sea trial vibration to be measured and calibrated with analysis. During operation and maintenance vibrations need to be monitored to verify that they are in design acceptable range. Considering marine-machinery induced vibration (propeller, engine etc.), bow slamming is to be considered.
				4.3.3. Damage to reactor core graphite.	Overall	Possible	Moderate	High (9)		
				4.3.4. Motion (see 4.2)						
				4.3.5. Radiological Leakage - Nuclear Technology Hazards (see 13.9)						
			4.3.2. Ship machinery, wave, bow slamming, propeller.	4.3.2. Damage to rotating component of Reactor system - magnetic bearing etc.	Asset	Possible	Major	Extreme (12)	4.3.1. Reactor will be certified by nuclear regulator.	Rec 34. Vessel specific motion study is to be conducted to determine acceleration values for vessel to be used in design for nuclear power plants and systems. Class society and IMO regulations are to be followed for these values with appropriate safety margin. Rec 35. Further study to be done on the optimum orientation and position of the reactors to minimize the impact of marine loads.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 37. Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has high impact on safety detailed inspection/maintenance/monitoring is to be considered. Rec 38. Magnetic bearing design and selection is to consider all ship loads. Rec 40. Detailed vibration study to be conducted and during commissioning and sea trial vibration to be measured and calibrated with analysis. During operation and maintenance vibrations need to be monitored to verify that they are in design acceptable range. Considering marine-machinery induced vibration (propeller, engine etc.), bow slamming is to be considered.
				4.3.4. Motion (see 4.2)						

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.3.5. Radiological Leakage - Nuclear Technology Hazards (see 13.9)						
4.4	Sloshing		4.4.1. Cargo moving & sloshing.	4.4.1. Stability Loss.	Overall	Possible	Major	Extreme (12)	4.4.1. Proper design.	Rec 34. Vessel specific motion study is to be conducted to determine acceleration values for vessel to be used in design for nuclear power plants and systems. Class society and IMO regulations are to be followed for these values with appropriate safety margin. Rec 35. Further study to be done on the optimum orientation and position of the reactors to minimize the impact of marine loads.
				4.4.2. Motion (see 4.2)						
				4.4.3. Radiological Leakage - Nuclear Technology Hazards (see 13.9)						

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.5	Grounding		4.5.1. Soft Grounding.	4.5.1. Flooding of reactor compartment.	Overall	Possible	Major	Extreme (12)	4.5.1. Creation of an emergency response and safe return to port plan. 4.5.3. Automatic Emergency Shut Down (ESD) in case of no load on reactor. 4.5.4. Good navigation practice and trained crew. 4.5.5. Pilotage in narrow channel and in port.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 43. Radiation shielding and insulation of reactors and reactors compartment to consider total flooding of compartment in shielding design or alternate justification to be provided. Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 46. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 47. Emergency shelter/port of refuge plan is to be considered and whether there is a port available in case of emergency considering nuclear technology on board. Rec 48. Further study is to be done on reactors safety considering various accidental scenarios and loads. The proper safety shutdown system is to be developed and provided (active and passive). Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 53. Grounding/collision/submergence etc. can lead to reactors' essential and auxiliary systems damage and their impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.5.2. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.5.3. Propeller damage.	Overall	Possible	Moderate	High (9)		
				4.5.5. Local hull damage.	Asset	Possible	Moderate	High (9)		
				4.5.6. Electrical damage.	Asset	Possible	Moderate	High (9)		
				4.5.7. Damage to Insulation, radiation shielding and reactor insulation.	Asset	Possible	Moderate	High (9)		
				4.5.8. Radiation leak.	Injury	Possible	Moderate	High (9)		
				4.5.12. General Comment. - Finance Risk & Liability (see 16.1)						

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.5.2. Hard Grounding.	4.5.1. Flooding of reactor compartment.	Overall	Possible	Major	Extreme (12)	4.5.1. Creation of an emergency response and safe return to port plan. 4.5.2. In a submerged condition the design is such that radiation leakage is not a possibility. 4.5.3. Automatic Emergency Shut Down (ESD) in case of no load on reactor. 4.5.4. Good navigation practice and trained crew. 4.5.5. Pilotage in narrow channel and in port.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 42. There is a possibility of reactors compartment flooding due to grounding, collision, submergence etc. therefore design is to consider such an event. Ships are currently designed per IMO/SOLAS/Class requirements for damage penetration, and this is to be investigated considering nuclear system safety and additional measures are to be implemented.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 43. Radiation shielding and insulation of reactors and reactors compartment to consider total flooding of compartment in shielding design or alternate justification to be provided. Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 46. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 47. Emergency shelter/port of refuge plan is to be considered and whether there is a port available in case of emergency considering nuclear technology on board. Rec 48. Further study is to be done on reactors safety considering various accidental scenarios and loads. The proper safety shutdown system is to be developed and provided (active and passive).

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 50. Consider increasing double bottom height to provide additional protection to reactors' compartment. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 52. In flooding condition electrical equipment can be damaged due to exposure to salt water and the support system will not be available etc. A study is to be conducted considering such a situation to identify the risk to reactors safety and consider appropriate electrical equipment e.g., IP rating. Rec 53. Grounding/collision/submergence etc. can lead to reactors' essential and auxiliary systems damage and their impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship. Rec 54. In case of damage due to grounding/collision etc., progressive flooding may be possibility and needs to be investigated to prevent such an event.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 55. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety and appropriate measures are to be in place. Rec 56. The reactors and their systems design need to consider steam formation; appropriate mitigation measures are to be provided to prevent radiation leakage or damage to reactors.
				4.5.2. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.5.3. Propeller damage.	Overall	Possible	Moderate	High (9)		
				4.5.4. Loss of stability.	Asset	Possible	Major	Extreme (12)		
				4.5.5. Local hull damage.	Asset	Possible	Moderate	High (9)		
				4.5.6. Electrical damage.	Asset	Possible	Moderate	High (9)		
				4.5.7. Damage to Insulation, radiation shielding and reactor insulation.	Asset	Possible	Moderate	High (9)		
				4.5.8. Radiation leak.	Injury	Possible	Moderate	High (9)		
				4.5.9. Sinking.	Overall	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.5.10. Hull splitting (shallow water) (see 4.8)						
				4.5.11. Hull splitting and sinking (see 4.9)						
				4.5.12. General Comment. - Finance Risk & Liability (see 16.1)						
			4.5.3. Collision (see 4.6)							
4.6	Collision		4.6.1. Collision.	4.6.1. Damage to the hull.	Asset	Possible	Moderate	High (9)	4.6.1. Position of reactor in safe position. 4.6.2. Three layers of protection. 4.6.3. Conformity with B/5 regulations prerequisite. 4.6.4. Good navigation practice and trained crew. 4.6.5. Pilotage on narrow channel and in port. 4.6.6. Automatic Emergency Shut Down (ESD) in case of reactor no load.	Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 52. In flooding condition electrical equipment can be damaged due to exposure to salt water and the support system will not be available etc. A study is to be conducted considering such a situation to identify the risk to reactors safety and consider appropriate electrical equipment e.g., IP rating. Rec 53. Grounding/collision/submergence etc. can lead to reactors' essential and auxiliary systems damage and their impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship. Rec 54. In case of damage due to grounding/collision etc., progressive flooding may be possibility and needs to be investigated to prevent such an event. Rec 56. The reactors and their systems design need to consider steam formation; appropriate mitigation measures are to be provided to prevent radiation leakage or damage to reactors. Rec 57. Further study is to be done on collision assessment considering nuclear reactors compartment. Rec 58. Any extra loads created during a collision incident are to be considered in the reactors design. Rec 59. Further study is to be done on the creation of an automatic passive water flooding system of the reactors to equalize pressure and prevent radiation leakage.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 60. Further study is to be done on the inclusion of additional protection bulkheads, possible to the extra available volume due to the removal of the piston engine. Rec 61. The position of the reactors ais at a higher level from the level the piston engine was positioned. Stability of Vessel needs to be rechecked Rec 62. Further study is to be done on the use of non-flammable foam on the sides of the ship. Rec 63. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system. Rec 64. Further study is to be done on the minimum necessary power needs of the vessel considering the regulations and the maximum power needed in case of collision avoidance. Battery use (larger size) is to be investigated as an alternative to thermal power damping in case the reactors are kept warm continuously.
				4.6.2. Damage to the reactor compartment.	Overall	Possible	Moderate	High (9)		
				4.6.3. Damage to control room.	Asset	Possible	Moderate	High (9)		
				4.6.4. Flooding.	Asset	Possible	Moderate	High (9)		

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.6.5. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.6.6. Loss of vessel stability.	Asset	Possible	Major	Extreme (12)		
				4.6.7. Grounding (see 4.5)						
				4.6.8. Capsizing (see 4.7)						
				4.6.9. Hull splitting (shallow water) (see 4.8) **Comment:** * Bring over AIL						
				4.6.10. Hull splitting and sinking (see 4.9) **Comment:** * Bring over AIL						
				4.6.11. Bilge System Inside Reactor Compartment - System Hazards (see 6.2)						
4.7	Capsizing		4.7.1. Extreme wave.	4.7.1. Partial flooding.	Overall	Possible	Moderate	High (9)	4.7.1. Vessel design to IMO/SOLAS and class rules. 4.7.2. Safe navigation practices. 4.7.3. Good navigation practice and trained crew.	Rec 12. Environmental impact study in case of flooding, sinking or capsizing events are to be conducted.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.7.4. Pilotage in narrow channel and in port. 4.7.5. Automatic Emergency Shut Down (ESD).	Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 65. Further study is to be done on reactors support systems that will have to maintain reactors in place in any accident. Rec 66. Further study is to be done on the ability of the reactors to continue operating in an inverted position. Investigate the possibility of water coming in from flipped funnel. Rec 67. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety.
				4.7.2. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.7.3. Large envelope heel.	Asset	Possible	Minor	Moderate (6)		

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.7.4. Vessel capsizing.	Asset	Unlikely	Moderate	Moderate (6)		
			4.7.2. Extreme roll and motion.	4.7.1. Partial flooding.	Overall	Possible	Moderate	High (9)	4.7.1. Vessel design to IMO/SOLAS and class rules. 4.7.2. Safe navigation practices.	Rec 12. Environmental impact study in case of flooding, sinking or capsizing events are to be conducted. Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 65. Further study is to be done on reactors support systems that will have to maintain reactors in place in any accident. Rec 66. Further study is to be done on the ability of the reactors to continue operating in an inverted position. Investigate the possibility of water coming in from flipped funnel. Rec 67. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.7.2. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.7.3. Large envelope heel.	Asset	Possible	Minor	Moderate (6)		
				4.7.4. Vessel capsizing.	Asset	Unlikely	Moderate	Moderate (6)		
			4.7.3. Soft grounding.	4.7.1. Partial flooding.	Overall	Possible	Moderate	High (9)	4.7.1. Vessel design to IMO/SOLAS and class rules. 4.7.2. Safe navigation practices. 4.7.3. Good navigation practice and trained crew. 4.7.4. Pilotage in narrow channel and in port. 4.7.5. Automatic Emergency Shut Down (ESD).	Rec 12. Environmental impact study in case of flooding, sinking or capsizing events are to be conducted. Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 65. Further study is to be done on reactors support systems that will have to maintain reactors in place in any accident. Rec 66. Further study is to be done on the ability of the reactors to continue operating in an inverted position. Investigate the possibility of water coming in from flipped funnel.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 67. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety.
				4.7.2. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.7.4. Vessel capsizing.	Asset	Unlikely	Moderate	Moderate (6)		
			4.7.4. Mistake - maintenance/operation of ballast water system.	4.7.2. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)	4.7.6. Trained crew.	Rec 12. Environmental impact study in case of flooding, sinking or capsizing events are to be conducted. Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 65. Further study is to be done on reactors support systems that will have to maintain reactors in place in any accident.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 66. Further study is to be done on the ability of the reactors to continue operating in an inverted position. Investigate the possibility of water coming in from flipped funnel. Rec 67. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety.
				4.7.4. Vessel capsizing.	Asset	Unlikely	Moderate	Moderate (6)		
			4.7.5. Gravity will not allow safety system e.g., drainage system to function.	4.7.1. Partial flooding.	Overall	Possible	Moderate	High (9)	4.7.1. Vessel design to IMO/SOLAS and class rules. 4.7.2. Safe navigation practices.	Rec 12. Environmental impact study in case of flooding, sinking or capsizing events are to be conducted. Rec 36. Reactors support and structure are to be designed to keep reactors, and their systems to stay in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should provide anti-floatation support and structure. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 65. Further study is to be done on reactors support systems that will have to maintain reactors in place in any accident.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 66. Further study is to be done on the ability of the reactors to continue operating in an inverted position. Investigate the possibility of water coming in from flipped funnel. Rec 67. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactors/systems safety.
				4.7.4. Vessel capsizing.	Asset	Unlikely	Moderate	Moderate (6)		
			4.7.6. Collision (see 4.6)							
			4.7.7. Hull splitting (shallow water) (see 4.8)	4.7.5. Hull splitting (shallow water) (see 4.8)	Overall	Unlikely	Major	High (8)		Rec 66. Further study is to be done on the ability of the reactors to continue operating in an inverted position. Investigate the possibility of water coming in from flipped funnel.
			4.7.8. Hull splitting and sinking (see 4.9)							
4.8	Hull splitting (shallow water)		4.8.1. Inappropriate load distribution (not following loading manual). **Comment:** not following loading manual	4.8.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.8.1. Creation of operational processes. 4.8.3. Small reactor footprint. 4.8.4. Emergency Shut Down (ESD) of reactor. 4.8.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 52. In flooding condition electrical equipment can be damaged due to exposure to salt water and the support system will not be available etc. A study is to be conducted considering such a situation to identify the risk to reactors safety and consider appropriate electrical equipment e.g., IP rating.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 59. Further study is to be done on the creation of an automatic passive water flooding system of the reactors to equalize pressure and prevent radiation leakage. Rec 68. Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.
				4.8.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Asset	Possible	Moderate	High (9)		
				4.8.3. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.8.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		
				4.8.5. Radiation leakage (Perceptions - Reputation).	Reputation	Possible	Major	Extreme (12)		
				4.8.6. Radiation leakage (Human Exposure to the Surroundings).	Injury	Possible	Moderate	High (9)		
				4.8.7. Capsizing (see 4.7)						

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.8.8. General Comment. - Finance Risk & Liability (see 16.1)						
			4.8.2. Weather loading.	4.8.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.8.1. Creation of operational processes. 4.8.3. Small reactor footprint. 4.8.4. Emergency Shut Down (ESD) of reactor. 4.8.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 52. In flooding condition electrical equipment can be damaged due to exposure to salt water and the support system will not be available etc. A study is to be conducted considering such a situation to identify the risk to reactors safety and consider appropriate electrical equipment e.g., IP rating. Rec 68. Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.
				4.8.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Asset	Possible	Moderate	High (9)		

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.8.3. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
			4.8.3. Hull degradation and fatigue.	4.8.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.8.2. Sufficient hull design. 4.8.3. Small reactor footprint. 4.8.4. Emergency Shut Down (ESD) of reactor. 4.8.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 52. In flooding condition electrical equipment can be damaged due to exposure to salt water and the support system will not be available etc. A study is to be conducted considering such a situation to identify the risk to reactors safety and consider appropriate electrical equipment e.g., IP rating.
				4.8.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Asset	Possible	Moderate	High (9)		
				4.8.3. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.8.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		
				4.8.5. Radiation leakage (Perceptions - Reputation).	Reputation	Possible	Major	Extreme (12)		
				4.8.6. Radiation leakage (Human Exposure to the Surroundings).	Injury	Possible	Moderate	High (9)		
				4.8.7. Capsizing (see 4.7)						
				4.8.8. General Comment. - Finance Risk & Liability (see 16.1)						
			4.8.4. Load shifting.	4.8.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.8.1. Creation of operational processes. 4.8.2. Sufficient hull design. 4.8.3. Small reactor footprint. 4.8.4. Emergency Shut Down (ESD) of reactor. 4.8.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 46. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 52. In flooding condition electrical equipment can be damaged due to exposure to salt water and the support system will not be available etc. A study is to be conducted considering such a situation to identify the risk to reactors safety and consider appropriate electrical equipment e.g., IP rating. Rec 68. Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.
				4.8.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Asset	Possible	Moderate	High (9)		
				4.8.3. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.8.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		
				4.8.5. Radiation leakage (Perceptions - Reputation).	Reputation	Possible	Major	Extreme (12)		
				4.8.6. Radiation leakage (Human Exposure to the Surroundings).	Injury	Possible	Moderate	High (9)		
				4.8.7. Capsizing (see 4.7)						

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.8.8. General Comment. - Finance Risk & Liability (see 16.1)						
			4.8.5. Grounding (see 4.5)							
			4.8.6. Collision (see 4.6)							
			4.8.7. Capsizing (see 4.7)							
4.9	Hull splitting and sinking		4.9.1. Inappropriate load distribution.	4.9.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.9.1. Creation of operational processes. 4.9.2. Sufficient hull design. 4.9.3. Small reactor footprint 4.9.4. Emergency Shut Down (ESD) of reactor. 4.9.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 46. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 57. Further study is to be done on collision assessment considering nuclear reactors compartment. Rec 59. Further study is to be done on the creation of an automatic passive water flooding system of the reactors to equalize pressure and prevent radiation leakage. Rec 68. Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.
				4.9.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Overall	Possible	Moderate	High (9)		
				4.9.3. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.9.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		
				4.9.7. High external pressure leading to reactor boundary collapse.	Overall	Possible	Major	Extreme (12)		

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.9.9. General Comment. - Finance Risk & Liability (see 16.1)						
			4.9.2. Weather loading.	4.9.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.9.1. Creation of operational processes. 4.9.2. Sufficient hull design. 4.9.3. Small reactor footprint 4.9.4. Emergency Shut Down (ESD) of reactor. 4.9.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 46. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 59. Further study is to be done on the creation of an automatic passive water flooding system of the reactors to equalize pressure and prevent radiation leakage. Rec 68. Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.
				4.9.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Overall	Possible	Moderate	High (9)		
				4.9.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.9.7. High external pressure leading to reactor boundary collapse.	Overall	Possible	Major	Extreme (12)		
				4.9.8. Capsizing (see 4.7)						
			4.9.3. Hull degradation and fatigue.	4.9.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.9.2. Sufficient hull design. 4.9.3. Small reactor footprint 4.9.4. Emergency Shut Down (ESD) of reactor. 4.9.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling).

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage. Rec 46. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 57. Further study is to be done on collision assessment considering nuclear reactors compartment.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 59. Further study is to be done on the creation of an automatic passive water flooding system of the reactors to equalize pressure and prevent radiation leakage. Rec 68. Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.
				4.9.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Overall	Possible	Moderate	High (9)		
				4.9.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		
				4.9.5. Radiation leakage (Perceptions - Reputation).	Reputation	Possible	Major	Extreme (12)		
				4.9.6. Radiation leakage (Human Exposure to the Surroundings).	Injury	Possible	Moderate	High (9)		
				4.9.7. High external pressure leading to reactor boundary collapse.	Overall	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.9.4. Load shifting.	4.9.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.9.1. Creation of operational processes. 4.9.2. Sufficient hull design. 4.9.3. Small reactor footprint 4.9.4. Emergency Shut Down (ESD) of reactor. 4.9.5. Triple pressure barrier design of the reactor that will keep the core protected up to 70 bars. 4.9.6. Loading manual and procedure.	Rec 15. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 41. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactors (cabling). Rec 44. Consider designing reactors' containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 45. Further study is to be done on the impact to the surrounding environment of any case of radiation leakage.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 46. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to handle extreme marine conditions (e.g., capsizing, severe listing, flooding, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 49. If the refloating of ship is considered after grounding, proper risk control is to be in place. Further study is to be conducted for such an operation. Rec 51. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc. Rec 57. Further study is to be done on collision assessment considering nuclear reactors compartment. Rec 59. Further study is to be done on the creation of an automatic passive water flooding system of the reactors to equalize pressure and prevent radiation leakage. Rec 68. Further study is to be done on the vessel cargo loading process and the cargo loading manual is to be updated.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.9.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Overall	Possible	Moderate	High (9)		
				4.9.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		
				4.9.7. High external pressure leading to reactor boundary collapse.	Overall	Possible	Major	Extreme (12)		
				4.9.8. Capsizing (see 4.7)						
			4.9.6. Collision (see 4.6)							
			4.9.7. Grounding (see 4.5)							
4.10	Seismic event	Location of vessel to be taken into account.	4.10.1. Earthquake while at shipyard.	4.10.1. Damage on the reactor couplers.	Asset	Possible	Major	Extreme (12)		Rec 5. "Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship Rec 26. The reactors and their systems are to consider seismic events, tsunami, etc. probability, in design while in shipyard, dry dock, port, channel etc.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 69. Normally port regulations require that in an emergency the ship must depart from port within one hour or less. Reactor designers are to consider such requirement in design for power availability to depart port on short notice.
				4.10.2. Damage to the reactor.	Asset	Possible	Major	Extreme (12)		
			4.10.2. Earthquake while at dry docking.	4.10.1. Damage on the reactor couplers.	Asset	Possible	Major	Extreme (12)		Rec 5. "Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship Rec 26. The reactors and their systems are to consider seismic events, tsunami, etc. probability, in design while in shipyard, dry dock, port, channel etc. Rec 69. Normally port regulations require that in an emergency the ship must depart from port within one hour or less. Reactor designers are to consider such requirement in design for power availability to depart port on short notice.
				4.10.2. Damage to the reactor.	Asset	Possible	Major	Extreme (12)		
			4.10.3. Tsunami.	4.10.1. Damage on the reactor couplers.	Asset	Possible	Major	Extreme (12)		Rec 26. The reactors and their systems are to consider seismic events, tsunami, etc. probability, in design while in shipyard, dry dock, port, channel etc.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 69. Normally port regulations require that in an emergency the ship must depart from port within one hour or less. Reactor designers are to consider such requirement in design for power availability to depart port on short notice.
				4.10.2. Damage to the reactor.	Asset	Possible	Major	Extreme (12)		
			4.10.4. Typhoon (see 4.11)	4.10.1. Damage on the reactor couplers.	Asset	Possible	Major	Extreme (12)		
				4.10.2. Damage to the reactor.	Asset	Possible	Major	Extreme (12)		
4.11	Typhoon		4.11.1. Typhoon inertia loads.	4.11.1. Vessel damage.	Asset	Possible	Major	Extreme (12)		Rec 70. Typhoon events are to be included during design of vessel and appropriate load is to be considered in reactors design.
				4.11.2. Reactor damage.	Asset	Possible	Major	Extreme (12)		
				4.11.3. Seismic event (see 4.10)						
				4.11.4. Reactor Availability - Global Hazards - Ship Operation (see 5.2)						
4.12	Cargo Fire		4.12.1. Cargo fire.	4.12.1. High heat, smoke and impact on nuclear reactor.	Asset	Possible	Moderate	High (9)	4.12.1. Emergency Shut Down (ESD). 4.12.2. Cofferdam between cargo hold #9 and engine room. 4.12.3. Fire Fighting System (FFS) for cargo fire.	Rec 71. Fire impact and fire load analysis is to be conducted depending on the cargo transported for worst case fire condition on nuclear power plants and its support system.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 5	**Name:** Global Hazards - Ship Operation	
Design Intent:		
Description: Global Hazards - Ship Operation		
Associated Drawings:		

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
5.1	General Recommendation		5.1.1. General Recommendation.							Rec 72. Considering nuclear ship propulsion regulations are not developed yet, but under consideration at IMO and nuclear agencies, suggest participating in such activity. Rec 73. Emergency protocol in case of accident related to nuclear systems are to be developed considering nuclear exposure hazards. Rec 74. Due to radiation exposure risk, in emergency radiation medication and other primary care on site are to be provided. Rec 75. Radiation dispersion analysis for escaped radiation in case of accident are to be conducted and how it will affect lifesaving appliances and crew area are to be analyzed. Rec 76. Location of the muster stations and their proximity to radiation zone and other high-risk areas are to be further studied based on radiation dispersion analysis. Rec 77. High efficiency filtration to capture radiation and minimize its impact is to be provided in all HVAC ducting where probability of radiation exists.

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 78. Considering radiation exposure possibility to crew in accidental situation consideration for propelled lifeboats to decrease escape time from ship and radiation zone around ship. Rec 79. In case of radiation detection in safe area appropriate security, evacuation procedures are to be developed.
5.2	Reactor Availability		5.2.1. Leaving port in emergency. **Comment:** Half or one hour departure prerequisite	5.2.1. Reactor not available within necessary timeframe.	Asset	Possible	Moderate	High (9)		Rec 1. Current reactors are designed for land-based applications for four design conditions - Normal Operation, Anticipated Operational occurrence, design basis accident and design extension condition. Which lacks additional loads and functional requirement needed for marine application. The maritime industry must develop functional requirements for the reactors to operate effectively in a marine environment throughout its life on the ship. Nuclear technology is to be approved by the nuclear regulatory and has to go through a complete technology qualification process to get approved for marine us. Rec 64. Further study is to be done on the minimum necessary power needs of the vessel considering the regulations and the maximum power needed in case of collision avoidance. Battery use (larger size) is to be investigated as an alternative to thermal power damping in case the reactors are kept warm continuously.

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 69. Normally port regulations require that in an emergency the ship must depart from port within one hour or less. Reactor designers are to consider such requirement in design for power availability to depart port on short notice. Rec 80. Further study is to be done on the availability of reserve power. Rec 81. Further study is to be done on the possibility of keeping the helium in hot conditions so that the emergency start up period can be reduced. Rec 82. Further study is to be done for the thermal stress impact on the materials in case of a rapid start up, which creates large thermal gradient. Rec 83. Loss of power due to reactors' unavailability is to be further studied and appropriate mitigation measures and procedures are to be developed.
				5.2.2. Power Availability - System Hazards - Power & Propulsion (see 7.1)						
			5.2.2. Typhoon - Global Hazards (see 4.11)							

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
5.3	Bunkering		5.3.1. Unavailability of fuel oil due to reactor shutdown (not enough capacity stored).	5.3.1. Loss of auxiliary power.	Overall	Possible	Moderate	High (9)	5.3.1. Bunkering of normal fuel.	Rec 84. Licensing, security protocols and docking agreements with ports are to be developed. Rec 85. Bunkering operations to take the fuel for the need for the electricity are to be considered and further analyzed.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 6	**Name:** System Hazards	
Design Intent:		
Description: System Hazards		
Associated Drawings:		

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
6.1	Piping, Pumps, Material and Supporting Equipment		6.1.1. General recommendation.							Rec 31. Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided. Rec 86. Further study is to be done on the choice of coating on deck to protect materials from contamination in case of Argon 41 dust particle deposition. Rec 87. Cooling water piping is to be designed considering high temperature, corrosion, thermal loads and vibrations. Rec 88. Consider providing a redundant water cooling system with a redundant water pump. Rec 89. Providing 2 x 100% propulsion motors.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 90. Considering supporting components to be installed away from reactors (more than 20 meters) to protect against radiation (neutron) and to provide protection against accident.
			6.1.2. High temperature of System - Thermal creep, fatigue.	6.1.2. Radiation leak - if equipment/piping fail.	Environmental	Unlikely	Moderate	Moderate (6)	6.1.2. Low pressure containment is connected to vent system to vent any radioactive material in safe manner through vent mast. 6.1.3. Normally helium is not radioactive. 6.1.4. Helium radioactivity is monitored, and appropriate alarm and control provided. 6.1.5. The nuclear system is certified/approved by nuclear regulator.	Rec 92. Piping, component, equipment are to be designed considering high temperature fatigue, creep etc.
				6.1.3. Thermal creep, fatigue leading to component/system failure.	Asset	Possible	Moderate	High (9)		
				6.1.4. System not available.	Overall	Possible	Moderate	High (9)		
				6.1.5. Hot surface.	Overall	Possible	Moderate	High (9)		
			6.1.3. Marine Environment - Salinity, chloride, humidity etc.	6.1.1. Corrosion - damage to piping and equipment.	Asset	Unlikely	Moderate	Moderate (6)	6.1.1. HolosGen System is installed inside low pressure boundary with low pressure helium environment. 6.1.2. Low pressure containment is connected to vent system to vent any radioactive material in safe manner through vent mast.	Rec 91. Material selection strategy to include marine environment and appropriate materials are to be selected to eliminate failure due to material degradation.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									6.1.3. Normally helium is not radioactive. 6.1.4. Helium radioactivity is monitored, and appropriate alarm and control provided. 6.1.5. The nuclear system is certified/approved by nuclear regulator.	
				6.1.2. Radiation leak - if equipment/piping fail.	Environmental	Unlikely	Moderate	Moderate (6)		
			6.1.4. Bubble creation.	6.1.1. Corrosion - damage to piping and equipment.	Asset	Unlikely	Moderate	Moderate (6)	6.1.6. HolosGen system is designed to be safe even after loss of cooling. 6.1.7. Reactor shutdown. 6.1.8. Water flow, temperature monitoring.	Rec 87. Cooling water piping is to be designed considering high temperature, corrosion, thermal loads and vibrations. Rec 88. Consider providing a redundant water cooling system with a redundant water pump. Rec 91. Material selection strategy to include marine environment and appropriate materials are to be selected to eliminate failure due to material degradation. Rec 92. Piping, component, equipment are to be designed considering high temperature fatigue, creep etc.
				6.1.2. Radiation leak - if equipment/piping fail.	Environmental	Unlikely	Moderate	Moderate (6)		
				6.1.3. Thermal creep, fatigue leading to component/system failure.	Asset	Possible	Moderate	High (9)		

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			6.1.5. Electrical fault propulsion motor.	6.1.6. Loss of propulsion.	Asset	Possible	Moderate	High (9)		Rec 89. Providing 2 x 100% propulsion motors.
			6.1.6. Cooling water supply failure.	6.1.7. Loss of heat removal from reactor.	Asset	Possible	Moderate	High (9)	6.1.5. The nuclear system is certified/approved by nuclear regulator. 6.1.6. HolosGen system is designed to be safe even after loss of cooling. 6.1.7. Reactor shutdown. 6.1.8. Water flow, temperature monitoring.	Rec 87. Cooling water piping is to be designed considering high temperature, corrosion, thermal loads and vibrations. Rec 88. Consider providing a redundant water cooling system with a redundant water pump.
				6.1.8. Reactor overheating.	Asset	Possible	Major	Extreme (12)		

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
6.2	Bilge System Inside Reactor Compartment		6.2.1. Water ingress.	6.2.1. Flooding of compartment.	Asset	Possible	Minor	Moderate (6)	6.2.1. IMO and Class requirements for flooding avoidance.	Rec 4. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event. Rec 93. Further study is needed to evaluate the bilge system's ability to drain water from both the nuclear reactors room and the Fire Fighting System (FFS), as well as its water quantity and storage capacity.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 94. Considering the radiation risk, the bilge system from any room with potential for radiation must be independent, and dedicated bilge storage should be provided to contain radioactive material. Further study is needed to identify risks, and appropriate mitigation measures are to be considered. Rec 95. Further study is needed on the safe storage and disposal of bilged water in the event of radioactivity.
				6.2.2. Contamination of water.	Environmental	Possible	Minor	Moderate (6)		
				6.2.3. General Fire Fighting Hazard - System Hazards - Fire Fighting System (FFS) (see 12.1)						
			6.2.2. Collision - Global Hazards (see 4.6)							
6.3	Electrical Cables		6.3.1. Exposure to radiation contamination.	6.3.1. Contaminated cable.	Asset	Possible	Moderate	High (9)	6.3.1. Triple redundancy. 6.3.2. Cable protection.	Rec 96. Further study is to be done on how electrical cables meet and be certified according to nuclear regulatory requirement to operate in radioactive environment. Rec 97. Cables are to be designed to withstand submerged conditions.

No.: 6	**Name:** System Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			6.3.2. Cable penetration.	6.3.2. Radiation leak.	Environmental	Possible	Moderate	High (9)	6.3.1. Triple redundancy. 6.3.2. Cable protection. 6.3.3. PPE. 6.3.4. Training.	Rec 96. Further study is to be done on how electrical cables meet and be certified according to nuclear regulatory requirement to operate in radioactive environment. Rec 97. Cables are to be designed to withstand submerged conditions. Rec 98. Further study is to be done on the optimum routing and distance of cables from the nuclear reactors to the motors.
				6.3.3. Radiation Leak.	Injury	Possible	Moderate	High (9)		
6.4	Power Need (Auxiliary & Back up)	START UP TIME / AMOUNT OF POWER ????	6.4.1. Long distance between reactor and motors.	6.4.1. Voltage drop.	Asset	Possible	Moderate	High (9)	6.4.1. Motors are to be placed as close as possible to the shaft.	Rec 3. Further study to be done on the location of the nuclear reactor to provide the highest protection against any external risk (Ed.GA. collision, flooding, grounding, dropped objects etc.). Possibility to be moved to the middle of the vessel. Rec 98. Further study is to be done on the optimum routing and distance of cables from the nuclear reactors to the motors.
			6.4.2. Fire.							Rec 99. Further study is to be done on the necessary auxiliary and emergency generators, backup power (e.g., UPS) and the availability and duration for how long they need to operate.
6.5	Emergency Response		6.5.1. General recommendation.						6.5.1. Personal Protection Equipment (PPE).	Rec 100. Emergency and evacuation procedures are to be developed in addition to existing ones in accordance with nuclear and maritime regulators.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 101. Emergency plan and firefighting plan, consider dispersion analysis, radiation zones and nuclear regulation, is to include quantity, location, and disposal of Personal Protection Equipment (PPE). Rec 102. Lab/Facility (radioactive laboratory) is to be provided on ship to track exposure limit for crew and for management to limit radiation exposure.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 7	**Name:** System Hazards - Power & Propulsion	
Design Intent:		
Description: System Hazards - Power & Propulsion		
Associated Drawings:		

No.: 7 **Name:** System Hazards - Power & Propulsion

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
7.1	Power Availability		7.1.1. General Recommendation.							Rec 83. Loss of power due to reactors' unavailability is to be further studied and appropriate mitigation measures and procedures are to be developed. Rec 103. Requirement for load testing on reactors is to be further studied considering marine engine testing in practice.
			7.1.2. Emergency departure.	7.1.1. Unable to leave port in time. **Comment:** Port regulation may require ship to leave port within hour due to emergency	Asset	Likely	Moderate	High (12)		Rec 69. Normally port regulations require that in an emergency the ship must depart from port within one hour or less. Reactor designers are to consider such requirement in design for power availability to depart port on short notice. Rec 83. Loss of power due to reactors' unavailability is to be further studied and appropriate mitigation measures and procedures are to be developed.
				7.1.2. Unable to leave port in time. **Comment:** Port regulation may require ship to leave port within hour due to emergency	Reputation	Likely	Moderate	High (12)		

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			7.1.3. Reactor Availability - Global Hazards - Ship Operation (see 5.2)							
7.2	Battery		7.2.1. Battery explosion. **Comment:** Li-Ion Battery is proposed for auxiliary backup power	7.2.1. Damage to reactor component.	Asset	Possible	Major	Extreme (12)	7.2.1. Reinforced cofferdam around reactor compartment. 7.2.2. Battery compartment outside reactor compartment. 7.2.3. Battery will meet class society requirement.	Rec 80. Further study is to be done on the availability of reserve power. Rec 104. Impact on reactors compartment due to fire and explosion from battery is to be further investigated.
				7.2.2. Reactor compartment damage due to high heat load.	Asset	Possible	Major	Extreme (12)		
			7.2.2. Battery fire.	7.2.1. Damage to reactor component.	Asset	Possible	Major	Extreme (12)	7.2.1. Reinforced cofferdam around reactor compartment.	Rec 80. Further study is to be done on the availability of reserve power. Rec 104. Impact on reactors compartment due to fire and explosion from battery is to be further investigated.
				7.2.2. Reactor compartment damage due to high heat load.	Asset	Possible	Major	Extreme (12)		

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 8	**Name:** System Hazards - Vent & Ventilation	
Design Intent:		
Description: System Hazards - Vent & Ventilation		
Associated Drawings:		

No.: 8 **Name:** System Hazards - Vent & Ventilation

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
8.1	General Recommendation		8.1.1. Radiation.							Rec 105. A detailed radiation leakage and shielding study to be conducted per nuclear regulatory requirement and appropriate radiation shielding is to be provided to maintain radiation within allowable limits by regulators and dispersion study for all condition of operations - normal, upset, emergency, accidental etc. are to be conducted to determine radiation zone/dispersion. Rec 106. Detailed radiation dispersion study for all conditions of operations - normal, upset, emergency, accidental etc. is to be conducted to determine radiation zone/dispersion around vent and ventilation outlets and to be considered in the general arrangement of ship to protect accommodation and other areas.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
8.2	Ionised Argon and Ionize Radiation	Argon is heavier than air.	8.2.1. Ionisation of argon inside the reactor core between the secondary pressure vessel and the container. **Comment:** In case of Helium breach	8.2.1. Ionised argon inside the vessel funnel.	Environmental	Possible	Moderate	High (9)	8.2.1. Adequate chimney height. **Comment:** > 26 meters from reactor level.	Rec 31. Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided. Rec 107. Radiation dispersion study is to be done for all normal, upset, accident and emergency modes of operation to determine chimney height considering radiation leakage (e.g., ionised Argon, Helium, and other radiation), to avoid any ingress of radiation/contaminated Argon 41 inside the accommodation area and deposition on the deck area. Rec 108. Considering air gap allowed and route chimney height is to be further studied for any risk. Rec 109. Further study is to be done on allowable radiation exposure levels and consequent maximum allowable period of crew stay on such a type of vessel; appropriate mitigation measures are to be provided.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 110. Considering reactors compartment vent system location and possibility of radiation may exist, all openings and air inlet are to be further studied and appropriate distance/separation to be provided. Rec 111. Vent lines from reactors modules are to be further studied as they have higher probability of radiation presence. Consider vent lines ducting from reactor modules to be jacketed with annular space maintained at positive pressure to minimize any possibility or leakage from vent lines ducting to other spaces. Rec 112. Further study is to be done on the reactors' room ventilation requirements and the air changes per hour etc. to keep the room temperature within acceptable limits. Ventilation ducting is to be further studied for any possibility of ionizing radiation and its impact. Consider ventilation ducting to be jacketed with annular space maintain at positive pressure to minimize any possibility or leakage from ventilation ducting to other spaces.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 113. Any radiation leakage between reactors pressure boundary and secondary low-pressure boundary is to be further studied and disposal of such radiation is to be further considered during a detailed design.
				8.2.2. Ionised Argon inside the accommodation area.	Injury	Possible	Major	Extreme (12)		
				8.2.3. Fall out of ionised Argon on ship deck due to rain presence.	Environmental	Possible	Moderate	High (9)		
				8.2.4. Reactive Material on Deck (see 8.6)						
				8.2.5. Other Machinery Spaces - Maintenance and Inspection (see 8.7)						
8.3	Contamination & Pollution		8.3.1. Radiation release.	8.3.1. Radiation sticking to surface, coating, paints etc.	Environmental	Likely	Moderate	High (12)		Rec 31. Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				8.3.2. Radiation sticking to surface, coating, paints etc.	Injury	Likely	Moderate	High (12)		
8.4	HVAC Air		8.4.1. General recommendation.							Rec 31. Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided. Rec 112. Further study is to be done on the reactors' room ventilation requirements and the air changes per hour etc. to keep the room temperature within acceptable limits. Ventilation ducting is to be further studied for any possibility of ionizing radiation and its impact. Consider ventilation ducting to be jacketed with annular space maintain at positive pressure to minimize any possibility or leakage from ventilation ducting to other spaces. Rec 116. Further study is to be done on nuclear waste storage and disposal. Rec 119. Further study is to be done on HVAC to minimize dust carry overhead.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 121. Further study to be done on traps to catch radionuclides is to be implemented. Rec 122. Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height and emergency procedure to protect crew. Rec 123. Thermodynamic analysis is to be done to determine the HVAC load for the reactors compartment so that the temperature is maintained within the acceptable limits.
			8.4.2. Humidity and salinity in air.	8.4.1. Condensation.	Asset	Possible	Moderate	High (9)	8.4.3. Reactor modules are enclosed with low pressure barrier in low pressure helium.	Rec 31. Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided. Rec 114. Bilge systems from reactors rooms are to be properly designed considering radiation and contaminated water and are to be independent of other systems.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 119. Further study is to be done on HVAC to minimize dust carry overhead. Rec 120. Further study is to be done on how to avoid ingress of condensation. Rec 121. Further study to be done on traps to catch radionuclides is to be implemented. Rec 124. Reactors modules are to be provided with water leakage detectors and proper coating to contain any leakage.
				8.4.3. Corrosion of piping, equipment.	Asset	Possible	Moderate	High (9)		
				8.4.4. Contaminated water.	Environmental	Possible	Moderate	High (9)		
			8.4.3. Radiation inside reactor compartment.	8.4.5. Contaminated air.	Environmental	Possible	Moderate	High (9)	8.4.1. Radiation filters. 8.4.2. Radiation detector. 8.4.4. Proper radiation shielding design per regulatory requirement.	Rec 112. Further study is to be done on the reactors' room ventilation requirements and the air changes per hour etc. to keep the room temperature within acceptable limits. Ventilation ducting is to be further studied for any possibility of ionizing radiation and its impact. Consider ventilation ducting to be jacketed with annular space maintain at positive pressure to minimize any possibility or leakage from ventilation ducting to other spaces. Rec 115. Further study is to be done on the monitoring of air exhaust.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 119. Further study is to be done on HVAC to minimize dust carry overhead. Rec 121. Further study to be done on traps to catch radionuclides is to be implemented. Rec 122. Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height and emergency procedure to protect crew. Rec 124. Reactors modules are to be provided with water leakage detectors and proper coating to contain any leakage.
				8.4.7. Other Machinery Spaces - Maintenance and Inspection (see 8.7)						
			8.4.4. Ventilation failure.	8.4.6. Unable to remove heat form compartment leading to reactor shutdown.	Asset	Possible	Moderate	High (9)		Rec 119. Further study is to be done on HVAC to minimize dust carry overhead. Rec 120. Further study is to be done on how to avoid ingress of condensation. Rec 121. Further study to be done on traps to catch radionuclides is to be implemented.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 122. Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height and emergency procedure to protect crew. Rec 124. Reactors modules are to be provided with water leakage detectors and proper coating to contain any leakage. Rec 125. Consider redundant extraction fan for reactors compartment.
				8.4.7. Other Machinery Spaces - Maintenance and Inspection (see 8.7)						
				8.4.8. Heat Removal & Cooling - Nuclear Technology Hazards (see 13.7)						
			8.4.5. Other systems (lifting) liquid leakages.	8.4.2. Contaminated materials if disposed improperly.	Environmental	Possible	Major	Extreme (12)		Rec 114. Bilge systems from reactors rooms are to be properly designed considering radiation and contaminated water and are to be independent of other systems.

No.: 8	**Name:** System Hazards - Vent & Ventilation								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 117. Further study is to be done on procedures and monitoring of storage of contaminated material. Rec 118. Water leakage monitoring inside reactors room.
8.5	Reactivity in the Air		8.5.1. Damage to existing piping.							Rec 31. Considering the radiation, the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided. Rec 112. Further study is to be done on the reactors' room ventilation requirements and the air changes per hour etc. to keep the room temperature within acceptable limits. Ventilation ducting is to be further studied for any possibility of ionizing radiation and its impact. Consider ventilation ducting to be jacketed with annular space maintain at positive pressure to minimize any possibility or leakage from ventilation ducting to other spaces.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
8.6	Reactive Material on Deck		8.6.1. Radiation leakage in reactor module. **Comment:** Can escape via vent and ventilation system to vent and ventilation outlet on deck and atmosphere	8.6.1. Radiation leakage through vent/ventilation outlet to the environment.	Environmental	Possible	Major	Extreme (12)	8.6.1. Nuclear reactor safety is design based on defense in depth concept required by nuclear regulator.	Rec 86. Further study is to be done on the choice of coating on deck to protect materials from contamination in case of Argon 41 dust particle deposition. Rec 107. Radiation dispersion study is to be done for all normal, upset, accident and emergency modes of operation to determine chimney height considering radiation leakage (e.g., ionised Argon, Helium, and other radiation), to avoid any ingress of radiation/contaminated Argon 41 inside the accommodation area and deposition on the deck area. Rec 126. Further study to be done on the maximum contaminant levels allowed, e.g., on open deck surface, which might be deposited in case of leakage through the funnel. Consider the option of installing a scrubber. Rec 127. Procedures notifying port authorities on nuclear pollutants on board are to be developed.
			8.6.2. Ionised Argon and Ionize Radiation (see 8.2)							

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
8.7	Other Machinery Spaces	Due to design being at concept stage no clear information is provided for other machinery space.	8.7.1. General Recommendation. **Comment:** Reactor major machinery is contained inside reactor module. The major support system requirement is cooling water system to remove heat. Other system requirement is electrical system to take off power and control system.							Rec 128. Surrounding machinery or other space to be provided with independent ventilation to minimize any possibility of radiation entering space or contamination including reverse flow. Ventilation outlet to be separated by distance from reactors compartment and modules ventilation/vent outlets.
			8.7.2. Ionised Argon and Ionize Radiation (see 8.2)							
			8.7.3. HVAC Air (see 8.4)							
8.8	Ventilation Philosophy		8.8.1. General recommendation.	8.8.1. Heat Removal & Cooling - Nuclear Technology Hazards (see 13.7)						Rec 112. Further study is to be done on the reactors' room ventilation requirements and the air changes per hour etc. to keep the room temperature within acceptable limits. Ventilation ducting is to be further studied for any possibility of ionizing radiation and its impact. Consider ventilation ducting to be jacketed with annular space maintain at positive pressure to minimize any possibility or leakage from ventilation ducting to other spaces.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 122. Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from funnel a dispersion study to be conducted for all operational, upset, emergency and accidental situation to determine safe ventilation funnel height and emergency procedure to protect crew.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 9	**Name:** Maintenance and Inspection	
Design Intent:		
Description:		
Associated Drawings:		

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
9.1	Maintenance, Live		9.1.1. Working inside reactor room and contaminated material.	9.1.1. Personnel exposure to radiation.	Injury	Possible	Critical	Extreme (15)	9.1.1. Radiation detectors. 9.1.2. Personal Protection Equipment (PPE). 9.1.3. Recording of exposure time inside the reactor compartment. 9.1.4. Special training and education of crew.	Rec 9. Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied. Rec 129. Further study is to be done on limitations in daily visual routine inspection. Rec 130. Further study is to be done on prohibiting of access to certain reactors area compartments.

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 131. Further study is to be done on crew training and education.
9.2	Maintenance, Shutdown		9.2.1. Drop object on reactor.	9.2.1. Damage to the reactor	Asset	Possible	Major	Extreme (12)	9.2.1. Reactor can tolerate an object fall from 3ft/1m.	

Title: Nuclear-Powered Bulk Carrier		**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 10	**Name:** System Hazards - Dry Docking		
Design Intent:			
Description: System Hazards - Dry Docking			
Associated Drawings:			

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
10.1	General Recommendation		10.1.1. General Recommendation.							Rec 2. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 10. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship.

No.: 10	**Name:** System Hazards - Dry Docking								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 132. Further study is to be done at the required time the reactors need to cool down (boundary C) and reach a safe condition before going to dry dock. Rec 135. For dry docking detailed study is to be done to maintain reactors in safe condition for dry docking period. A study is to be conducted that will include safety monitoring, security of reactors, auxiliary power, and system requirements to maintain reactors in safe condition. Rec 136. Dry docking shipyard selection is to consider earthquake and typhoon risk; reactors design is to consider such threats as well.
			10.1.2. Radiation inside reactor compartment.	10.1.1. Radiation exposure to Crew/SY worker.	Injury	Possible	Moderate	High (9)		Rec 134. Proper procedure and radiation exposure limits are to be established before anyone entering reactors compartment.
			10.1.3. Loss of cooling water supply or utility.	10.1.2. Reactor safety compromise.	Asset	Possible	Moderate	High (9)		Rec 132. Further study is to be done at the required time the reactors need to cool down (boundary C) and reach a safe condition before going to dry dock. Rec 135. For dry docking detailed study is to be done to maintain reactors in safe condition for dry docking period. A study is to be conducted that will include safety monitoring, security of reactors, auxiliary power, and system requirements to maintain reactors in safe condition.

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			10.1.4. Hurricane, earthquake.							Rec 136. Dry docking shipyard selection is to consider earthquake and typhoon risk; reactors design is to consider such threats as well.
			10.1.5. Security breach.							Rec 137. Security of reactors is to be further studied, and proper arrangement is to be provided to prevent any security issues.
			10.1.6. Dropped Object.	10.1.3. Damage to reactor compartment/reactor.	Asset	Possible	Moderate	High (9)		Rec 30. Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane, other load etc.). Rec 133. Any overhead lifting is to be further investigated and restricted areas are to be further developed.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 11	**Name:** System Hazards - Dropped Object & Energy Release	
Design Intent:		
Description: Dropped Object & Energy Release Hazards		
Associated Drawings:		

No.: 11 **Name:** System Hazards - Dropped Object & Energy Release

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
11.1	General Dry-Docking Hazards		11.1.1. General recommendation.							Rec 30. Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane, other load etc.). Rec 133. Any overhead lifting is to be further investigated and restricted areas are to be further developed.
11.2	Crane		11.2.1. Dropped object from crane (reactor maintenance).							Rec 133. Any overhead lifting is to be further investigated and restricted areas are to be further developed.
11.3	Kinetic or Stored Energy		11.3.1. Turbine broken blade.						11.3.1. System design to accommodate blade dismantling.	Rec 139. Any kinetic and potential energy release inside or outside or reactors modules is to be identified (pressurised system, rotating system, turbine, dropped object/load etc.) and its impact on reactors or any safety system is to be further studied for risk on nuclear system and appropriate mitigations are to be provided or to eliminate hazards.
			11.3.2. Pressurised pipe failure.							Rec 138. Further study is to be done on potential energy impact and appropriate mitigation measures defined.

No.: 11 | **Name:** System Hazards - Dropped Object & Energy Release

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
										Rec 139. Any kinetic and potential energy release inside or outside or reactors modules is to be identified (pressurised system, rotating system, turbine, dropped object/load etc.) and its impact on reactors or any safety system is to be further studied for risk on nuclear system and appropriate mitigations are to be provided or to eliminate hazards.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)	
Design Intent:		
Description: System Hazards - Fire Fighting System		
Associated Drawings:		

No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
12.1	General Fire Fighting Hazard		12.1.1. General recommendation.							Rec 7. Considering possibility of fire internal/external outside of reactor compartment and considering radiation leakage possibility, design principle should include following: 1. Consider arranging each reactor in separate compartments and providing enough isolation to prevent fire migration and protection against fire incident. 2. Minimize fire possibility by using appropriate material. 3. Appropriate means are to be provided to fight fire in reactor and machinery compartment. 4. Structural design to consider fire load in design and its survivability. Rec 71. Fire impact and fire load analysis is to be conducted depending on the cargo transported for worst case fire condition on nuclear power plants and its support system.

No.: 12 | **Name:** System Hazards - Fire Fighting System (FFS)

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
										Rec 142. Considering the possibility of fire inside/outside reactors compartment and considering radiation leakage possibility, design principle should include minimizing fire possibility by using appropriate material. General arrangement is to avoid outside fire impact on reactors compartments and appropriate means are to be provided to fight fire in reactors and machinery compartment. Also, detailed fire load analysis is to be conducted during design to improve structural capacity of structure to survive fire load. Rec 143. Consider in general arrangement to keep any fire hazards as far as away from reactors compartment.
			12.1.2. Fire in surrounding area outside reactor module.	12.1.1. Oxidisation of graphite inside reactor. **Comment:** (In case of oxygen ingress)	Asset	Possible	Major	Extreme (12)	12.1.1. Flame retardant design of cabling. 12.1.2. Fire resistant design of motor components. 12.1.3. All electrical components inside reactor (inside boundary B) are in an inert (Helium) environment. 12.1.4. High temperature tolerance of the graphite. **Comment:** TRISO will not melt. 12.1.5. Fire Fighting System (FFS). **Comment:** HolosGen to define.	Rec 142. Considering the possibility of fire inside/outside reactors compartment and considering radiation leakage possibility, design principle should include minimizing fire possibility by using appropriate material. General arrangement is to avoid outside fire impact on reactors compartments and appropriate means are to be provided to fight fire in reactors and machinery compartment. Also, detailed fire load analysis is to be conducted during design to improve structural capacity of structure to survive fire load. Rec 143. Consider in general arrangement to keep any fire hazards as far as away from reactors compartment.

No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				12.1.2. Radiation leak.	Environmental	Unlikely	Major	High (8)		
			12.1.3. Electrical fire inside reactor module (generator winding, start motor winding, cables etc.).	12.1.1. Oxidisation of graphite inside reactor. **Comment:** (In case of oxygen ingress)	Asset	Possible	Major	Extreme (12)	12.1.1. Flame retardant design of cabling. 12.1.2. Fire resistant design of motor components. 12.1.3. All electrical components inside reactor (inside boundary B) are in an inert (Helium) environment. 12.1.4. High temperature tolerance of the graphite. **Comment:** TRISO will not melt. 12.1.5. Fire Fighting System (FFS). **Comment:** HolosGen to define.	Rec 140. Further studies to be done on fire analysis and appropriate mitigations are to be provided. Rec 141. Fire/smoke detectors are to be provided. Rec 142. Considering the possibility of fire inside/outside reactors compartment and considering radiation leakage possibility, design principle should include minimizing fire possibility by using appropriate material. General arrangement is to avoid outside fire impact on reactors compartments and appropriate means are to be provided to fight fire in reactors and machinery compartment. Also, detailed fire load analysis is to be conducted during design to improve structural capacity of structure to survive fire load.
			12.1.4. Fire in cargo area.	12.1.3. Damage to reactor.	Asset	Possible	Major	Extreme (12)	12.1.6. Cargo area firefighting.	Rec 71. Fire impact and fire load analysis is to be conducted depending on the cargo transported for worst case fire condition on nuclear power plants and its support system.
			12.1.5. Bilge System Inside Reactor Compartment - System Hazards (see 6.2)							

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 13	**Name:** Nuclear Technology Hazards	
Design Intent:		
Description: Nuclear Technology Hazards		
Associated Drawings:		

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.1	Crew, Training, Human Factor		13.1.1. Availability of personnel.	13.1.1. Unavailability of seafarers.	Overall	Possible	Moderate	High (9)	13.1.1. SOLAS requirements. 13.1.2. STCW convention.	Rec 144. Further study to be done on the organisations that will be involved in the training and certification (and validation thereof from the regulator) of the personnel. Rec 145. Detailed training and certification programmes are to be developed considering various regulatory agencies involved. Rec 147. Crew security clearance certificate is to be further investigated.
				13.1.2. Higher cost of crew.	Asset	Likely	Moderate	High (12)		
			13.1.2. Human error.	13.1.3. Crew injury.	Injury	Possible	Major	Extreme (12)		Rec 144. Further study to be done on the organisations that will be involved in the training and certification (and validation thereof from the regulator) of the personnel. Rec 145. Detailed training and certification programmes are to be developed considering various regulatory agencies involved. Rec 146. Human factor studies are to be done for the operation of the ship, for the nuclear reactors. Rec 147. Crew security clearance certificate is to be further investigated.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.1.3. Security & External Threat (see 13.3)	13.1.3. Crew injury.	Injury	Possible	Major	Extreme (12)		Rec 147. Crew security clearance certificate is to be further investigated.
13.2	Public Perception		13.2.1. Not in my port mentality.	13.2.1. Inability to enter port.	Reputation	Possible	Moderate	High (9)		Rec 84. Licensing, security protocols and docking agreements with ports are to be developed. Rec 148. Legislation is to be developed for countries and ports involved in secure trade routes.
			13.2.2. Curiosity of port personnel.	13.2.2. Violation of security measures.	Overall	Possible	Major	Extreme (12)	13.2.1. Security protocols.	Rec 84. Licensing, security protocols and docking agreements with ports are to be developed.
13.3	Security & External Threat		13.3.1. High jacking, piracy, terrorism.							Rec 23. Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation. Rec 150. Terrorist threats are to be addressed.
			13.3.2. Ship attack.	13.3.1. Crew, Training, Human Factor (see 13.1)						Rec 23. Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.3.3. Plane/drone attack.							Rec 23. Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation.
			13.3.4. Cyber-attack.						13.3.1. Emergency Shut Down (ESD) through a satellite command. 13.3.2. Hard wire control, not wi-fi.	Rec 23. Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation. Rec 149. Development of restart protocol in case of Emergency Shut Down (ESD) shutdown due to Cyber-attack. Transponder is to be programmed to provide location of the reactors/vessel. Rec 150. Terrorist threats are to be addressed. Rec 151. Implement any automation safety features stemming from repositioning of the reactors.
			13.3.5. Unauthorised access.							Rec 23. Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.3.6. Torpedo attack.							Rec 23. Legislation and requirements are to be developed for external threats or risk such as hijacking, piracy, terror, flying objects (missile, plane etc.) attack, etc. Ship designers and technology developers are to consider such threats in design and operation for the life of vessels for all modes of operation. Rec 150. Terrorist threats are to be addressed.
13.4	Fuel Charging & Refuelling		13.4.1. Inability to load fuel.							Rec 8. Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 years), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design. Rec 28. Vessel modification including engine removal, structural modification etc. are to be further investigated to accommodate nuclear power plant.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 32. Considering treaty on the nonproliferation of nuclear weapons and risk of ship trading worldwide, technology developers are to design proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them or use them in a harmful manner. Further, the impact of treaty on design and operation is to be further studied. Rec 152. Considering the dry docking period (5 years) and fuel lifetime (7 years) mismatch, further study is to be done on the alignment of them. Rec 153. Considering HolosGen design is delivering on a continuous basis 10 MWe for a period of eight years and further power consumption may vary, additional studies are to be done with developer to achieve optimum dry docking/recharging cycle. Rec 154. Further study is to be done on the refuelling process of the vessel and on how the reactor, as a complete system, would be removed.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.4.2. General Recommendation.							Rec 8. Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 years), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design. Rec 32. Considering treaty on the nonproliferation of nuclear weapons and risk of ship trading worldwide, technology developers are to design proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them or use them in a harmful manner. Further, the impact of treaty on design and operation is to be further studied. Rec 155. Reactors replacement timing is to be further investigated.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.5	Reactor Barrier(s)		13.5.1. Heat inside the reactor compartment. **Comment:** Reactor not insulated, only has radiological shield.	13.5.1. Structural damage to structural component - high thermal stress.	Asset	Possible	Moderate	High (9)	13.5.1. Reactor compartment is restricted for entry when reactor is in operation.	Rec 112. Further study is to be done on the reactors' room ventilation requirements and the air changes per hour etc. to keep the room temperature within acceptable limits. Ventilation ducting is to be further studied for any possibility of ionizing radiation and its impact. Consider ventilation ducting to be jacketed with annular space maintain at positive pressure to minimize any possibility or leakage from ventilation ducting to other spaces. Rec 156. Reactors modules' surface temperature is to be maintained within allowable acceptable limits or insulation is to be provided. Rec 157. Reactors modules support to consider thermal impact in design.
				13.5.2. Support damage due to thermal stress.	Asset	Possible	Moderate	High (9)		
				13.5.3. Hot surface.	Injury	Likely	Moderate	High (12)		
				13.5.4. Hot environment inside reactor compartment.	Injury	Likely	Moderate	High (12)		
			13.5.2. Leakage from the cofferdam.							Rec 158. Reactor compartment is surrounded by cofferdam and at this point it is not known whether it will be filled with water or concrete or another material to capture neutron. When determined, further risk assessment is to be performed.
			13.5.3. Blocked circulation of cooling water.							Rec 159. A detailed HAZOP and other risk assessments are to be conducted on the entire reactors systems for further identification of risk.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.5.4. Collapse of barrier from outside (sinking, dropped object, collision etc.).	13.5.5. Damage to reactor.	Asset	Possible	Major	Extreme (12)		Rec 160. Accidental damage analysis for reactors barrier is to be conducted.
			13.5.5. loss of control of reaction inside reactor.	13.5.6. Explosion.	Overall	Unlikely	Critical	Extreme (10)		Rec 161. HolosGen is to provide further details and regulators to address such issues for all possible failure.
13.6	Supporting Systems		13.6.1. Black out.	13.6.2. No power available for reactor safety, cooling etc.	Overall	Possible	Major	Extreme (12)	13.6.1. Reactor technology is designed so it does not need cooling; can go in safe state just by convection heat dissipation. 13.6.2. Reactor safety system.	Rec 53. Grounding/collision/submergence etc. can lead to reactors' essential and auxiliary systems damage and their impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship. Rec 99. Further study is to be done on the necessary auxiliary and emergency generators, backup power (e.g., UPS) and the availability and duration for how long they need to operate.
			13.6.2. Automation failures.	13.6.3. Unable to control reactor.	Overall	Possible	Moderate	High (9)	13.6.2. Reactor safety system. 13.6.3. Reactor is designed based on defense in depth principle and usually all critical safety system is redundant or triple redundant.	Rec 163. Automation failure to be considered in detailed risk assessment for control system function FME(C)A.
			13.6.3. Low cooling water purity.	13.6.1. Blockage of heat exchanger channels. **Comment:** Printed HE (Small diameter channels	Asset	Possible	Moderate	High (9)		Rec 162. Water quality requirements are to be further developed, and intermediate cooling type circuits are to be provided with expansion tank.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.6.4. Ventilation failure.	13.6.4. Unable to remove heat form compartment leading to reactor shutdown	Asset	Possible	Moderate	High (9)		Rec 125. Consider redundant extraction fan for reactors compartment.
13.7	Heat Removal & Cooling		13.7.1. Cooling water is not available.	13.7.1. Reactor overheating.	Asset	Unlikely	Moderate	Moderate (6)	13.7.1. Reactor shutdown system upon detection of cooling circuit failure. 13.7.2. Cooling circuit temperature monitoring. 13.7.3. Flow monitoring. 13.7.4. Reactor design such that it does not need continuous cooling after shutdown to maintain safe condition.	Rec 164. Thermal analysis for operational and shutdown conditions and detailed environmental procedural analysis are to be developed.
				13.7.2. Damage to graphite.	Asset	Unlikely	Moderate	Moderate (6)		
			13.7.2. HVAC Air - System Hazards - Vent & Ventilation (see 8.4)							
			13.7.3. Ventilation Philosophy - System Hazards - Vent & Ventilation (see 8.8)							
13.8	Nuclear Waste Storage, Handling, & Disposal		13.8.1. Radioactive waste and materials.	13.8.1. Exposure of humans.	Injury	Possible	Moderate	High (9)		Rec 165. Further study to be done on detailed plan of handling of radioactive material at the end of ship life, before end of ship lifetime, or normal operation, maintenance e.g., hull, reactors core, piping, heat exchangers, pumps, any other exposed material. Rec 166. Further study to be done on handling waste fuel during ship lifetime.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 167. Further study to be done on radioactive waste disposal procedures. Rec 168. Vessel design is to consider proper arrangement for nuclear waste storage and handling and monitoring on board vessels for radioactive/nuclear waste generated during normal operation, maintenance, accident, upset condition etc. per nuclear regulatory requirements prior to proper disposal.
13.9	Radiological Leakage		13.9.1. General Recommendations.							Rec 105. A detailed radiation leakage and shielding study to be conducted per nuclear regulatory requirement and appropriate radiation shielding is to be provided to maintain radiation within allowable limits by regulators and dispersion study for all condition of operations - normal, upset, emergency, accidental etc. are to be conducted to determine radiation zone/dispersion. Rec 109. Further study is to be done on allowable radiation exposure levels and consequent maximum allowable period of crew stay on such a type of vessel; appropriate mitigation measures are to be provided. Rec 169. Considering possibility of radiation leakage and exposure to crew members a facility/space to be provided next to reactors room for treatment with basic medical equipment per nuclear regulators recommendations.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.9.2. Degradation of system components.							Rec 9. Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied. Rec 39. Inspection and maintenance plans need to be developed to verify the integrity or the reactors foundation and radiation biological shielding.
			13.9.3. Motion - Global Hazards (see 4.2)							
			13.9.4. Vibration - Global Hazards (see 4.3)							
			13.9.5. Sloshing - Global Hazards (see 4.4)							
13.10	Magnetic Bearings	Populated from Global Hazards node	13.10.1. Bearing failure.	13.10.1. Damage to reactor component.	Asset	Possible	Moderate	High (9)		Rec 170. Magnetic bearings design is to be further evaluated for all possible failure modes and have appropriate reliability and availability.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.11	Power Availability		13.11.1. Auxiliary power not available for startup. **Comment:** During startup reactor need heat and torquing power (electrical motor)	13.11.1. Unable to start reactor.	Asset	Possible	Moderate	High (9)	13.11.1. Back up Li-Ion battery provided. 13.11.2. Ship auxiliary generator.	Rec 99. Further study is to be done on the necessary auxiliary and emergency generators, backup power (e.g., UPS) and the availability and duration for how long they need to operate.
			13.11.2. Reactor shutdown.	13.11.2. Power not available.	Overall	Possible	Major	Extreme (12)	13.11.3. Redundant Reactor module.	
13.12	Liability		13.12.1. General recommendation.							Rec 16. Considering that regulations framework and classification requirements are still in development for nuclear power marine application, regulation development framework is to be developed and work with appropriate regulatory agency for development of requirements from design, licensing, operation, and liability related issues.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor	
Design Intent:		
Description: Nuclear Technology Hazards - Small Modular Reactor		
Associated Drawings:		

No.: 14 **Name:** Nuclear Technology Hazards - Small Modular Reactor

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
14.1	Uncontrolled Reaction		14.1.1. Failure of all shutdown rod and the redundancy.	14.1.1. Overheating, reactor oscillation, dropper effect.	Overall	Unlikely	Major	High (8)	14.1.1. Major safety critical system is redundant or triple redundant and independent. 14.1.2. System will stabilize by itself due to design. Doppler effect kick in. 14.1.3. Injection of poison, killing of neutrons. 14.1.4. Triple redundancy safeguard (1 pseudo-passive, 2 active systems). 14.1.5. Design is such that no release of radioactive nuclei will occur.	
				14.1.2. Uncontrolled chain reaction. **Comment:** Oscillation, not explosion	Overall	Unlikely	Critical	Extreme (10)		
			14.1.2. Failure of drum and the redundancy.	14.1.1. Overheating, reactor oscillation, dropper effect.	Overall	Unlikely	Major	High (8)	14.1.2. System will stabilize by itself due to design. Doppler effect kick in. 14.1.3. Injection of poison, killing of neutrons. 14.1.4. Triple redundancy safeguard (1 pseudo-passive, 2 active systems). 14.1.5. Design is such that no release of radioactive nuclei will occur.	

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				14.1.2. Uncontrolled chain reaction. **Comment:** Oscillation, not explosion	Overall	Unlikely	Critical	Extreme (10)		
			14.1.3. Security & External Threat - Nuclear Technology Hazards (see 13.3)	14.1.1. Overheating, reactor oscillation, dropper effect.	Overall	Unlikely	Major	High (8)	14.1.2. System will stabilize by itself due to design. Doppler effect kick in. 14.1.3. Injection of poison, killing of neutrons. 14.1.4. Triple redundancy safeguard (1 pseudo-passive, 2 active systems). 14.1.5. Design is such that no release of radioactive nuclei will occur.	
				14.1.2. Uncontrolled chain reaction. **Comment:** Oscillation, not explosion	Overall	Unlikely	Critical	Extreme (10)		
14.2	Safety System		14.2.1. No additional risks identified.							
14.3	Inspection/Maintenance		14.3.1. Malfunction of sensors.						14.3.1. Redundant control systems.	Rec 171. Further study to be done on sensors calibration. Rec 172. Further study to be done on pump periodic maintenance plan. Rec 173. Detailed inspection maintenance plan for the entire nuclear system and its supporting systems is to be developed considering radiation exposure and risk, and further study such as RAM (Reliability, Availability, Maintainability) analysis is to be considered.

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 174. Detailed training plan for maintenance plan is to be developed. Rec 175. Spare part inventory is to be further analyzed, and requirements are to be defined.
14.4	Operation		14.4.1. No additional risks identified.							
14.5	Power Availability		14.5.1. No additional risk identified.							
14.6	Escape & Evacuation		14.6.1. General recommendation.							Rec 177. Further study is to be done on the way a contaminated person can be transported to a hospital. Rec 178. Spaces on the ship that can treat contaminated persons, including special types of showers. Rec 179. Further study is to be done on procedures in case of contaminated crew. Rec 180. Emergency evacuation and escape study to be conducted for all spaces for all modes of operation considering additional risk of radiation exposure as applicable.
14.7	Harbor Operation		14.7.1. Partial load of reactor.							Rec 181. Detailed electrical and power simulation load study to be done for all modes of operation. Rec 182. Further study to be done on partial load/low load operation of the reactor considering normal ship operation.

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			14.7.2. Emergency Shelter - Nuclear Technology Hazards - Impact on Ports (see 15.1)							

Title: Nuclear-Powered Bulk Carrier		**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 15	**Name:** Nuclear Technology Hazards - Impact on Ports		
Design Intent:			
Description: Nuclear Technology Hazards - Impact on Ports			
Associated Drawings:			

No.: 15	**Name:** Nuclear Technology Hazards - Impact on Ports									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
15.1	Emergency Shelter		15.1.1. General recommendation.	15.1.1. Harbor Operation - Nuclear Technology Hazards - Small Modular Reactor (see 14.7)						Rec 21. Operation in port areas or traditional water is to be considered in any licensing process. Ports do not have any regulations at the moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues in future regulations development. Rec 47. Emergency shelter/port of refuge plan is to be considered and whether there is a port available in case of emergency considering nuclear technology on board. Rec 183. Further study is to be done on acceptance of technology from port authorities.

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 16	**Name:** Nuclear Technology Hazards - Ship Recycling & Salvage	
Design Intent:		
Description: Nuclear Technology Hazards - Ship Recycling & Salvage		
Associated Drawings:		

No.: 16 **Name:** Nuclear Technology Hazards - Ship Recycling & Salvage

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
16.1	General Comment.	Deactivation & Decommissioning Activity (NRC Terminology)	16.1.1. General recommendation.						16.1.1. Inventory of Hazardous Materials (IHM).	Rec 176. The inventory of Hazardous Materials (IHM) is to be kept. Rec 184. Further study to be done on the dismantling of the reactor. Rec 185. Plan for disposal of the SSC (System Structure and Components). Rec 186. Radiation survey on SSC prior to vessel dismantling.
			16.1.2. Grounding - Global Hazards (see 4.5)							
			16.1.3. Hull splitting (shallow water) - Global Hazards (see 4.8)							
			16.1.4. Hull splitting and sinking - Global Hazards (see 4.9)							

Title: Nuclear-Powered Bulk Carrier	**Company:** Laskaridis Shipping Company	**Method:** HAZID
No.: 17	**Name:** Finance Risk & Liability	
Design Intent:		
Description: Financial Risk		
Associated Drawings:		

No.: 17 **Name:** Finance Risk & Liability

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
17.1	General Financing Hazard		17.1.1. General recommendation.							Rec 16. Considering that regulations framework and classification requirements are still in development for nuclear power marine application, regulation development framework is to be developed and work with appropriate regulatory agency for development of requirements from design, licensing, operation, and liability related issues. Rec 187. P&I Club, and insurance entities are to be involved. Rec 188. Considering the availability of nuclear technology and availability of spare parts, further study is to be done. Rec 189. Any accident or nuclear related incident is to be further included in the financial analysis.
			17.1.2. General Licensing & Approval Comment - Licensing & Approval Process (see 2.1)							

Appendix VII – List of Recommendations – Container Ship with VHTR/HTGR

No.	References	Action
1	1.1 General Recommendations – General Vessel Arrangement 4.1 General Global Hazard Comments – Global Hazards 12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Considering possibility of fire internal/external outside of reactor compartment and considering radiation leakage possibility, design principle should include following: 1. Consider arranging each reactor in separate compartments and providing enough isolation to prevent fire migration and protection against fire incident. 2. Minimize fire possibility by using appropriate material. 3. Appropriate means are to be provided to fight fire in reactor and machinery compartment. 4. Structural design to consider fire load in design and its survivability.
2	1.1 General Recommendations – General Vessel Arrangement 16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Considering radioactivity, end of life disposal is to be considered from beginning of the ship design to facilitate safe handling, removal and disposal of any parts, equipment and material that might be contaminated with radioactive material.
3	1.1 General Recommendations – General Vessel Arrangement 4.5 Collision – Global Hazards 16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Considering new materials and chemicals due to nuclear technology, Inventory of Hazardous Materials (IHM) is to be maintained, and any additional risk is to be studied and understood.
4	1.1 General Recommendations – General Vessel Arrangement 4.1 General Global Hazard Comments – Global Hazards 4.2 Motion – Global Hazards 4.6 Capsizing – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc.
5	1.1 General Recommendations – General Vessel Arrangement 4.1 General Global Hazard Comments – Global Hazards 4.7 Hull splitting (shallow water, up to 350 m) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards 11.3 Kinetic or Stored Energy – System Hazards - Dropped Object & Energy Release	Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel
6	1.1 General Recommendations – General Vessel Arrangement 4.4 Grounding – Global Hazards 4.7 Hull splitting (shallow water, up to 350 m) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event.
7	1.1 General Recommendations – General Vessel Arrangement 4.8 Hull splitting and sinking – Global Hazards	Nuclear technology is to be approved by nuclear regulators and has to go through a complete technology qualification process to get approved for marine use.

8	1.1 General Recommendations – General Vessel Arrangement 3.1 General Ship Construction Comments – Ship Construction	Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 year), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design.
9	1.1 General Recommendations – General Vessel Arrangement 5.1 General Recommendation – Global Hazards - Ship Operation 6.3 Emergency Response – System Hazards 9.1 Maintenance, Live – Maintenance and Inspection	Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied.
10	1.1 General Recommendations – General Vessel Arrangement 17.1 General Financing Hazard – Finance Risk & Liability	The Reactor and its systems are to be designed to meet the design life of the ship (typically 30 years), considering the possibility to install/reuse for another project are to be further investigated to improve economics.
11	1.1 General Recommendations – General Vessel Arrangement 4.1 General Global Hazard Comments – Global Hazards 4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards 4.6 Capsizing – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed.
12	1.1 General Recommendations – General Vessel Arrangement	The Reactor to be certified for marine environment. Current reactors are designed for land-based applications. The Maritime industry has to develop functional requirements for the reactor to operate in a marine environment for life of reactor on ship.
13	1.1 General Recommendations – General Vessel Arrangement	The general arrangement of the vessel is to be further studied for radiation hazards to other surrounding spaces next to reactor room.
14	1.1 General Recommendations – General Vessel Arrangement 4.5 Collision – Global Hazards	Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design.
15	1.1 General Recommendations – General Vessel Arrangement 2.1 General Licensing & Approval Comment – Licensing & Approval Process 3.1 General Ship Construction Comments – Ship Construction 4.9 Seismic event – Global Hazards 10.1 General Risk – System Hazards - Dry Docking 13.2 Fuel Charging & Refuelling – Nuclear Technology Hazards	Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship.
16	1.1 General Recommendations – General Vessel Arrangement 2.1 General Licensing & Approval Comment – Licensing & Approval Process	Nuclear-Powered vessels will travel to various countries and there are existing regulations related to export/licensing, nonproliferation treaty etc. a legislation need to be developed so ship can travel between various country or legislation between country and owner/technology OEM to be developed to facilitate trade and trading route. Legislation to do trade across countries is to be developed.
17	1.1 General Recommendations – General Vessel Arrangement	Considering nuclear room reactor and machinery space is located on tank top elevation and there is various machinery below reactor deck level need to consider any potential for fire, explosion and proper mitigation to be provided e.g. Sewage plant has potential to release methane /sewer has which is fire/explosion hazards, any hydraulic system can also pose fire hazards, any rotating machinery may pose flying object hazards, etc.

18	2.1 General Licensing & Approval Comment – Licensing & Approval Process 4.4 Grounding – Global Hazards 4.6 Capsizing – Global Hazards 4.7 Hull splitting (shallow water, up to 350 m) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards 13.1 Manning, Training, Human Factor – Nuclear Technology Hazards 16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process.
19	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Considering that regulation framework and classification requirements are still in development for nuclear power marine application, regulation development framework is to be developed for design, licensing, operation and liability related issues.
20	2.1 General Licensing & Approval Comment – Licensing & Approval Process 4.1 General Global Hazard Comments – Global Hazards	Further study is to be done on geo-political issues that may affect routes and destinations.
21	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Export control legislation is to be further investigated for the trading route and ownership by the shipowner.
22	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Operation in port areas or traditional water is to be considered in any licensing process. Ports do not have any regulation at moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues in future regulation development.
23	2.1 General Licensing & Approval Comment – Licensing & Approval Process 3.1 General Ship Construction Comments – Ship Construction	Considering maritime industry has limited to no knowledge on nuclear construction, further training/cooperation is to be developed between shipyards and specialised equipment providers.
24	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Legislation and requirements are to be developed for external threat/risk such as hijacking, piracy, terror, flying object (missile, plane etc.) attack, etc. The ship designer and Technology developer need to consider such threat in design and operation for life of vessel for all modes of operation.
25	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Considering that licensing legislation/requirement to construct, operate and maintain nuclear power plants on ships does not exist and may force cost escalation, industry has to develop requirements to eliminate uncertainty. Participation in such activities is recommended.
26	2.1 General Licensing & Approval Comment – Licensing & Approval Process	Per nuclear regulation and technology provider there will be specialised training needed to operate NPP, and special accreditation needed by the regulator. A special training programne in cooperation with the regulator and technology provider are to be developed and certification requirements are to be determine.
27	2.1 General Licensing & Approval Comment – Licensing & Approval Process 17.1 General Financing Hazard – Finance Risk & Liability	Further study is to be done for long-term fuel availability, licensing etc.
28	2.1 General Licensing & Approval Comment – Licensing & Approval Process 17.1 General Financing Hazard – Finance Risk & Liability	Design aspects for the external risk issues are to be considered.
29	2.1 General Licensing & Approval Comment – Licensing & Approval Process 17.1 General Financing Hazard – Finance Risk & Liability	Considering there is no rule and regulation which defines Liability for nuclear power ships. The following are to be considered: 1) Further rules and regulations are to be developed in cooperation with shipowners, P&I club, and regulators, etc. 2) Responsible parties for liabilities are to be defined by regulatory procedure
30	3.1 General Ship Construction Comments – Ship Construction 4.9 Seismic event – Global Hazards	The reactors and their system are to consider seismic events, tsunamis, etc. probability, in design while in shipyard, dry dock, port, channel etc.

31	3.1 General Ship Construction Comments – Ship Construction	Detail procedure for sea trial and reactor trial is to be developed with OEM, SY, Owner and regulator.
32	3.1 General Ship Construction Comments – Ship Construction 13.2 Fuel Charging & Refuelling – Nuclear Technology Hazards	Vessel modification including engine removal, structural modification etc. are to be further investigated to accommodate NPP.
33	3.1 General Ship Construction Comments – Ship Construction	Installation and removal of NPP while it is loaded with fuel are to be further studied for all possible cases during design and for construction and proper procedure are to be developed.
34	3.1 General Ship Construction Comments – Ship Construction 11.1 General Hazards – System Hazards - Dropped Object & Energy Release 11.2 Dropped Object – System Hazards - Dropped Object & Energy Release	Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane or other load)
35	3.1 General Ship Construction Comments – Ship Construction 6.1 Piping, Material and Supporting Material – System Hazards	Considering the radiation the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.
36	3.1 General Ship Construction Comments – Ship Construction 16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	In order to manage the core which has spent fuel, alternate options on how to remove the core before it arrives to the shipyard such as using special purpose barge or other alternate methods are to be considered to minimize the risk in the dry dock/salvage/scrape yard area.
37	3.1 General Ship Construction Comments – Ship Construction	Considering GA alternative arrangement such as vertical installation of reactor assembly to facilitate easy installation and removal are to be considered at detail design stage
38	4.1 General Global Hazard Comments – Global Hazards 13.2 Fuel Charging & Refuelling – Nuclear Technology Hazards	Considering the treaty on the nonproliferation of nuclear weapons and risk of ship traveling worldwide, technology developers need to design proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them or use them in harmful way. Also, the impact of treaty on design and operation is to be further studied.
39	4.1 General Global Hazard Comments – Global Hazards 4.4 Grounding – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Consider designing reactor containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.
40	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards	Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such with appropriate safety margin.
41	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards	Further study is to be done on the optimum orientation and position of the reactor to minimize the impact of marine loads.
42	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards 4.6 Capsizing – Global Hazards	Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure.
43	4.2 Motion – Global Hazards	Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. The reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has a high impact on safety, detailed inspection/maintenance/monitoring is to be considered.
44	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards	Inspection and maintenance plans need to be developed to verify the integrity of reactor foundation, radiation biological shielding.
45	4.2 Motion – Global Hazards	All equipment, piping to be designed considering marine loads.
46	4.2 Motion – Global Hazards	Consider designing the reactor and system for marine environment and marine operating condition (22.5-degree, 30-degree damage +- 10-degree heave motion]

47	4.2 Motion – Global Hazards	Consider hybrid system to increase availability to have capability to maintain propulsion.
48	4.2 Motion – Global Hazards 4.3 Vibration – Global Hazards	Considering ship motion and acceleration can produce additional loads on reactor components may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactors, its component for life of design. In addition, considering it has a high impact on safety detailed inspection/maintenance/monitoring is to be considered.
49	4.2 Motion – Global Hazards	Due to the high roll and gyroscopic effects, there can be excitation effects and analysis is to be conducted on the functionality of the reactor following these events.
50	4.3 Vibration – Global Hazards	Detailed vibration study to be conducted and during commissioning and sea trial vibration to be measured and calibrated with analysis. During operation and maintenance vibrations need to be monitored to verify that they are in design acceptable range. Considering marine-machinery induced vibration (propeller, engine etc.), bow slamming is to be considered.
51	4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards 4.7 Hull splitting (shallow water, up to 350 m) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling).
52	4.4 Grounding – Global Hazards	Radiation shielding and insulation of the reactor and reactor compartment to consider total flooding of compartment or alternate justification to be provided.
53	4.4 Grounding – Global Hazards 4.7 Hull splitting (shallow water, up to 350 m) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards 14.2 Uncontrolled Reaction – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills.
54	4.4 Grounding – Global Hazards 15.2 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	An emergency shelter plan is to be considered and whether there are any port restrictions.
55	4.4 Grounding – Global Hazards	Further study to be done on reactor safety considering various accidental scenarios and loads. The proper safety shutdown system is to be developed and provided (active and passive).
56	4.4 Grounding – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	If the refloating of ships is considered after grounding, proper risk control should be in place. Further study is to be conducted for such an operation.
57	4.4 Grounding – Global Hazards	Consider increasing double bottom height to provide additional protection to reactor compartment.
58	4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards	In flooding conditions electrical equipment can be damaged due to exposure to salt water and a support system will not be available etc. A study to be conducted considering such a situation to identify risk to reactor safety and consider appropriate electrical equipment e.g., IP Rating.
59	4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards	Grounding/collision/submergence etc. can lead to reactors essential and auxiliary system damage and its impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship.
60	4.4 Grounding – Global Hazards 4.5 Collision – Global Hazards	In case of damage due to grounding/collision etc., progressive flooding may be possibility and need to be investigated to prevent such event.
61	4.4 Grounding – Global Hazards	Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety and appropriate measure are to be in place.
62	4.4 Grounding – Global Hazards	Reactor and its system design need to consider steam formation and appropriate mitigation to be provided to prevent radiation leakage or damage to reactor.

63	4.4 Grounding – Global Hazards	Further study to be conducted regarding grounding and flip-over situations considering cooling and other system may not be available.
64	4.4 Grounding – Global Hazards	In case of flooding and depending on which systems are impacted helium loss of circulation may happen. Design needs to consider such an event and appropriate mitigations are to be provided.
65	4.5 Collision – Global Hazards	A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.
66	4.5 Collision – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Further study to be done on collision assessment considering nuclear reactor compartment to understand risk of damage and reactor radiation safety.
67	4.5 Collision – Global Hazards	Any extra loads created during a collision incident are to be taken into account in the reactor design.
68	4.5 Collision – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Further study is to be done on the creation of an automatic passive water flooding system of the reactor to equalize pressure and prevent radiation leakage.
69	4.5 Collision – Global Hazards	Further study to be done on the inclusion of additional protection bulkheads, possible to the extra available volume due to the removal of the piston engine.
70	4.5 Collision – Global Hazards	Considering the position of the reactor at a higher level from the level the piston engine was positioned stability need to be rechecked.
71	4.5 Collision – Global Hazards	Further study is to be done on the use of non-flammable foam on the sides of the ship.
72	4.5 Collision – Global Hazards 5.2 Reactor Availability – Global Hazards - Ship Operation	Further study to be done on the minimum necessary power needs of the vessel considering the regulations and the maximum power needed in case of collision avoidance. Battery use (larger size) is to be investigated as an alternative to thermal power damping in case the reactor is kept warm continuously.
73	4.5 Collision – Global Hazards	Further study to be done on the minimum necessary power needs of the vessel considering the regulations and the maximum power needed in case of collision avoidance. Battery use (larger size) is to be investigated as an alternative to thermal power damping in case the reactor is kept warm continuously.
74	4.6 Capsizing – Global Hazards	Considering that the reactor is installed inside the four-barrier containment, during capsizing or when reactor is shut down without cooling, the reactor heat decay removal is to be further evaluated.
75	4.6 Capsizing – Global Hazards	Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety.
76	4.6 Capsizing – Global Hazards	Further study and testing are to be conducted for capsizing situations and the impact on the reactor system, reactivity, safety, drainage etc.
77	4.7 Hull splitting (shallow water, up to 350 m) – Global Hazards 4.8 Hull splitting and sinking – Global Hazards	Further study to be done on vessel cargo loading process and cargo loading manual to be updated.
78	4.7 Hull splitting (shallow water, up to 350 m) – Global Hazards	Further study to be done on vessel cargo loading process and cargo loading manual to be updated.
79	4.8 Hull splitting and sinking – Global Hazards	Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc.
80	4.9 Seismic event – Global Hazards	Consider earthquake load when ship is in dry dock.
81	4.10 Typhoon – Global Hazards	Typhoon event is to be included during design of vessel and appropriate load is to be considered in reactor design.
82	4.11 Cargo Fire – Global Hazards	Fire impact and fire load analysis is to be conducted depending on the cargo transported for worst case fire condition on NPP and its support system and its impact on the reactor compartment and the surrounding compartments. Appropriate mitigation measures are to be provided. Reactor compartment and room structural fire rating to be based on above analysis.

83	4.11 Cargo Fire – Global Hazards	The cargo stowage manual is to be further analyzed considering fire impact on NPP and reactor compartment.
84	4.11 Cargo Fire – Global Hazards	Consider providing cofferdam on cargo bays or around the reactor room/machinery compartment to minimize impact of cargo fire.
85	4.11 Cargo Fire – Global Hazards	Fire Fighting System (FFS) of the container carrier is to be further analyzed considering impact on nuclear reactor.
86	5.1 General Recommendation – Global Hazards - Ship Operation 5.2 Reactor Availability – Global Hazards - Ship Operation 7.1 General Comments – System Hazards - Power & Propulsion	Normally, port regulation requires that in an emergency ships need to leave port in hour or less depending on the local port regulation and types of emergencies. Reactor designers to consider such operational requirements in the NPP design for power availability to depart port on short notice from total shutdown or partial operational condition.
87	5.1 General Recommendation – Global Hazards - Ship Operation	Nuclear power ships regulations are not available yet, but under consideration at IMO and various nuclear agencies, it is recommended that shipowners, ship operators, class societies and insurers participate in such activity to develop proper maritime regulation.
88	5.1 General Recommendation – Global Hazards - Ship Operation 6.3 Emergency Response – System Hazards 8.4 Reactive material on deck – System Hazards - Vent & Ventilation 14.9 Escape & Evacuation – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	Emergency protocol in case of accident related to nuclear system or radiation leak are to be developed considering nuclear exposure hazards. 1. Develop detailed evacuation and shelter protocols for radiation incidents, with muster stations and escape routes designed to minimize exposure. Equip the vessel with sufficient shelter areas to protect crew in radiation emergencies, ensuring proper training and access to emergency supplies. 2. Emergency evacuation and escape study to be conducted for all spaces for all modes of operation considering risk of radiation exposure. 3. Consider impact on port and surrounding and appropriate emergency plan in consultation with local authority and regulator to be developed and implemented. 4. Emergency plans are to be practiced regularly. Crew and other emergency responders are to be trained considering radiation possibility exist.
89	5.1 General Recommendation – Global Hazards - Ship Operation	Due to radiation exposure risk in an emergency, radiation medication and other primary care on site are to be provided.
90	5.1 General Recommendation – Global Hazards - Ship Operation	Radiation dispersion analysis for escaped radiation in case of accident is to be conducted and how it will affect lifesaving appliances, escape routes, accommodations, and other areas are to be analyzed.
91	5.1 General Recommendation – Global Hazards - Ship Operation	Location of muster stations and their proximity to radiation zones and other high-risk areas be further studied based on radiation dispersion analysis.
92	5.1 General Recommendation – Global Hazards - Ship Operation	Considering radiation exposure possibility to crew in accidental situation consideration for propelled lifeboats to decrease escape time from ship and radiation zone around ship.
93	5.2 Reactor Availability – Global Hazards - Ship Operation	Further study is to be done on the availability of reserve power.
94	5.2 Reactor Availability – Global Hazards - Ship Operation	Further study is to be done on the possibility of keeping the reactor cooling fluid (helium) in hot conditions so that the emergency start up period can be reduced.
95	5.2 Reactor Availability – Global Hazards - Ship Operation	Further study is to be done on the heat stress of the materials in case of a rapid start up.
96	5.3 Bunkering – Global Hazards - Ship Operation	Security protocols and docking agreements with ports are to be developed.
97	5.3 Bunkering – Global Hazards - Ship Operation	Bunkering operations to take the fuel for the need of the electricity in are to be considered and further analyzed.
98	6.2 Bilge System – System Hazards	Further study to be done on separate independent bilge system considering existence of radioactive material.
99	6.2 Bilge System – System Hazards	Further study to be done on potentially safely storing and disposal of bilged water in case of radioactivity.
100	6.2 Bilge System – System Hazards	Water from the decontamination facility is to be directed to a special storage tank.
101	6.3 Emergency Response – System Hazards	Facility (radioactive laboratory) to manage/investigate exposure limits.

102	6.3 Emergency Response – System Hazards	Firefighting plan is to include location of Personal Protection/radiation protection Equipment (PPE).
103	7.1 General Comments – System Hazards - Power & Propulsion	Normally port regulations require that in an emergency the ship must depart from port within one hour or less. The reactor designer is to consider such requirement in design for power availability to depart port on short notice.
104	7.1 General Comments – System Hazards - Power & Propulsion	Loss of power due to reactors' unavailability is to be further studied and appropriate mitigation measures and procedures are to be developed.
105	7.1 General Comments – System Hazards - Power & Propulsion 13.5 Cooling Fluid – Nuclear Technology Hazards 14.10 Harbor Operation – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	Considering ship power needs vary considerably depending on operation (low/ partial/full power etc.) and typically reactors operate on constant heat generation mode following are to be considered: 1. A detailed study for reactor design is to be conducted to accommodate ship load variation requirement. 2. Impact of load variation may produce higher demand on control system and are to be consider in design for various control system component for reactors 3. Load variation may produce higher fatigue load on reactors, their components and system, which need to be considered in design. 4. Requirements for load testing of NPP to be developed considering maritime regulation for engines and load variation 5. In case reactors cannot manage load variation for Balance of Power (BOP) an appropriate provision is to be provided to manage extra energy generated that is not needed for ship powering need.
106	7.1 General Comments – System Hazards - Power & Propulsion	Considering power ramp-up rate has limitation for nuclear technology 1 MWe/Min. may impact ships ability to maneuver in certain situations, this may need additional crew/pilot training.
107	7.1 General Comments – System Hazards - Power & Propulsion	Reactor design needs to further analyze the ramp up period, from cold to full power for both cold and warm conditions.
108	7.1 General Comments – System Hazards - Power & Propulsion	Electrical load fluctuations, electrical interface between reactors and electrical systems, and how to adjust the power is to be further studied.
109	7.1 General Comments – System Hazards - Power & Propulsion 14.10 Harbor Operation – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	Electrical load analysis and power simulation load analysis at the detailed design stage is to be conducted for all modes of ship operation.
110	7.2 Battery – System Hazards - Power & Propulsion	Considering NPP supports power requirement to start from the cold condition, additional reserved power will be needed in case ship auxiliary power is not available. At the detailed design stage, reserved power required for Nuclear Power Plants is to be studied for all operational modes.
111	7.2 Battery – System Hazards - Power & Propulsion	Impact on reactors compartment due to fire and explosion from battery is to be further investigated.
112	8.1 Ventilation Philosophy – System Hazards - Vent & Ventilation	Develop ventilation philosophy for reactor compartment and surrounding machinery rooms/area. Develop a ventilation system to maintain negative pressure within the reactor rooms as there is no forced ventilation considered to prevent radioactive contamination from spreading. This includes high-efficiency filtration and radiation monitoring in vent systems (if installed), ensuring safe air quality in areas where vents are discharging.
113	8.1 Ventilation Philosophy – System Hazards - Vent & Ventilation	The possibility of emitting radiation from the vent line is to be further analyzed and radiation analysis is to be done.
114	8.2 HVAC Air – System Hazards - Vent & Ventilation	Further study to be done on ventilation requirements and mitigation measures in case of contaminated vent lines during an incident or normal operation.
115	8.2 HVAC Air – System Hazards - Vent & Ventilation	Further study to be done on material selection based on corrosivity and salinity tolerance.
116	8.2 HVAC Air – System Hazards - Vent & Ventilation 8.4 Reactive material on deck – System Hazards - Vent & Ventilation 8.5 Other Machinery Spaces – System Hazards - Vent & Ventilation	Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from the funnel a dispersion study to be conducted for all operational, upset and emergency situation to determine safe ventilation funnel height.

117	8.2 HVAC Air – System Hazards - Vent & Ventilation 13.3 Reactor Barrier(s) – Nuclear Technology Hazards	Design of reactor and reactor room to consider how to remove heat and maintain room temperature within acceptable limit.
118	8.3 Reactivity in the air – System Hazards - Vent & Ventilation	Considering the possibility of radiation inside the reactor room, design needs to be further developed to remove the heat from the reactors room and prevent radiation from escaping.
119	8.3 Reactivity in the air – System Hazards - Vent & Ventilation	Further study is to be done on additional fire structural/radiation barriers provided.
120	8.3 Reactivity in the air – System Hazards - Vent & Ventilation 8.4 Reactive material on deck – System Hazards - Vent & Ventilation	Further study is to be done on the dispersion of compromised air from the exhaust system.
121	8.4 Reactive material on deck – System Hazards - Vent & Ventilation	Further study to be done on port operation procedures and emergency plan to host a vessel following a radioactive release.
122	8.4 Reactive material on deck – System Hazards - Vent & Ventilation	Further study to be done on how to contain radioactive release within the compartment.
123	8.4 Reactive material on deck – System Hazards - Vent & Ventilation	Further study to be done on other machinery space outside reactor room and its ventilation in order to minimize radioactive exposure to such space
124	8.5 Other Machinery Spaces – System Hazards - Vent & Ventilation	Further study to be done on ventilation ducts to avoid ventilation with nuclear compartment.
125	9.1 Maintenance, Live – Maintenance and Inspection	Reactor compartment should not be accessible while in operation, consider remote inspection/monitoring while in operation
126	9.1 Maintenance, Live – Maintenance and Inspection 13.1 Manning, Training, Human Factor – Nuclear Technology Hazards 13.7 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards 13.8 Radiological Leakage – Nuclear Technology Hazards 14.9 Escape & Evacuation – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank.
127	9.1 Maintenance, Live – Maintenance and Inspection 17.1 General Financing Hazard – Finance Risk & Liability	At the design stage a detailed analysis for installation, removal and maintenance of the reactor modules is to be conducted. The study should include the financial analysis of all supporting vessels needed during the maintenance process.
128	9.1 Maintenance, Live – Maintenance and Inspection	Helium storage/space needed for onsite maintenance is to be further analyzed.
129	9.1 Maintenance, Live – Maintenance and Inspection	Sensors require periodic calibration/maintenance. Considering radiation risk proper design/plan needs to be developed for such activity.
130	9.1 Maintenance, Live – Maintenance and Inspection	Further study to be done on pump periodic maintenance plan.
131	9.1 Maintenance, Live – Maintenance and Inspection 14.1 General Comment – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	In a marine propulsion, availability of power plants is of high importance, considering the proposed NPP system is a compact integral system, followings are to be considered: 1. The reliability and availability of the NPP are to be further analyzed and defined, based on the operational needs of the ship, regulation, owner and operator requirements. 2. RAM (Reliability, Availability, Maintainability) analysis is to be performed with design development. 3. Detailed inspection maintenance plan for the entire nuclear system and its supporting systems is to be developed considering radiation exposure and risk and criticality of the NPP.
132	9.1 Maintenance, Live – Maintenance and Inspection	Detailed crew training plans for education and maintenance of reactor and support system are to be developed.
133	9.1 Maintenance, Live – Maintenance and Inspection	Spare part inventory is to be further analyzed, and requirements are to be defined.
134	9.2 Maintenance, Shutdown – Maintenance and Inspection	Further study is to be done on the development of a maintenance plan defining responsibilities between general and specialised crew considering the regulatory requirements.

135	9.2 Maintenance, Shutdown – Maintenance and Inspection	Any contaminated component/machinery requires maintenance, proper procedure and protocol to be developed.
136	10.1 General Risk – System Hazards - Dry Docking	Further study is to be done on procedure for dry docking security measures.
137	10.1 General Risk – System Hazards - Dry Docking	Further study to be done on dry docking survey and maintenance requirements from typical existing procedures to accommodate for nuclear power needs.
138	10.1 General Risk – System Hazards - Dry Docking	Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies to be done.
139	10.1 General Risk – System Hazards - Dry Docking	Further study to be done on the possibility of earthquake while in dry dock
140	11.1 General Hazards – System Hazards - Dropped Object & Energy Release	Handling of HolosGen container is to be further analyzed from a dropped object risk point of view.
141	11.3 Kinetic or Stored Energy – System Hazards - Dropped Object & Energy Release	Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
142	12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Further studies are to be done on fine detector system and its placement inside reactor room/compartment.
143	12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Consider additional class notations for container ship considering cargo fire
144	12.1 General Fire Fighting Hazard – System Hazards - Fire Fighting System (FFS)	Further studies are to be done to consider increasing the safety margins to the structure and adequacy of fire insulation.
145	13.1 Manning, Training, Human Factor – Nuclear Technology Hazards	POB study to be conducted considering the nuclear reactor.
146	13.1 Manning, Training, Human Factor – Nuclear Technology Hazards	Special consideration for lashing crew, training, requirements for certification, background check.
147	13.1 Manning, Training, Human Factor – Nuclear Technology Hazards	Investigate if regulator is required on board at all times or not.
148	13.1 Manning, Training, Human Factor – Nuclear Technology Hazards	Port personnel to be trained in emergency and risk.
149	13.1 Manning, Training, Human Factor – Nuclear Technology Hazards	Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements.
150	13.1 Manning, Training, Human Factor – Nuclear Technology Hazards	Human Factor Engineering (HFE) analysis is to be considered for the regulatory requirements.
151	13.1 Manning, Training, Human Factor – Nuclear Technology Hazards	The regulatory requirements to be checked for citizen ship and security clearance requirement.
152	13.2 Fuel Charging & Refuelling – Nuclear Technology Hazards	Ship design to consider nuclear fuel loading and removal in a safe manner per regulatory requirements. If the entire module is to be removed this needs to be considered from design stage to facilitate such operation during fuelling interval.
153	13.2 Fuel Charging & Refuelling – Nuclear Technology Hazards	Study to be done for refuelling frequency, duration and location what permitting needed.
154	13.2 Fuel Charging & Refuelling – Nuclear Technology Hazards	Maintenance/inspection to be considered during refuelling event.
155	13.3 Reactor Barrier(s) – Nuclear Technology Hazards	Radiation shielding to be further developed considering marine environment and applicable marine loads and flooding.
156	13.3 Reactor Barrier(s) – Nuclear Technology Hazards	Barriers B and C of HOLOS design are to be further investigated for various marine loads and accidental event
157	13.4 Emergency Response – Nuclear Technology Hazards	Considering the longer time required to maintain reactor safety the auxiliary and emergency generators are to be further studied.
158	13.4 Emergency Response – Nuclear Technology Hazards 14.2 Uncontrolled Reaction – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	Control and monitoring systems in case of emergency may require more monitoring time than normal marine practices and are to be further studied with the regulators and the technology providers.

159	13.4 Emergency Response – Nuclear Technology Hazards	Emergency systems are to be operational at a much higher angle of list and need to be considered for the system availability in plant/equipment design.
160	13.4 Emergency Response – Nuclear Technology Hazards	Human need is to be further investigated in case of entering the control room.
161	13.4 Emergency Response – Nuclear Technology Hazards	Human interface and human need for the emergency situation considered in the reactor safety are to be further investigated considering the abatement of the ship.
162	13.5 Cooling Fluid – Nuclear Technology Hazards	The cooling circuit will use intermediate cooling medium according to the purity specifications required.
163	13.6 Security & External Threat – Nuclear Technology Hazards	Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.
164	13.6 Security & External Threat – Nuclear Technology Hazards	Proper security and access control measures on board and at the port are to be developed in communication with regulators.
165	13.6 Security & External Threat – Nuclear Technology Hazards	External threats are to be further evaluated and protocol to be developed in cooperation with the regulator and regulation to be developed.
166	13.6 Security & External Threat – Nuclear Technology Hazards	Consider further flying object study and strength of hull in way of reactor.
167	13.6 Security & External Threat – Nuclear Technology Hazards	Develop a control mechanism on the container content to minimize fire risk
168	13.6 Security & External Threat – Nuclear Technology Hazards	Reactor(s) location(s) are dropped object, to be further analyzed considering threat from dropped containers, sabotage, RPG/missile attack, plane/helicopter crash etc.
169	13.7 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Vessel design is to consider on board radioactive waste storage, monitoring and disposal. Procedures are to be developed, and security protocols are to be in place.
170	13.7 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards	Further study to be done on detailed plan of handling of radioactive material at the end of ship life, before the end of ship lifetime, or normal operation and during maintenance e.g., hull, reactor core, piping, heat exchangers, pumps, any other exposed material.
171	13.7 Nuclear Waste Storage, Handling, & Disposal – Nuclear Technology Hazards 15.1 General Recommendation – Nuclear Technology Hazards - Impact on Ports	Further study is to be done on the impact of radioactive waste handling to ports.
172	13.8 Radiological Leakage – Nuclear Technology Hazards	Considering the marine application of biological shielding, further study to be done on the possible use of polymers as an additional level of shielding survivability.
173	13.8 Radiological Leakage – Nuclear Technology Hazards	Radiological shield design to consider marine loads, environment, space confinement, vibration, motion, flooding etc. in design and proper inspection and maintenance plan to be developed
174	13.9 Control system – Nuclear Technology Hazards 14.2 Uncontrolled Reaction – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	The control system is to be redundant duplicate and developed based on Defense in depth principle
175	14.3 Magnetic Bearings – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	The electrical system is designed to block electromagnetic pulse.
176	14.3 Magnetic Bearings – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	Bearing individual components of the rotating machines should have a FMECA.
177	14.4 Helium Leakage – Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	In case of helium leakage detections and maintenance approaches are to be further developed .
178	15.1 General Recommendation – Nuclear Technology Hazards - Impact on Ports	International regulations are to be developed on international travel either by IMO, NRC or IAEA. Special consideration on passage through canals such as Panama, Suez, Singapore straights.

179	15.1 General Recommendation – Nuclear Technology Hazards - Impact on Ports	Further study is to be done if the reactor runs on partial load mode and a large amount of heat has to be dissipated and the impact on the marine environment e.g., increases in water temperature. All systems are to be dimensioned so that the vessel can operate globally.
180	15.2 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports 16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Port of Refuge and Shelter law is to be further study as in emergency port of refuge can be questionable.
181	15.2 Emergency Shelter – Nuclear Technology Hazards - Impact on Ports	Further study is to be done on the potential of contamination in a port environment and the consequences for the local community.
182	16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Considering restrictions in nuclear technology disposal at the ship end of life it is necessary to consider which yard will be chosen and whether the removal of the ship will be in one or two stages (removal of the reactor in one shipyard and dismantling of the ship in another one). Further, special consideration should be given to the disposal of radioactive materials.
183	16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Design to consider the possibility of a reactor transferred to another ship/location.
184	16.1 General Recycling and Salvage Comment. – Nuclear Technology Hazards - Ship Recycling & Salvage	Further study is to be done on how the reactor will stay in place in case of the salvage process and radiation is contained.
185	17.1 General Financing Hazard – Finance Risk & Liability	Further study to be done on the P&I contract.

Appendix VIII – HAZID Register – Container Ship with VHTR/HTGR

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 1	**Name:** General Vessel Arrangement	
Design Intent:		
Description: General Comments & Notes		
Associated Drawings:		

No.: 1	**Name:** General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
1.1	General Recommendations		1.1.1. General Comment.							Rec 1. Considering possibility of fire internal/external outside of reactor compartment and considering radiation leakage possibility, design principle should include following: 1. Consider arranging each reactor in separate compartments and providing enough isolation to prevent fire migration and protection against fire incident. 2. Minimize fire possibility by using appropriate material. 3. Appropriate means are to be provided to fight fire in reactor and machinery compartment. 4. Structural design to consider fire load in design and its survivability. Rec 2. Considering radioactivity, end of life disposal is to be considered from beginning of the ship design to facilitate safe handling, removal and disposal of any parts, equipment and material that might be contaminated with radioactive material.

No.: 1	**Name:** General Vessel Arrangement								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 3. Considering new materials and chemicals due to nuclear technology, Inventory of Hazardous Materials (IHM) is to be maintained, and any additional risk is to be studied and understood. Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 5. Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel

No.: 1	**Name:** General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event. Rec 7. Nuclear technology is to be approved by nuclear regulators and has to go through a complete technology qualification process to get approved for marine use.

No.: 1	**Name:** General Vessel Arrangement								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 8. Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 year), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design. Rec 9. Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied.

No.: 1	**Name:** General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 10. The Reactor and its systems are to be designed to meet the design life of the ship (typically 30 years), considering the possibility to install/reuse for another project are to be further investigated to improve economics. Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed. Rec 12. The Reactor to be certified for marine environment. Current reactors are designed for land-based applications. The Maritime industry has to develop functional requirements for the reactor to operate in a marine environment for life of reactor on ship. Rec 13. The general arrangement of the vessel is to be further studied for radiation hazards to other surrounding spaces next to reactor room. Rec 14. Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design.

No.: 1	**Name:** General Vessel Arrangement									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 16. Nuclear-Powered vessels will travel to various countries and there are existing regulations related to export/licensing, nonproliferation treaty etc. a legislation need to be developed so ship can travel between various country or legislation between country and owner/technology OEM to be developed to facilitate trade and trading route. Legislation to do trade across countries is to be developed. Rec 17. Considering nuclear room reactor and machinery space is located on tank top elevation and there is various machinery below reactor deck level need to consider any potential for fire, explosion and proper mitigation to be provided e.g. Sewage plant has potential to release methane /sewer has which is fire/explosion hazards, any hydraulic system can also pose fire hazards, any rotating machinery may pose flying object hazards, etc.

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 2	**Name:** Licensing & Approval Process	
Design Intent:		
Description: Licensing & Approval Process		
Associated Drawings:		

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
2.1	General Licensing & Approval Comment		2.1.1. General Comment.							Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 16. Nuclear- Powered vessels will travel to various countries and there are existing regulations related to export/licensing, nonproliferation treaty etc. a legislation need to be developed so ship can travel between various country or legislation between country and owner/technology OEM to be developed to facilitate trade and trading route. Legislation to do trade across countries is to be developed.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 19. Considering that regulation framework and classification requirements are still in development for nuclear power marine application, regulation development framework is to be developed for design, licensing, operation and liability related issues. Rec 20. Further study is to be done on geo-political issues that may affect routes and destinations. Rec 21. Export control legislation is to be further investigated for the trading route and ownership by the shipowner.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 22. Operation in port areas or traditional water is to be considered in any licensing process. Ports do not have any regulation at moment for allowing nuclear-powered vessels. Further study is to be done on a gap analysis that will incorporate port regulatory issues in future regulation development. Rec 23. Considering maritime industry has limited to no knowledge on nuclear construction, further training/cooperation is to be developed between shipyards and specialised equipment providers. Rec 24. Legislation and requirements are to be developed for external threat/risk such as hijacking, piracy, terror, flying object (missile, plane etc.) attack, etc. The ship designer and Technology developer need to consider such threat in design and operation for life of vessel for all modes of operation. Rec 25. Considering that licensing legislation/requirement to construct, operate and maintain nuclear power plants on ships does not exist and may force cost escalation, industry has to develop requirements to eliminate uncertainty. Participation in such activities is recommended.

No.: 2	**Name:** Licensing & Approval Process									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 26. Per nuclear regulation and technology provider there will be specialised training needed to operate NPP, and special accreditation needed by the regulator. A special training programme in cooperation with the regulator and technology provider are to be developed and certification requirements are to be determine. Rec 27. Further study is to be done for long-term fuel availability, licensing etc. Rec 28. Design aspects for the external risk issues are to be considered. Rec 29. Considering there is no rule and regulation which defines Liability for nuclear power ships. The following are to be considered: 1) Further rules and regulations are to be developed in cooperation with shipowners, P&I club, and regulators, etc. 2) Responsible parties for liabilities are to be defined by regulatory procedure

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 3	**Name:** Ship Construction	
Design Intent:		
Description: Ship Construction		
Associated Drawings:		

No.: 3 **Name:** Ship Construction

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
3.1	General Ship Construction Comments		3.1.1. General Comment.	3.1.1. Radiation leakage during construction	Injury	Possible	Major	Extreme (12)		Rec 8. Ship design and construction are to consider nuclear reactor installation sequence, fuelling/refuelling sequence (if applicable), removal of reactor module for refuelling/maintenance/replacement (8-10 year), technology provider restriction. Ship yard licensing issue and regulatory agency requirement, installation of reactor and system may not happen in one place etc., This may require special provision in ship section where reactor module is installed to facilitate construction/maintenance/salvage sequence and may pose challenge for construction and design. Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship.

No.: 3	**Name:** Ship Construction									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 23. Considering maritime industry has limited to no knowledge on nuclear construction, further training/cooperation is to be developed between shipyards and specialised equipment providers. Rec 30. The reactors and their system are to consider seismic events, tsunamis, etc. probability, in design while in shipyard, dry dock, port, channel etc. Rec 31. Detail procedure for sea trial and reactor trial is to be developed with OEM, SY, Owner and regulator. Rec 32. Vessel modification including engine removal, structural modification etc. are to be further investigated to accommodate NPP. Rec 33. Installation and removal of NPP while it is loaded with fuel are to be further studied for all possible cases during design and for construction and proper procedure are to be developed. Rec 34. Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane or other load)

No.: 3	**Name:** Ship Construction									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 35. Considering the radiation the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided. Rec 36. In order to manage the core which has spent fuel, alternate options on how to remove the core before it arrives to the shipyard such as using special purpose barge or other alternate methods are to be considered to minimize the risk in the dry dock/salvage/scrape yard area. Rec 37. Considering GA alternative arrangement such as vertical installation of reactor assembly to facilitate easy installation and removal are to be considered at detail design stage

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 4	**Name:** Global Hazards	
Design Intent:		
Description: Global Hazards		
Associated Drawings:		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.1	General Global Hazard Comments		4.1.1. General Comment.						4.1.1. Design of ship according to pertinent regulations.	Rec 1. Considering possibility of fire internal/external outside of reactor compartment and considering radiation leakage possibility, design principle should include following: 1. Consider arranging each reactor in separate compartments and providing enough isolation to prevent fire migration and protection against fire incident. 2. Minimize fire possibility by using appropriate material. 3. Appropriate means are to be provided to fight fire in reactor and machinery compartment. 4. Structural design to consider fire load in design and its survivability.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 5. Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed. Rec 20. Further study is to be done on geo-political issues that may affect routes and destinations. Rec 38. Considering the treaty on the nonproliferation of nuclear weapons and risk of ship traveling worldwide, technology developers need to design proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them or use them in harmful way. Also, the impact of treaty on design and operation is to be further studied. Rec 39. Consider designing reactor containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.1.2. Marine environment with high humidity and salty conditions.						4.1.1. Design of ship according to pertinent regulations.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.2	Motion		4.2.1. Marine environment.	4.2.1. Green water on deck.	Overall	Likely	Moderate	High (12)	4.2.1. Proper machinery support. 4.2.2. The Reactor compartment is gas tight.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 43. Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. The reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has a high impact on safety, detailed inspection/maintenance/monitoring is to be considered.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 44. Inspection and maintenance plans need to be developed to verify the integrity of reactor foundation, radiation biological shielding. Rec 45. All equipment, piping to be designed considering marine loads. Rec 46. Consider designing the reactor and system for marine environment and marine operating condition (22.5-degree, 30-degree damage +- 10-degree heave motion]
				4.2.3. Damage to machinery.	Asset	Possible	Minor	Moderate (6)		
				4.2.4. Impact on reactor operability.	Overall	Possible	Major	Extreme (12)		
				4.2.5. Equipment damage.	Asset	Possible	Major	Extreme (12)		
				4.2.6. Inability to control reaction etc. due to internal damage.	Overall	Possible	Major	Extreme (12)		
			4.2.2. Vessel motion.	4.2.3. Damage to machinery.	Asset	Possible	Minor	Moderate (6)	4.2.1. Proper machinery support. 4.2.2. The Reactor compartment is gas tight.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 40. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such with appropriate safety margin. Rec 41. Further study is to be done on the optimum orientation and position of the reactor to minimize the impact of marine loads. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 43. Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. The reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has a high impact on safety, detailed inspection/maintenance/monitoring is to be considered. Rec 47. Consider hybrid system to increase availability to have capability to maintain propulsion.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.2.3. Vessel acceleration.	4.2.2. High acceleration of reactor/machinery foundations leading to foundation damage.	Asset	Possible	Moderate	High (9)	4.2.1. Proper machinery support. 4.2.2. The Reactor compartment is gas tight.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 40. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such with appropriate safety margin. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 47. Consider hybrid system to increase availability to have capability to maintain propulsion.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 48. Considering ship motion and acceleration can produce additional loads on reactor components may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactors, its component for life of design. In addition, considering it has a high impact on safety detailed inspection/maintenance/monitoring is to be considered.
				4.2.3. Damage to machinery.	Asset	Possible	Minor	Moderate (6)		
				4.2.4. Impact on reactor operability.	Overall	Possible	Major	Extreme (12)		
				4.2.5. Equipment damage.	Asset	Possible	Major	Extreme (12)		
				4.2.6. Inability to control reaction etc. due to internal damage.	Overall	Possible	Major	Extreme (12)		
			4.2.4. Bottom slamming.	4.2.2. High acceleration of reactor/machinery foundations leading to foundation damage.	Asset	Possible	Moderate	High (9)	4.2.1. Proper machinery support. 4.2.2. The Reactor compartment is gas tight.	Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 43. Considering ship motion and high mass of reactor core can produce very loads and may have potential to damage reactor and its internal components and machinery. The reactor design needs to consider such load and impact on reactor, its component for life of design. Considering it has a high impact on safety, detailed inspection/maintenance/monitoring is to be considered.
				4.2.3. Damage to machinery.	Asset	Possible	Minor	Moderate (6)		
				4.2.4. Impact on reactor operability.	Overall	Possible	Major	Extreme (12)		
				4.2.5. Equipment damage.	Asset	Possible	Major	Extreme (12)		
				4.2.6. Inability to control reaction etc. due to internal damage.	Overall	Possible	Major	Extreme (12)		
			4.2.5. Freak wave hitting ship.	4.2.2. High acceleration of reactor/machinery foundations leading to foundation damage.	Asset	Possible	Moderate	High (9)	4.2.1. Proper machinery support. 4.2.2. The Reactor compartment is gas tight.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 48. Considering ship motion and acceleration can produce additional loads on reactor components may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactors, its component for life of design. In addition, considering it has a high impact on safety detailed inspection/maintenance/monitoring is to be considered.
				4.2.3. Damage to machinery.	Asset	Possible	Minor	Moderate (6)		
				4.2.4. Impact on reactor operability.	Overall	Possible	Major	Extreme (12)		
				4.2.5. Equipment damage.	Asset	Possible	Major	Extreme (12)		
				4.2.6. Inability to control reaction etc. due to internal damage.	Overall	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.2.6. Parametric roll.	4.2.7. High angle of roll due to loss of stability.						Rec 48. Considering ship motion and acceleration can produce additional loads on reactor components may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactors, its component for life of design. In addition, considering it has a high impact on safety detailed inspection/maintenance/monitoring is to be considered. Rec 49. Due to the high roll and gyroscopic effects, there can be excitation effects and analysis is to be conducted on the functionality of the reactor following these events.
				4.2.8. Capsizing (see 4.6)						
			4.2.7. Vibration (see 4.3)							
4.3	Vibration		4.3.1. Fluid induced vibration.	4.3.1. Damage on the foundations of the reactor.	Asset	Possible	Moderate	High (9)		Rec 40. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such with appropriate safety margin. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 44. Inspection and maintenance plans need to be developed to verify the integrity of reactor foundation, radiation biological shielding. Rec 48. Considering ship motion and acceleration can produce additional loads on reactor components may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactors, its component for life of design. In addition, considering it has a high impact on safety detailed inspection/maintenance/monitoring is to be considered. Rec 50. Detailed vibration study to be conducted and during commissioning and sea trial vibration to be measured and calibrated with analysis. During operation and maintenance vibrations need to be monitored to verify that they are in design acceptable range. Considering marine-machinery induced vibration (propeller, engine etc.), bow slamming is to be considered.
				4.3.3. Damage to reactor core Graphite.	Overall	Possible	Moderate	High (9)		
				4.3.4. Motion (see 4.2)						
				4.3.5. Radiological Leakage - Nuclear Technology Hazards (see 13.8)						

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.3.2. Ship machinery, waves, bow slamming, propeller.	4.3.2. Damage to rotating component of Reactor system.	Asset	Possible	Major	Extreme (12)		Rec 40. Vessel specific motion study is to be conducted to determine acceleration value for vessel to be used in design for NPP and system. Class society and IMO regulations are to be followed for such with appropriate safety margin. Rec 41. Further study is to be done on the optimum orientation and position of the reactor to minimize the impact of marine loads. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 44. Inspection and maintenance plans need to be developed to verify the integrity of reactor foundation, radiation biological shielding. Rec 48. Considering ship motion and acceleration can produce additional loads on reactor components may have potential to damage reactor and its internal components and machinery. Reactor design needs to consider such load and impact on reactors, its component for life of design. In addition, considering it has a high impact on safety detailed inspection/maintenance/monitoring is to be considered.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 50. Detailed vibration study to be conducted and during commissioning and sea trial vibration to be measured and calibrated with analysis. During operation and maintenance vibrations need to be monitored to verify that they are in design acceptable range. Considering marine-machinery induced vibration (propeller, engine etc.), bow slamming is to be considered.
				4.3.4. Motion (see 4.2)						
				4.3.5. Radiological Leakage - Nuclear Technology Hazards (see 13.8)						

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.4	Grounding		4.4.1. Soft Grounding.	4.4.1. Flooding of reactor compartment.	Overall	Possible	Major	Extreme (12)	4.4.1. Creation of an emergency response and safe return to port plan. 4.4.2. In a submerged condition the design is such that radiation leakage is not a possibility. 4.4.3. Automatic Emergency Shut Down (ESD) in case of reactor no load. **Comment:** Further study to be done on the compartment flooding. 4.4.4. Good navigation practice and trained crew. 4.4.5. Pilotage in narrow channels and in ports. 4.4.6. Adequate design of ship. B/20 standard margin. 4.4.7. Compartmentalisation. 4.4.8. Thermal management. 4.4.9. Radioactivity management. **Comment:** Active/Passive control rod lifting 4.4.10. Monitoring of water ingress in critical compartments.	Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event. Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.4.11. Release mechanism to avoid overpressure in reactor compartment. 4.4.12. All essential supporting equipment is to be positioned outside the flooding zone. **Comment:** Heating & Cooling system.	Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 39. Consider designing reactor containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling). Rec 52. Radiation shielding and insulation of the reactor and reactor compartment to consider total flooding of compartment or alternate justification to be provided.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 54. An emergency shelter plan is to be considered and whether there are any port restrictions. Rec 55. Further study to be done on reactor safety considering various accidental scenarios and loads. The proper safety shutdown system is to be developed and provided (active and passive). Rec 56. If the refloating of ships is considered after grounding, proper risk control should be in place. Further study is to be conducted for such an operation. Rec 59. Grounding/collision/submergence etc. can lead to reactors essential and auxiliary system damage and its impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship. Rec 63. Further study to be conducted regarding grounding and flip-over situations considering cooling and other system may not be available.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 64. In case of flooding and depending on which systems are impacted helium loss of circulation may happen. Design needs to consider such an event and appropriate mitigations are to be provided.
				4.4.2. Steam formation/steam explosion due to sea water exposure leading to reactor/room damage.	Overall	Possible	Moderate	High (9)		
				4.4.3. Propeller damage.	Overall	Possible	Moderate	High (9)		
				4.4.4. Loss of stability.	Asset	Possible	Major	Extreme (12)		
				4.4.5. Progressive flooding, loss of stability.	Asset	Unlikely	Major	High (8)		
				4.4.6. Local hull damage.	Asset	Possible	Moderate	High (9)		
				4.4.7. Electrical damage.	Asset	Possible	Moderate	High (9)		
				4.4.8. Damage to Insulation, radiation shielding and reactor insulation.	Asset	Possible	Moderate	High (9)		
				4.4.9. Radiation leak.	Injury	Possible	Moderate	High (9)		
				4.4.10. Loss of ship.	Overall	Possible	Critical	Extreme (15)		
				4.4.11. Ship tilt of side (90 degree).	Asset	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.4.12. Damage to the reactor.	Asset	Possible	Major	Extreme (12)		
				4.4.13. Loss of reactor.	Asset	Unlikely	Major	High (8)		
				4.4.14. Over pressurisation of reactor compartment due to steam generation.	Overall	Possible	Moderate	High (9)		
				4.4.15. Damage of auxiliary machinery spaces (cooling water circuit, cooling water tank).	Asset	Unlikely	Moderate	Moderate (6)		
				4.4.16. Hull splitting (shallow water, up to 350 m) (see 4.7)						
				4.4.17. Hull splitting and sinking (see 4.8)						
				4.4.18. Bilge System - System Hazards (see 6.2)						
				4.4.19. General Recycling and Salvage Comment. - Nuclear Technology Hazards - Ship Recycling & Salvage (see 16.1)						

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.4.2. Hard Grounding.	4.4.1. Flooding of reactor compartment.	Overall	Possible	Major	Extreme (12)	4.4.1. Creation of an emergency response and safe return to port plan. 4.4.2. In a submerged condition the design is such that radiation leakage is not a possibility. 4.4.3. Automatic Emergency Shut Down (ESD) in case of reactor no load. **Comment:** Further study to be done on the compartment flooding. 4.4.4. Good navigation practice and trained crew. 4.4.5. Pilotage in narrow channels and in ports. 4.4.6. Adequate design of ship. B/20 standard margin. 4.4.7. Compartmentalisation. 4.4.8. Thermal management. 4.4.9. Radioactivity management. **Comment:** Active/Passive control rod lifting 4.4.10. Monitoring of water ingress in critical compartments.	Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event. Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.4.11. Release mechanism to avoid overpressure in reactor compartment. 4.4.12. All essential supporting equipment is to be positioned outside the flooding zone. **Comment:** Heating & Cooling system.	Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 39. Consider designing reactor containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling). Rec 52. Radiation shielding and insulation of the reactor and reactor compartment to consider total flooding of compartment or alternate justification to be provided.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 54. An emergency shelter plan is to be considered and whether there are any port restrictions. Rec 55. Further study to be done on reactor safety considering various accidental scenarios and loads. The proper safety shutdown system is to be developed and provided (active and passive). Rec 56. If the refloating of ships is considered after grounding, proper risk control should be in place. Further study is to be conducted for such an operation. Rec 57. Consider increasing double bottom height to provide additional protection to reactor compartment. Rec 58. In flooding conditions electrical equipment can be damaged due to exposure to salt water and a support system will not be available etc. A study to be conducted considering such a situation to identify risk to reactor safety and consider appropriate electrical equipment e.g., IP Rating.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 59. Grounding/collision/submergence etc. can lead to reactors essential and auxiliary system damage and its impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship. Rec 60. In case of damage due to grounding/collision etc., progressive flooding may be possibility and need to be investigated to prevent such event. Rec 61. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety and appropriate measure are to be in place. Rec 62. Reactor and its system design need to consider steam formation and appropriate mitigation to be provided to prevent radiation leakage or damage to reactor. Rec 63. Further study to be conducted regarding grounding and flip-over situations considering cooling and other system may not be available. Rec 64. In case of flooding and depending on which systems are impacted helium loss of circulation may happen. Design needs to consider such an event and appropriate mitigations are to be provided.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.4.2. Steam formation/steam explosion due to sea water exposure leading to reactor/room damage.	Overall	Possible	Moderate	High (9)		
				4.4.3. Propeller damage.	Overall	Possible	Moderate	High (9)		
				4.4.4. Loss of stability.	Asset	Possible	Major	Extreme (12)		
				4.4.5. Progressive flooding, loss of stability.	Asset	Unlikely	Major	High (8)		
				4.4.6. Local hull damage.	Asset	Possible	Moderate	High (9)		
				4.4.7. Electrical damage.	Asset	Possible	Moderate	High (9)		
				4.4.8. Damage to Insulation, radiation shielding and reactor insulation.	Asset	Possible	Moderate	High (9)		
				4.4.9. Radiation leak.	Injury	Possible	Moderate	High (9)		
				4.4.10. Loss of ship.	Overall	Possible	Critical	Extreme (15)		
				4.4.11. Ship tilt of side (90 degree).	Asset	Possible	Major	Extreme (12)		
				4.4.12. Damage to the reactor.	Asset	Possible	Major	Extreme (12)		
				4.4.13. Loss of reactor.	Asset	Unlikely	Major	High (8)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.4.14. Over pressurisation of reactor compartment due to steam generation.	Overall	Possible	Moderate	High (9)		
				4.4.15. Damage of auxiliary machinery spaces (cooling water circuit, cooling water tank).	Asset	Unlikely	Moderate	Moderate (6)		
				4.4.16. Hull splitting (shallow water, up to 350 m) (see 4.7)						
				4.4.17. Hull splitting and sinking (see 4.8)						
				4.4.18. Bilge System - System Hazards (see 6.2)						
				4.4.19. General Recycling and Salvage Comment. - Nuclear Technology Hazards - Ship Recycling & Salvage (see 16.1)						
			4.4.3. Collision (see 4.5)							
4.5	Collision		4.5.1. Collision with other ship & side impact.	4.5.1. Damage to the hull.	Asset	Possible	Moderate	High (9)	4.5.1. Design has a separate control room on the bridge. 4.5.2. Position of reactor in a safe position.	Rec 14. Further study to be done on the location of the nuclear control room considering nuclear regulation, collision/grounding/flooding etc. and the impact on current design.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.5.3. Three layers of protection. 4.5.4. Conformity with B/5 regulations prerequisite. 4.5.5. Good navigation practice and trained crew. 4.5.6. Pilotage in narrow channels and in port. 4.5.7. Automatic Emergency Shut Down (ESD) in case of reactor no load.	Rec 59. Grounding/collision/submergence etc. can lead to reactors essential and auxiliary system damage and its impact are to be further investigated and appropriate design improvement to be considered to maintain safety of ship. Rec 65. A probabilistic damage stability assessment is to be conducted, accounting for the effects of damage penetration and crash worthiness of ship and nuclear system.
				4.5.2. Damage to gas turbine plant.	Asset	Possible	Moderate	High (9)		
				4.5.3. Damage to the reactor compartment.	Overall	Unlikely	Major	High (8)		
				4.5.4. Damage to control room.	Asset	Possible	Minor	Moderate (6)		
				4.5.5. Breach of outer shell and inner shell.	Asset	Possible	Major	Extreme (12)		
				4.5.6. Flooding.	Asset	Possible	Moderate	High (9)		
				4.5.7. Exposure of reactor.	Asset	Possible	Critical	Extreme (15)		
				4.5.13. Bilge System - System Hazards (see 6.2)						
			4.5.2. Flying objects. **Comment:** Due to typhoon.	4.5.1. Damage to the hull.	Asset	Possible	Moderate	High (9)	4.5.1. Design has a separate control room on the bridge.	

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.5.2. Position of reactor in a safe position. 4.5.3. Three layers of protection. 4.5.4. Conformity with B/5 regulations prerequisite. 4.5.7. Automatic Emergency Shut Down (ESD) in case of reactor no load.	
				4.5.2. Damage to gas turbine plant.	Asset	Possible	Moderate	High (9)		
				4.5.3. Damage to the reactor compartment.	Overall	Unlikely	Major	High (8)		
				4.5.4. Damage to control room.	Asset	Possible	Minor	Moderate (6)		
				4.5.5. Breach of outer shell and inner shell.	Asset	Possible	Major	Extreme (12)		
				4.5.6. Flooding.	Asset	Possible	Moderate	High (9)		
				4.5.7. Exposure of reactor.	Asset	Possible	Critical	Extreme (15)		
				4.5.8. Damage of auxiliary machinery spaces (cooling water circuit, cooling water tank).	Asset	Unlikely	Moderate	Moderate (6)		
			4.5.3. Jet engine falling.	4.5.1. Damage to the hull.	Asset	Possible	Moderate	High (9)		
				4.5.2. Damage to gas turbine plant.	Asset	Possible	Moderate	High (9)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.5.3. Damage to the reactor compartment.	Overall	Unlikely	Major	High (8)		
				4.5.4. Damage to control room.	Asset	Possible	Minor	Moderate (6)		
				4.5.5. Breach of outer shell and inner shell.	Asset	Possible	Major	Extreme (12)		
				4.5.6. Flooding.	Asset	Possible	Moderate	High (9)		
				4.5.7. Exposure of reactor.	Asset	Possible	Critical	Extreme (15)		
				4.5.8. Damage of auxiliary machinery spaces (cooling water circuit, cooling water tank).	Asset	Unlikely	Moderate	Moderate (6)		
			4.5.4. Airplane crash.							
			4.5.5. Hull splitting and sinking (see 4.8)							
4.6	Capsizing		4.6.1. Partial flooding.	4.6.1. Vessel capsizing.	Overall	Unlikely	Major	High (8)	4.6.1. Vessel design to IMO/SOLAS and class rules.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed. Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 74. Considering that the reactor is installed inside the four-barrier containment, during capsizing or when reactor is shut down without cooling, the reactor heat decay removal is to be further evaluated. Rec 75. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 76. Further study and testing are to be conducted for capsizing situations and the impact on the reactor system, reactivity, safety, drainage etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Coolant not available.	Overall	Possible	Major	Extreme (12)		
				4.6.4. Cross flooding leading to capsizing during grounding.	Overall	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.6.2. Rock grounding.	4.6.1. Vessel capsizing.	Overall	Unlikely	Major	High (8)	4.6.1. Vessel design to IMO/SOLAS and class rules. 4.6.2. Safe navigation practices.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 75. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 76. Further study and testing are to be conducted for capsizing situations and the impact on the reactor system, reactivity, safety, drainage etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.6.3. Coolant not available.	Overall	Possible	Major	Extreme (12)		
				4.6.4. Cross flooding leading to capsizing during grounding.	Overall	Possible	Major	Extreme (12)		
			4.6.3. Extreme roll and motion.	4.6.3. Coolant not available.	Overall	Possible	Major	Extreme (12)		Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 76. Further study and testing are to be conducted for capsizing situations and the impact on the reactor system, reactivity, safety, drainage etc.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.6.4. Cross flooding leading to capsizing during grounding.	Overall	Possible	Major	Extreme (12)		
			4.6.4. Mistake - maintenance/operation of ballast water system.	4.6.1. Vessel capsizing.	Overall	Unlikely	Major	High (8)	4.6.1. Vessel design to IMO/SOLAS and class rules. 4.6.2. Safe navigation practices.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 75. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		
				4.6.3. Coolant not available.	Overall	Possible	Major	Extreme (12)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.6.5. Extreme waves, wave induced loading.	4.6.1. Vessel capsizing.	Overall	Unlikely	Major	High (8)	4.6.1. Vessel design to IMO/SOLAS and class rules. 4.6.2. Safe navigation practices.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 75. Vessel routing is to be studied to avoid any probability of grounding, hitting rock etc. considering nuclear reactor/system safety. Rec 76. Further study and testing are to be conducted for capsizing situations and the impact on the reactor system, reactivity, safety, drainage etc.
				4.6.2. Large envelope heel.	Asset	Unlikely	Moderate	Moderate (6)		

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.6.3. Coolant not available.	Overall	Possible	Major	Extreme (12)		
				4.6.4. Cross flooding leading to capsizing during grounding.	Overall	Possible	Major	Extreme (12)		
				4.6.5. Springing and slamming induced weeping.						
				4.6.6. Fatigue loads and ultimate strength.						
				4.6.7. Hull splitting (shallow water, up to 350 m) (see 4.7)						
			4.6.6. Gravity will not allow safety systems e.g., drainage systems to function.	4.6.3. Coolant not available.	Overall	Possible	Major	Extreme (12)		Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc.

No.: 4	Name: Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 11. In case of major accidents, due to the marine event and if there is a possibility of leakage, either in submerge or, flooding condition, the impact of such event on the surrounding environment are to be studied and appropriate emergency, salvage and mitigation plans are to be developed. Rec 42. Reactor support and structure are to be designed to keep the reactor, and its system stays in place considering various dynamic loads, maximum heel/roll of ship is intact and damage condition, sinking of vessel, flooding of reactor compartment etc. consideration should be to provide anti floatation support and structure. Rec 76. Further study and testing are to be conducted for capsizing situations and the impact on the reactor system, reactivity, safety, drainage etc.
			4.6.7. Collision (see 4.5)							
			4.6.8. Hull splitting (shallow water, up to 350 m) (see 4.7)							
			4.6.9. Hull splitting and sinking (see 4.8)							
			4.6.10. Motion (see 4.2)							

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.7	Hull splitting (shallow water, up to 350 m)		4.7.1. Inappropriate load distribution (not following loading manual).	4.7.1. Capsizing (see 4.6)						Rec 5. Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling). Rec 77. Further study to be done on vessel cargo loading process and cargo loading manual to be updated. Rec 78. Further study to be done on vessel cargo loading process and cargo loading manual to be updated.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.7.2. Weather loading.	4.7.1. Capsizing (see 4.6)						Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling). Rec 78. Further study to be done on vessel cargo loading process and cargo loading manual to be updated.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.7.3. Hull degradation and fatigue.	4.7.1. Capsizing (see 4.6)						Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling).

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.7.4. Load shifting	4.7.1. Capsizing (see 4.6)						Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling).

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 77. Further study to be done on vessel cargo loading process and cargo loading manual to be updated. Rec 78. Further study to be done on vessel cargo loading process and cargo loading manual to be updated.
			4.7.5. Grounding (see 4.4)							
			4.7.6. Collision (see 4.5)							
			4.7.7. Capsizing (see 4.6)							

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
4.8	Hull splitting and sinking		4.8.1. Inappropriate load distribution.	4.8.1. Hull split.	Asset	Possible	Major	Extreme (12)	4.8.1. Creation of operational processes. 4.8.2. Sufficient hull design. 4.8.3. Small reactor footprint. 4.8.4. Emergency Shut Down (ESD) of reactor. 4.8.5. Triple pressure barrier design of the reactor.	Rec 4. Various additional loads and operational conditions which exist for marine application for nuclear technology, its machinery, system (primary, secondary, auxiliary) are to be considered. In particular ship normal operational/accidental condition, ship motion and dynamic loads, vibration, flexibility of ship structure, marine environment, congestion of system and equipment, collision, stranding/grounding, capsizing, heavy listing, sinking shallow water/deep water, compartment flooding and earthquake load during dry docking, etc. Rec 6. There is a possibility of reactor compartment flooding due to grounding, collision, submergence etc. design needs to consider such an event and following are to be considered: 1) Ships are currently designed per IMO/SOLAS/Class requirement for damage penetration and this needs to be investigated considering nuclear system risk and safety and additional measures are to be implemented. 2) Consider providing appropriate sensors to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shutdown (ESD) as appropriate. 3) In case of damage due to grounding/collision etc. a progressive flooding may be possibility and need to be investigated to prevent such event.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 7. Nuclear technology is to be approved by nuclear regulators and has to go through a complete technology qualification process to get approved for marine use. Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 39. Consider designing reactor containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling).

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 66. Further study to be done on collision assessment considering nuclear reactor compartment to understand risk of damage and reactor radiation safety. Rec 68. Further study is to be done on the creation of an automatic passive water flooding system of the reactor to equalize pressure and prevent radiation leakage. Rec 77. Further study to be done on vessel cargo loading process and cargo loading manual to be updated. Rec 79. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc.
				4.8.2. Reactor compartment flooding damage to reactor, shielding, electrical equipment.	Asset	Possible	Moderate	High (9)		

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.8.3. Steam formation due to sea water exposure leading to reactor damage.	Asset	Possible	Moderate	High (9)		
				4.8.4. Radiation leakage (Environmental).	Environmental	Possible	Moderate	High (9)		
				4.8.7. High external pressure leading to reactor boundary collapse.	Overall	Possible	Major	Extreme (12)		
			4.8.2. Weather loading.							Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 39. Consider designing reactor containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling). Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 68. Further study is to be done on the creation of an automatic passive water flooding system of the reactor to equalize pressure and prevent radiation leakage. Rec 77. Further study to be done on vessel cargo loading process and cargo loading manual to be updated.

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.8.3. Hull degradation and fatigue.							Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 39. Consider designing reactor containers in a way that in case of accident it can be removed from the ship to minimize sea contamination and exposure to humans. Rec 51. Further study to be done or investigation on the submergence conditions and the capability of the triple barrier design to withstand crushing pressure (in shallow waters) or alternatively water flooding options need to be considered to prevent barrier crushing and any radiation leakage. Including all penetrations into the compartment and reactor (cabling).

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 56. If the refloating of ships is considered after grounding, proper risk control should be in place. Further study is to be conducted for such an operation. Rec 66. Further study to be done on collision assessment considering nuclear reactor compartment to understand risk of damage and reactor radiation safety. Rec 68. Further study is to be done on the creation of an automatic passive water flooding system of the reactor to equalize pressure and prevent radiation leakage. Rec 77. Further study to be done on vessel cargo loading process and cargo loading manual to be updated. Rec 79. Marine salvage operation is to be considered from the initial stage of design and detailed operational procedures are to be developed for salvage companies to follow to protect environment, crew/people from radiation exposure etc.
			4.8.4. Load shifting.	4.8.1. Hull split.	Asset	Possible	Major	Extreme (12)		

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Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.8.9. Capsizing (see 4.6)						
			4.8.5. Grounding (see 4.4)							
			4.8.6. Collision (see 4.5)							
4.9	Seismic event		4.9.1. Earthquake while at shipyard.	4.9.1. Damage to reactor and its component.	Asset	Possible	Critical	Extreme (15)		Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 30. The reactors and their system are to consider seismic events, tsunamis, etc. probability, in design while in shipyard, dry dock, port, channel etc. Rec 80. Consider earthquake load when ship is in dry dock.
				4.9.2. Damage on the reactor couplers.	Asset	Likely	Major	Extreme (16)		
				4.9.3. General Risk - System Hazards - Dry Docking (see 10.1)						

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			4.9.2. Earthquake while at dry docking.	4.9.1. Damage to reactor and its component.	Asset	Possible	Critical	Extreme (15)		Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 30. The reactors and their system are to consider seismic events, tsunamis, etc. probability, in design while in shipyard, dry dock, port, channel etc. Rec 80. Consider earthquake load when ship is in dry dock.
				4.9.2. Damage on the reactor couplers.	Asset	Likely	Major	Extreme (16)		
			4.9.3. Tsunami.	4.9.1. Damage to reactor and its component.	Asset	Possible	Critical	Extreme (15)		Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 30. The reactors and their system are to consider seismic events, tsunamis, etc. probability, in design while in shipyard, dry dock, port, channel etc. Rec 80. Consider earthquake load when ship is in dry dock.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				4.9.2. Damage on the reactor couplers.	Asset	Likely	Major	Extreme (16)		
				4.9.4. Emergency Shelter - Nuclear Technology Hazards - Impact on Ports (see 15.2)						
4.10	Typhoon		4.10.1. Typhoon inertia loads.	4.10.1. Vessel damage.	Asset	Possible	Major	Extreme (12)		Rec 81. Typhoon event is to be included during design of vessel and appropriate load is to be considered in reactor design.
				4.10.2. Reactor damage.	Asset	Possible	Critical	Extreme (15)		
			4.10.2. Flying objects due to typhoon.	4.10.1. Vessel damage.	Asset	Possible	Major	Extreme (12)		Rec 81. Typhoon event is to be included during design of vessel and appropriate load is to be considered in reactor design.
				4.10.2. Reactor damage.	Asset	Possible	Critical	Extreme (15)		
				4.10.3. Reactor Availability - Global Hazards - Ship Operation (see 5.2)						
4.11	Cargo Fire		4.11.1. Cargo fire.	4.11.1. High heat, smoke and impact on nuclear reactor.	Asset	Possible	Major	Extreme (12)	4.11.1. Emergency Shut Down (ESD). 4.11.2. Coffer dam between cargo hold and engine room. 4.11.3. Fire Fighting System (FFS) for cargo fire.	Rec 82. Fire impact and fire load analysis is to be conducted depending on the cargo transported for worst case fire condition on NPP and its support system and its impact on the reactor compartment and the surrounding compartments. Appropriate mitigation measures are to be provided. Reactor compartment and room structural fire rating to be based on above analysis.

No.: 4	**Name:** Global Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									4.11.4. Prohibition on carrying dangerous goods close to the nuclear compartment. Creation of a buffer zone.	Rec 83. The cargo stowage manual is to be further analyzed considering fire impact on NPP and reactor compartment. Rec 84. Consider providing cofferdam on cargo bays or around the reactor room/machinery compartment to minimize impact of cargo fire. Rec 85. Fire Fighting System (FFS) of the container carrier is to be further analyzed considering impact on nuclear reactor.

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 5	**Name:** Global Hazards - Ship Operation	
Design Intent:		
Description:		
Associated Drawings:		

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
5.1	General Recommendation		5.1.1. General Comment.							Rec 9. Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied.

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 86. Normally, port regulation requires that in an emergency ships need to leave port in hour or less depending on the local port regulation and types of emergencies. Reactor designers to consider such operational requirements in the NPP design for power availability to depart port on short notice from total shutdown or partial operational condition. Rec 87. Nuclear power ships regulations are not available yet, but under consideration at IMO and various nuclear agencies, it is recommended that shipowners, ship operators, class societies and insurers participate in such activity to develop proper maritime regulation.

No.: 5	**Name:** Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 88. Emergency protocol in case of accident related to nuclear system or radiation leak are to be developed considering nuclear exposure hazards. 1. Develop detailed evacuation and shelter protocols for radiation incidents, with muster stations and escape routes designed to minimize exposure. Equip the vessel with sufficient shelter areas to protect crew in radiation emergencies, ensuring proper training and access to emergency supplies. 2. Emergency evacuation and escape study to be conducted for all spaces for all modes of operation considering risk of radiation exposure. 3. Consider impact on port and surrounding and appropriate emergency plan in consultation with local authority and regulator to be developed and implemented. 4. Emergency plans are to be practiced regularly. Crew and other emergency responders are to be trained considering radiation possibility exist. Rec 89. Due to radiation exposure risk in an emergency, radiation medication and other primary care on site are to be provided. Rec 90. Radiation dispersion analysis for escaped radiation in case of accident is to be conducted and how it will affect lifesaving appliances, escape routes, accommodations, and other areas are to be analyzed.

No.: 5	Name: Global Hazards - Ship Operation								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 91. Location of muster stations and their proximity to radiation zones and other high-risk areas be further studied based on radiation dispersion analysis. Rec 92. Considering radiation exposure possibility to crew in accidental situation consideration for propelled lifeboats to decrease escape time from ship and radiation zone around ship.
5.2	Reactor Availability		5.2.1. Leaving port in emergency.	5.2.1. Reactors are not available within necessary period.	Asset	Possible	Moderate	High (9)	5.2.1.	Rec 72. Further study to be done on the minimum necessary power needs of the vessel considering the regulations and the maximum power needed in case of collision avoidance. Battery use (larger size) is to be investigated as an alternative to thermal power damping in case the reactor is kept warm continuously. Rec 86. Normally, port regulation requires that in an emergency ships need to leave port in hour or less depending on the local port regulation and types of emergencies. Reactor designers to consider such operational requirements in the NPP design for power availability to depart port on short notice from total shutdown or partial operational condition. Rec 93. Further study is to be done on the availability of reserve power.

No.: 5	Name: Global Hazards - Ship Operation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 94. Further study is to be done on the possibility of keeping the reactor cooling fluid (helium) in hot conditions so that the emergency start up period can be reduced. Rec 95. Further study is to be done on the heat stress of the materials in case of a rapid start up.
				5.2.2. General Comments - Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology) (see 7.1)						
			5.2.2. Typhoon - Global Hazards (see 4.10)							
5.3	Bunkering		5.3.1. Unavailability of fuel oil due to reactor shutdown (not enough capacity stored).	5.3.1. Loss of auxiliary power.	Overall	Possible	Moderate	High (9)	5.3.1. Bunkering of normal fuel.	Rec 96. Security protocols and docking agreements with ports are to be developed. Rec 97. Bunkering operations to take the fuel for the need of the electricity in are to be considered and further analyzed.

Title: Nuclear-Powered Container Carrier		**Company:**	**Method:** HAZID
No.: 6	**Name:** System Hazards		
Design Intent:			
Description: System Hazards			
Associated Drawings:			

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
6.1	Piping, Material and Supporting Material		6.1.1. High temperature.	6.1.1. Pipe degradation due to high temperature.	Asset	Possible	Moderate	High (9)	6.1.1. Selection of appropriate piping.	Rec 35. Considering the radiation the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.
				6.1.2. Pump failure.	Asset	Possible	Moderate	High (9)		
				6.1.3. Pump failure.	Injury	Possible	Moderate	High (9)		
			6.1.2. Corrosion.	6.1.1. Pipe degradation due to high temperature.	Asset	Possible	Moderate	High (9)	6.1.1. Selection of appropriate piping. 6.1.2. Selection of appropriate pump.	Rec 35. Considering the radiation the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.
				6.1.2. Pump failure.	Asset	Possible	Moderate	High (9)		
				6.1.3. Pump failure.	Injury	Possible	Moderate	High (9)		

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				6.1.4. Reactivity in the air - System Hazards - Vent & Ventilation (see 8.3)						
			6.1.3. Bubble creation.	6.1.2. Pump failure.	Asset	Possible	Moderate	High (9)	6.1.2. Selection of appropriate pump.	Rec 35. Considering the radiation the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.
			6.1.4. Sloshing.	6.1.2. Pump failure.	Asset	Possible	Moderate	High (9)	6.1.2. Selection of appropriate pump.	Rec 35. Considering the radiation the materials used for the construction of the wall of the room are to be further investigated to make sure and verify that there are no elements in the material that can be activated and become a long-term problem. No cobalt should be used in stainless steel. Painting and coatings should be avoided.
6.2	Bilge System		6.2.1. Cooling system leakage.	6.2.1. Flooding.	Overall	Possible	Moderate	High (9)	6.2.1. Bilge system inside reactor compartment.	Rec 98. Further study to be done on separate independent bilge system considering existence of radioactive material. Rec 99. Further study to be done on potentially safely storing and disposal of bilged water in case of radioactivity. Rec 100. Water from the decontamination facility is to be directed to a special storage tank.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				6.2.2. Water in bilge system inside reactor compartment.	Asset	Possible	Moderate	High (9)		
				6.2.3. Contaminated water.	Overall	Possible	Moderate	High (9)		
			6.2.2. Condensations.	6.2.1. Flooding.	Overall	Possible	Moderate	High (9)	6.2.1. Bilge system inside reactor compartment.	Rec 98. Further study to be done on separate independent bilge system considering existence of radioactive material. Rec 99. Further study to be done on potentially safely storing and disposal of bilged water in case of radioactivity.
				6.2.2. Water in bilge system inside reactor compartment.	Asset	Possible	Moderate	High (9)		
			6.2.3. Vent lines water ingress.	6.2.1. Flooding.	Overall	Possible	Moderate	High (9)	6.2.1. Bilge system inside reactor compartment.	Rec 98. Further study to be done on separate independent bilge system considering existence of radioactive material. Rec 99. Further study to be done on potentially safely storing and disposal of bilged water in case of radioactivity. Rec 100. Water from the decontamination facility is to be directed to a special storage tank.
				6.2.2. Water in bilge system inside reactor compartment.	Asset	Possible	Moderate	High (9)		
				6.2.3. Contaminated water.	Overall	Possible	Moderate	High (9)		

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			6.2.4. Grounding - Global Hazards (see 4.4)							
			6.2.5. Collision - Global Hazards (see 4.5)							
6.3	Emergency Response		6.3.1. General Comment.						6.3.1. Personal Protection Equipment (PPE)	Rec 9. Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied.

No.: 6	**Name:** System Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 88. Emergency protocol in case of accident related to nuclear system or radiation leak are to be developed considering nuclear exposure hazards. 1. Develop detailed evacuation and shelter protocols for radiation incidents, with muster stations and escape routes designed to minimize exposure. Equip the vessel with sufficient shelter areas to protect crew in radiation emergencies, ensuring proper training and access to emergency supplies. 2. Emergency evacuation and escape study to be conducted for all spaces for all modes of operation considering risk of radiation exposure. 3. Consider impact on port and surrounding and appropriate emergency plan in consultation with local authority and regulator to be developed and implemented. 4. Emergency plans are to be practiced regularly. Crew and other emergency responders are to be trained considering radiation possibility exist. Rec 101. Facility (radioactive laboratory) to manage/investigate exposure limits. Rec 102. Firefighting plan is to include location of Personal Protection/radiation protection Equipment (PPE).

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 7	**Name:** System Hazards - Power & Propulsion	
Design Intent:		
Description: System Hazards - Power & Propulsion		
Associated Drawings:		

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
7.1	General Comments		7.1.1. General Recommendation.							Rec 86. Normally, port regulation requires that in an emergency ships need to leave port in hour or less depending on the local port regulation and types of emergencies. Reactor designers to consider such operational requirements in the NPP design for power availability to depart port on short notice from total shutdown or partial operational condition. Rec 104. Loss of power due to reactors' unavailability is to be further studied and appropriate mitigation measures and procedures are to be developed.

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 105. Considering ship power needs vary considerably depending on operation (low/ partial/full power etc.) and typically reactors operate on constant heat generation mode following are to be considered: 1. A detailed study for reactor design is to be conducted to accommodate ship load variation requirement. 2. Impact of load variation may produce higher demand on control system and are to be consider in design for various control system component for reactors 3. Load variation may produce higher fatigue load on reactors, their components and system, which need to be considered in design. 4. Requirements for load testing of NPP to be developed considering maritime regulation for engines and load variation 5. In case reactors cannot manage load variation for Balance of Power (BOP) an appropriate provision is to be provided to manage extra energy generated that is not needed for ship powering need.
			7.1.2. Emergency departure.	7.1.1. Unable to leave port in time. **Comment:** Port regulation may require ship to leave port within hour due to emergency	Asset	Likely	Moderate	High (12)	7.1.1. Battery back up.	Rec 103. Normally port regulations require that in an emergency the ship must depart from port within one hour or less. The reactor designer is to consider such requirement in design for power availability to depart port on short notice.

No.: 7	**Name:** System Hazards - Power & Propulsion								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 104. Loss of power due to reactors' unavailability is to be further studied and appropriate mitigation measures and procedures are to be developed. Rec 107. Reactor design needs to further analyze the ramp up period, from cold to full power for both cold and warm conditions. Rec 108. Electrical load fluctuations, electrical interface between reactors and electrical systems, and how to adjust the power is to be further studied. Rec 109. Electrical load analysis and power simulation load analysis at the detailed design stage is to be conducted for all modes of ship operation.
				7.1.2. Unable to leave port in time. **Comment:** Port regulation may require ship to leave port within hour due to emergency	Reputation	Likely	Moderate	High (12)		
				7.1.3. Sudden increase/decrease on power need. **Comment:** For steering needs (2-3 MWatt in less than half a minute).	Overall	Likely	Moderate	High (12)		

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			7.1.3. Sudden change of direction, emergency maneuvering.	7.1.3. Sudden increase/decrease on power need. **Comment:** For steering needs (2-3 MWatt in less than half a minute).	Overall	Likely	Moderate	High (12)		Rec 106. Considering power ramp-up rate has limitation for nuclear technology 1 MWe/Min. may impact ships ability to maneuver in certain situations, this may need additional crew/pilot training. Rec 107. Reactor design needs to further analyze the ramp up period, from cold to full power for both cold and warm conditions. Rec 108. Electrical load fluctuations, electrical interface between reactors and electrical systems, and how to adjust the power is to be further studied.
			7.1.4. Shallow water navigation.	7.1.3. Sudden increase/decrease on power need. **Comment:** For steering needs (2-3 MWatt in less than half a minute).	Overall	Likely	Moderate	High (12)	7.1.1. Battery back up.	Rec 106. Considering power ramp-up rate has limitation for nuclear technology 1 MWe/Min. may impact ships ability to maneuver in certain situations, this may need additional crew/pilot training. Rec 107. Reactor design needs to further analyze the ramp up period, from cold to full power for both cold and warm conditions. Rec 108. Electrical load fluctuations, electrical interface between reactors and electrical systems, and how to adjust the power is to be further studied. Rec 109. Electrical load analysis and power simulation load analysis at the detailed design stage is to be conducted for all modes of ship operation.

No.: 7	**Name:** System Hazards - Power & Propulsion									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			7.1.5. Reactor Availability - Global Hazards - Ship Operation (see 5.2)							
7.2	Battery		7.2.1. Battery explosion.							Rec 110. Considering NPP supports power requirement to start from the cold condition, additional reserved power will be needed in case ship auxiliary power is not available. At the detailed design stage, reserved power required for Nuclear Power Plants is to be studied for all operational modes. Rec 111. Impact on reactors compartment due to fire and explosion from battery is to be further investigated.
			7.2.2. Battery fire.	7.2.1. Damage to the reactor component.	Overall	Possible	Major	Extreme (12)	7.2.1. Reinforced cofferdam around the reactor compartment. 7.2.2. Battery compartment outside reactor compartment. 7.2.3. Battery will meet class society requirement.	Rec 110. Considering NPP supports power requirement to start from the cold condition, additional reserved power will be needed in case ship auxiliary power is not available. At the detailed design stage, reserved power required for Nuclear Power Plants is to be studied for all operational modes. Rec 111. Impact on reactors compartment due to fire and explosion from battery is to be further investigated.
				7.2.2. Reactor compartment damage due to high heat load.	Asset	Possible	Major	Extreme (12)		

Title: Nuclear-Powered Container Carrier		**Company:**	**Method:** HAZID
No.: 8	**Name:** System Hazards - Vent & Ventilation		
Design Intent:			
Description: System Hazards - Vent & Ventilation			
Associated Drawings:			

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
8.1	Ventilation Philosophy		8.1.1. General Comment.							Rec 112. Develop ventilation philosophy for reactor compartment and surrounding machinery rooms/area. Develop a ventilation system to maintain negative pressure within the reactor rooms as there is no forced ventilation considered to prevent radioactive contamination from spreading. This includes high-efficiency filtration and radiation monitoring in vent systems (if installed), ensuring safe air quality in areas where vents are discharging. Rec 113. The possibility of emitting radiation from the vent line is to be further analyzed and radiation analysis is to be done.
8.2	HVAC Air		8.2.1. Moisture and salinity in air. **Comment:** Machinery compartment will be provided with HVAC. Reactor room has no HVAC but cooling radiator to maintain temperature.	8.2.1. Corrosion.	Overall	Possible	Moderate	High (9)	8.2.1. Inlet dumpers to stop air leaving from reactor compartment.	Rec 115. Further study to be done on material selection based on corrosivity and salinity tolerance.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				8.2.2. Radioactive leakage.	Injury	Possible	Major	Extreme (12)		
			8.2.2. Radiation inside reactor compartment.	8.2.2. Radioactive leakage.	Injury	Possible	Major	Extreme (12)	8.2.1. Inlet dumpers to stop air leaving from reactor compartment.	Rec 114. Further study to be done on ventilation requirements and mitigation measures in case of contaminated vent lines during an incident or normal operation. Rec 116. Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from the funnel a dispersion study to be conducted for all operational, upset and emergency situation to determine safe ventilation funnel height.
			8.2.3. High temperature.							Rec 117. Design of reactor and reactor room to consider how to remove heat and maintain room temperature within acceptable limit.
8.3	Reactivity in the air		8.3.1. Radiation leak.	8.3.1. Contamination of air inside reactor/machinery space. **Comment:** Activated Argon/Neutron	Overall	Unlikely	Moderate	Moderate (6)	8.3.1. Filters. 8.3.2. Dumpers at ventilation exhaust inlet. 8.3.3. Air storage. 8.3.4. Temperature monitoring. 8.3.5. Pressure monitoring. 8.3.6. Radiation monitoring. 8.3.7. Gas tight design of vent duct.	Rec 118. Considering the possibility of radiation inside the reactor room, design needs to be further developed to remove the heat from the reactors room and prevent radiation from escaping. Rec 119. Further study is to be done on additional fire structural/radiation barriers provided. Rec 120. Further study is to be done on the dispersion of compromised air from the exhaust system.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			8.3.2. Piping, Material and Supporting Material - System Hazards (see 6.1)							
8.4	Reactive material on deck		8.4.1. Radiation leak inside reactor compartment.	8.4.1. Release of radioactive air.	Environmental	Unlikely	Moderate	Moderate (6)	8.4.1. Filters. 8.4.2. Dumpers at ventilation exhaust inlet. 8.4.3. Radioactive monitoring in the inlet of the vent stack.	Rec 88. Emergency protocol in case of accident related to nuclear system or radiation leak are to be developed considering nuclear exposure hazards. 1. Develop detailed evacuation and shelter protocols for radiation incidents, with muster stations and escape routes designed to minimize exposure. Equip the vessel with sufficient shelter areas to protect crew in radiation emergencies, ensuring proper training and access to emergency supplies. 2. Emergency evacuation and escape study to be conducted for all spaces for all modes of operation considering risk of radiation exposure. 3. Consider impact on port and surrounding and appropriate emergency plan in consultation with local authority and regulator to be developed and implemented. 4. Emergency plans are to be practiced regularly. Crew and other emergency responders are to be trained considering radiation possibility exist.

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 116. Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from the funnel a dispersion study to be conducted for all operational, upset and emergency situation to determine safe ventilation funnel height. Rec 120. Further study is to be done on the dispersion of compromised air from the exhaust system. Rec 121. Further study to be done on port operation procedures and emergency plan to host a vessel following a radioactive release. Rec 122. Further study to be done on how to contain radioactive release within the compartment. Rec 123. Further study to be done on other machinery space outside reactor room and its ventilation in order to minimize radioactive exposure to such space
				8.4.2. Exposure of people in port or port facilities.	Injury	Unlikely	Moderate	Moderate (6)		
				8.4.3. Exposure of people on bridge or bridge itself.	Injury	Unlikely	Moderate	Moderate (6)		

No.: 8	**Name:** System Hazards - Vent & Ventilation									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
8.5	Other Machinery Spaces		8.5.1. General Comment.							Rec 116. Considering where ventilation funnel is located and surrounding crew/accommodation area and considering possibility of radiation from the funnel a dispersion study to be conducted for all operational, upset and emergency situation to determine safe ventilation funnel height. Rec 124. Further study to be done on ventilation ducts to avoid ventilation with nuclear compartment.

Title: Nuclear-Powered Container Carrier		**Company:**	**Method:** HAZID
No.: 9	**Name:** Maintenance and Inspection		
Design Intent:			
Description:			
Associated Drawings:			

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
9.1	Maintenance, Live		9.1.1. Exposure to radiated component.	9.1.1. Personnel exposure.	Injury	Possible	Critical	Extreme (15)	9.1.1. Radiation detectors. 9.1.2. Personal Protection Equipment (PPE). 9.1.3. Recording of exposure time inside the reactor compartment. 9.1.4. Special training and education of crew.	Rec 9. Considering NPP radiation risk following to be considered: 1) Design reactor compartments with comprehensive radiation shielding and robust monitoring systems for each area/compartment. 2) Consider additional protection and monitoring of radiation due to proximity of crew in various area of the ship. 3) Implement protocols for rapid containment of radiation leaks and minimize crew exposure through protective equipment (PPE) and specialised high-efficiency filtration systems in HVAC and vent ducts near high-risk zones are to be considered. 4) Quantity, location and disposal of Personal Protection Equipment (PPE) to be further studied. Rec 125. Reactor compartment should not be accessible while in operation, consider remote inspection/monitoring while in operation

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 126. If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank. Rec 132. Detailed crew training plans for education and maintenance of reactor and support system are to be developed.
				9.1.2. Inspection/Maintenance - Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology) (see 14.7)						
			9.1.2. Sensor malfunction.	9.1.1. Personnel exposure.	Injury	Possible	Critical	Extreme (15)	9.1.5. Redundant control systems.	Rec 126. If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank.

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 129. Sensors require periodic calibration/maintenance. Considering radiation risk proper design/plan needs to be developed for such activity. Rec 130. Further study to be done on pump periodic maintenance plan. Rec 131. In a marine propulsion, availability of power plants is of high importance, considering the proposed NPP system is a compact integral system, followings are to be considered: 1. The reliability and availability of the NPP are to be further analyzed and defined, based on the operational needs of the ship, regulation, owner and operator requirements. 2. RAM (Reliability, Availability, Maintainability) analysis is to be performed with design development. 3. Detailed inspection maintenance plan for the entire nuclear system and its supporting systems is to be developed considering radiation exposure and risk and criticality of the NPP. Rec 132. Detailed crew training plans for education and maintenance of reactor and support system are to be developed. Rec 133. Spare part inventory is to be further analyzed, and requirements are to be defined.

No.: 9 **Name:** Maintenance and Inspection

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
			9.1.3. Fuel Charging & Refuelling - Nuclear Technology Hazards (see 13.2)							
			9.1.4. Helium Leakage - Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology) (see 14.4)							Rec 126. If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank. Rec 127. At the design stage a detailed analysis for installation, removal and maintenance of the reactor modules is to be conducted. The study should include the financial analysis of all supporting vessels needed during the maintenance process. Rec 128. Helium storage/space needed for onsite maintenance is to be further analyzed.
9.2	Maintenance, Shutdown		9.2.1. General Comment.						9.2.1. Systems check prior to reactor start up.	Rec 134. Further study is to be done on the development of a maintenance plan defining responsibilities between general and specialised crew considering the regulatory requirements.

No.: 9	**Name:** Maintenance and Inspection									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 135. Any contaminated component/machinery requires maintenance, proper procedure and protocol to be developed.
			9.2.2. Refuelling.	9.2.1. Inspection/Maintenance - Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology) (see 14.7)						Rec 134. Further study is to be done on the development of a maintenance plan defining responsibilities between general and specialised crew considering the regulatory requirements. Rec 135. Any contaminated component/machinery requires maintenance, proper procedure and protocol to be developed.

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 10	**Name:** System Hazards - Dry Docking	
Design Intent:		
Description: System Hazards - Dry Docking		
Associated Drawings:		

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
10.1	General Risk		10.1.1. General Comment.							Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 136. Further study is to be done on procedure for dry docking security measures. Rec 137. Further study to be done on dry docking survey and maintenance requirements from typical existing procedures to accommodate for nuclear power needs. Rec 138. Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies to be done.
			10.1.2. Radiation inside reactor compartment.	10.1.1. Loss of circulation pump.	Asset	Possible	Moderate	High (9)	10.1.1. Backup power.	

No.: 10	**Name:** System Hazards - Dry Docking								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				10.1.2. Loss of reactor support system.	Overall	Possible	Major	Extreme (12)		
				10.1.3. Loss of core cooling.	Asset	Possible	Moderate	High (9)		
				10.1.4. Core temperature rise.	Asset	Possible	Moderate	High (9)		
			10.1.3. Loss of cooling water supply.	10.1.2. Loss of reactor support system.	Overall	Possible	Major	Extreme (12)	10.1.1. Backup power.	
				10.1.3. Loss of core cooling.	Asset	Possible	Moderate	High (9)		
				10.1.4. Core temperature rise.	Asset	Possible	Moderate	High (9)		
				10.1.5. Damage to reactors, the support or the internal component.	Overall	Possible	Major	Extreme (12)		
			10.1.4. Hurricane.	10.1.1. Loss of circulation pump.	Asset	Possible	Moderate	High (9)	10.1.1. Backup power.	
				10.1.2. Loss of reactor support system.	Overall	Possible	Major	Extreme (12)		
				10.1.3. Loss of core cooling.	Asset	Possible	Moderate	High (9)		
				10.1.4. Core temperature rise.	Asset	Possible	Moderate	High (9)		
				10.1.5. Damage to reactors, the support or the internal component.	Overall	Possible	Major	Extreme (12)		
				10.1.6. Damage to the ship.	Asset	Possible	Moderate	High (9)		

No.: 10	**Name:** System Hazards - Dry Docking									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			10.1.5. Security breach.							Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 136. Further study is to be done on procedure for dry docking security measures. Rec 137. Further study to be done on dry docking survey and maintenance requirements from typical existing procedures to accommodate for nuclear power needs. Rec 138. Considering maintenance need of the reactor e.g., refuelling, main on central core and general arrangement to be revisited for the capability of maintenance and RAM studies to be done. Rec 139. Further study to be done on the possibility of earthquake while in dry dock
			10.1.6. Seismic event - Global Hazards (see 4.9)							

Title: Nuclear-Powered Container Carrier		**Company:**	**Method:** HAZID
No.: 11	**Name:** System Hazards - Dropped Object & Energy Release		
Design Intent:			
Description: Dropped Object & Energy Release Hazards			
Associated Drawings:			

No.: 11	**Name:** System Hazards - Dropped Object & Energy Release									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
11.1	General Hazards		11.1.1. Dropping HolosGen module.							Rec 34. Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane or other load) Rec 140. Handling of HolosGen container is to be further analyzed from a dropped object risk point of view.
11.2	Dropped Object		11.2.1. Dropped object from crane (reactor maintenance).							Rec 34. Dropped object study to be performed for: 1. During construction and installation process to prevent any damage to reactor and its system 2. Dropped object due to cargo operation (e.g., dropped container, crane or other load)

No.: 11	**Name:** System Hazards - Dropped Object & Energy Release								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
11.3	Kinetic or Stored Energy		11.3.1. Turbine (expander/compander) broken blade.	11.3.1. Release of fragment.	Overall	Possible	Moderate	High (9)	11.3.1. Reactor compartment protected by cofferdam.	Rec 5. Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel Rec 141. Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
				11.3.2. Breach of reactor barrier or damage to reactor due to kinetic energy of the blade.	Asset	Possible	Major	Extreme (12)		
				11.3.3. Leakage of radioactive material.	Injury	Possible	Major	Extreme (12)		

No.: 11	**Name:** System Hazards - Dropped Object & Energy Release									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			11.3.2. Pressurised pipe failure.	11.3.1. Release of fragment.	Overall	Possible	Moderate	High (9)	11.3.1. Reactor compartment protected by cofferdam.	Rec 5. Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel Rec 141. Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
				11.3.2. Breach of reactor barrier or damage to reactor due to kinetic energy of the blade.	Asset	Possible	Major	Extreme (12)		
				11.3.3. Leakage of radioactive material.	Injury	Possible	Major	Extreme (12)		
				11.3.4. Breach of control room.						

No.: 11	**Name:** System Hazards - Dropped Object & Energy Release								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			11.3.3. Battery explosion.	11.3.1. Release of fragment.	Overall	Possible	Moderate	High (9)	11.3.1. Reactor compartment protected by cofferdam.	Rec 5. Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel Rec 141. Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
				11.3.2. Breach of reactor barrier or damage to reactor due to kinetic energy of the blade.	Asset	Possible	Major	Extreme (12)		
				11.3.3. Leakage of radioactive material.	Injury	Possible	Major	Extreme (12)		
				11.3.4. Breach of control room.						

No.: 11	**Name:** System Hazards - Dropped Object & Energy Release									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			11.3.4. Cargo explosion.	11.3.1. Release of fragment.	Overall	Possible	Moderate	High (9)	11.3.1. Reactor compartment protected by cofferdam.	Rec 5. Study to be conducted for positioning of the NPP to minimize external risk due collision, grounding, capsizing, hull splitting, sinking, flooding, dropped object, kinetic and potential energy, cargo fire, explosion and other external impacts and consider additional structural reinforcements and distance from hull boundary to ensure stability and safety during such events. Consider providing appropriate sensor to detect water accumulation and the control systems are to be linked to sensors and initiate alarm and Emergency Shut Down (ESD) as appropriate. Examine the possibility of moving the reactor to the middle of the vessel Rec 141. Further study to be done on steam pipe failure/turbine blade failure and impact on reactor.
				11.3.2. Breach of reactor barrier or damage to reactor due to kinetic energy of the blade.	Asset	Possible	Major	Extreme (12)		
				11.3.3. Leakage of radioactive material.	Injury	Possible	Major	Extreme (12)		
				11.3.4. Breach of control room.						

Title: Nuclear-Powered Container Carrier		**Company:**	**Method:** HAZID
No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)		
Design Intent:			
Description: System Hazards - Fire Fighting System			
Associated Drawings:			

No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
12.1	General Fire Fighting Hazard		12.1.1. Fire in the area close to reactor system.	12.1.1. Elevated temperatures inside reactor room. **Comment:** Boiling of shielding water	Asset	Possible	Moderate	High (9)	12.1.1. Fire Fighting System (FFS). 12.1.2. Water spray system. 12.1.3. Reactor Emergency Shut Down (ESD). 12.1.4. Cofferdam to protect reactor compartment. 12.1.5. Adequate vessel structure design.	Rec 1. Considering possibility of fire internal/external outside of reactor compartment and considering radiation leakage possibility, design principle should include following: 1. Consider arranging each reactor in separate compartments and providing enough isolation to prevent fire migration and protection against fire incident. 2. Minimize fire possibility by using appropriate material. 3. Appropriate means are to be provided to fight fire in reactor and machinery compartment. 4. Structural design to consider fire load in design and its survivability. Rec 142. Further studies are to be done on fine detector system and its placement inside reactor room/compartment. Rec 143. Consider additional class notations for container ship considering cargo fire Rec 144. Further studies are to be done to consider increasing the safety margins to the structure and adequacy of fire insulation.

No.: 12	**Name:** System Hazards - Fire Fighting System (FFS)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
				12.1.2. Collapse of structure reactor compartment.	Overall	Unlikely	Major	High (8)		
				12.1.3. Loss of control instrumentation due to heat gain.	Asset	Possible	Moderate	High (9)		

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 13	**Name:** Nuclear Technology Hazards	
Design Intent:		
Description: Nuclear Technology Hazards		
Associated Drawings:		

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.1	Manning, Training, Human Factor		13.1.1. General comment.						13.1.1. SOLAS requirements. 13.1.2. STCW convention.	Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process.

No.: 13	**Name:** Nuclear Technology Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 126. If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank. Rec 145. POB study to be conducted considering the nuclear reactor. Rec 146. Special consideration for lashing crew, training, requirements for certification, background check. Rec 147. Investigate if regulator is required on board at all times or not. Rec 148. Port personnel to be trained in emergency and risk. Rec 149. Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements. Rec 150. Human Factor Engineering (HFE) analysis is to be considered for the regulatory requirements. Rec 151. The regulatory requirements to be checked for citizen ship and security clearance requirement.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.1.2. Availability of personnel due to citizenship requirement.						13.1.1. SOLAS requirements. 13.1.2. STCW convention.	Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 146. Special consideration for lashing crew, training, requirements for certification, background check. Rec 147. Investigate if regulator is required on board at all times or not. Rec 148. Port personnel to be trained in emergency and risk. Rec 149. Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements. Rec 150. Human Factor Engineering (HFE) analysis is to be considered for the regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 151. The regulatory requirements to be checked for citizen ship and security clearance requirement.
			13.1.3. Human error.						13.1.1. SOLAS requirements. 13.1.2. STCW convention.	Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 146. Special consideration for lashing crew, training, requirements for certification, background check. Rec 147. Investigate if regulator is required on board at all times or not. Rec 148. Port personnel to be trained in emergency and risk. Rec 149. Special training for the nuclear reactor operators is to be developed and certification procedures according to regulator, manufacturer, owner and flag requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 150. Human Factor Engineering (HFE) analysis is to be considered for the regulatory requirements. Rec 151. The regulatory requirements to be checked for citizen ship and security clearance requirement.
13.2	Fuel Charging & Refuelling		13.2.1. Inability to load fuel.	13.2.1. Down time.	Overall	Unlikely	Major	High (8)		Rec 15. Further study to be done on the process of choosing a shipyard considering nuclear regulation, proliferation matters, design and construction requirements for nuclear power plant related systems, licensing requirement from OEM and regulatory agency, specialised and licensing requirements, the capability of shipyard to construct or service such a specialised ship. Rec 32. Vessel modification including engine removal, structural modification etc. are to be further investigated to accommodate NPP. Rec 38. Considering the treaty on the nonproliferation of nuclear weapons and risk of ship traveling worldwide, technology developers need to design proliferation resistant fuel and technologies for the nuclear reactor and make it impossible to access them or use them in harmful way. Also, the impact of treaty on design and operation is to be further studied.

No.: 13	**Name:** Nuclear Technology Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 152. Ship design to consider nuclear fuel loading and removal in a safe manner per regulatory requirements. If the entire module is to be removed this needs to be considered from design stage to facilitate such operation during fuelling interval. Rec 153. Study to be done for refuelling frequency, duration and location what permitting needed. Rec 154. Maintenance/inspection to be considered during refuelling event.
				13.2.3. Maintenance, Live - Maintenance and Inspection (see 9.1)						
13.3	Reactor Barrier(s)		13.3.1. Heat inside the reactor compartment. **Comment:** Reactor not insulated, only has radiological shield.						13.3.1. Gas tight. 13.3.2. Watertight. 13.3.3. Compartment division.	Rec 117. Design of reactor and reactor room to consider how to remove heat and maintain room temperature within acceptable limit. Rec 155. Radiation shielding to be further developed considering marine environment and applicable marine loads and flooding.
			13.3.2. Radiation.	13.3.1. Radiation above limit.	Overall	Possible	Major	Extreme (12)	13.3.3. Compartment division. 13.3.4. Biological shielding per regulatory requirement.	Rec 155. Radiation shielding to be further developed considering marine environment and applicable marine loads and flooding.
			13.3.3. Failure of barrier (A, B, C).	13.3.1. Radiation above limit.	Overall	Possible	Major	Extreme (12)		Rec 156. Barriers B and C of HOLOS design are to be further investigated for various marine loads and accidental event

No.: 13	**Name:** Nuclear Technology Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.4	Emergency Response		13.4.1. Black out.	13.4.1. Support system not available.	Overall	Possible	Moderate	High (9)	13.4.1. Emergency Shut Down (ESD). 13.4.2. Redundancy. 13.4.3. Certification. 13.4.4. Testing. 13.4.5. Cyber security. 13.4.6. Nuclear Agency Regulations.	Rec 157. Considering the longer time required to maintain reactor safety the auxiliary and emergency generators are to be further studied. Rec 158. Control and monitoring systems in case of emergency may require more monitoring time than normal marine practices and are to be further studied with the regulators and the technology providers. Rec 159. Emergency systems are to be operational at a much higher angle of list and need to be considered for the system availability in plant/equipment design. Rec 160. Human need is to be further investigated in case of entering the control room. Rec 161. Human interface and human need for the emergency situation considered in the reactor safety are to be further investigated considering the abatement of the ship.
			13.4.2. Automation failures.	13.4.1. Support system not available.	Overall	Possible	Moderate	High (9)	13.4.1. Emergency Shut Down (ESD). 13.4.2. Redundancy. 13.4.3. Certification. 13.4.4. Testing. 13.4.5. Cyber security. 13.4.6. Nuclear Agency Regulations.	Rec 157. Considering the longer time required to maintain reactor safety the auxiliary and emergency generators are to be further studied. Rec 158. Control and monitoring systems in case of emergency may require more monitoring time than normal marine practices and are to be further studied with the regulators and the technology providers.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 159. Emergency systems are to be operational at a much higher angle of list and need to be considered for the system availability in plant/equipment design. Rec 160. Human need is to be further investigated in case of entering the control room. Rec 161. Human interface and human need for the emergency situation considered in the reactor safety are to be further investigated considering the abatement of the ship.

No.: 13	**Name:** Nuclear Technology Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
13.5	Cooling Fluid		13.5.1. General Comment.	13.5.1. Radioactivity entering the cooling fluid side.	Overall	Possible	Minor	Moderate (6)	13.5.1. Intermediate cooling circuit. 13.5.2. Nonradioactive properties of Helium. 13.5.3. Radioactivity monitoring on the Helium side. 13.5.4. Storage and testing of water.	Rec 105. Considering ship power needs vary considerably depending on operation (low/ partial/full power etc.) and typically reactors operate on constant heat generation mode following are to be considered: 1. A detailed study for reactor design is to be conducted to accommodate ship load variation requirement. 2. Impact of load variation may produce higher demand on control system and are to be consider in design for various control system component for reactors 3. Load variation may produce higher fatigue load on reactors, their components and system, which need to be considered in design. 4. Requirements for load testing of NPP to be developed considering maritime regulation for engines and load variation 5. In case reactors cannot manage load variation for Balance of Power (BOP) an appropriate provision is to be provided to manage extra energy generated that is not needed for ship powering need. Rec 162. The cooling circuit will use intermediate cooling medium according to the purity specifications required.
			13.5.2. Contamination of water coolant, pin hole leak in heat exchanger.	13.5.1. Radioactivity entering the cooling fluid side.	Overall	Possible	Minor	Moderate (6)	13.5.1. Intermediate cooling circuit. 13.5.2. Nonradioactive properties of Helium.	Rec 162. The cooling circuit will use intermediate cooling medium according to the purity specifications required.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									13.5.3. Radioactivity monitoring on the Helium side. 13.5.4. Storage and testing of water.	
13.6	Security & External Threat		13.6.1. High jacking, piracy, terrorism.	13.6.1. Control of reactor/radioactive material.	Overall	Possible	Critical	Extreme (15)	13.6.2. High freeboard. 13.6.3. High speed. 13.6.4. Water canon. 13.6.5. Restricted area of operation. 13.6.6. Guarded personnel. 13.6.7. Reactor room is secured. 13.6.8. Strong radiation in the reactor room.	Rec 163. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements. Rec 164. Proper security and access control measures on board and at the port are to be developed in communication with regulators. Rec 165. External threats are to be further evaluated and protocol to be developed in cooperation with the regulator and regulation to be developed.
				13.6.2. Damage to the reactor.	Asset	Possible	Critical	Extreme (15)		
				13.6.3. Breach of reactor barrier or damage to the reactor.	Asset	Possible	Critical	Extreme (15)		
				13.6.4. Leakage of Helium/fuel.	Overall	Possible	Critical	Extreme (15)		
				13.6.5. Removal of reactor.						
			13.6.2. Ship attack, sabotage, bomb inside a container.	13.6.1. Control of reactor/radioactive material.	Overall	Possible	Critical	Extreme (15)	13.6.1. Security measures on access to all critical machinery spaces. 13.6.2. High freeboard. 13.6.3. High speed. 13.6.4. Water canon. 13.6.5. Restricted area of operation.	Rec 163. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									13.6.6. Guarded personnel. 13.6.7. Reactor room is secured. 13.6.8. Strong radiation in the reactor room. 13.6.9. Reactor inside hull. 13.6.10. Doppler effect (inherent safety feature).	Rec 164. Proper security and access control measures on board and at the port are to be developed in communication with regulators. Rec 165. External threats are to be further evaluated and protocol to be developed in cooperation with the regulator and regulation to be developed. Rec 167. Develop a control mechanism on the container content to minimize fire risk Rec 168. Reactor(s) location(s) are dropped object, to be further analyzed considering threat from dropped containers, sabotage, RPG/missile attack, plane/helicopter crash etc.
				13.6.2. Damage to the reactor.	Asset	Possible	Critical	Extreme (15)		
				13.6.3. Breach of reactor barrier or damage to the reactor.	Asset	Possible	Critical	Extreme (15)		
				13.6.4. Leakage of Helium/fuel.	Overall	Possible	Critical	Extreme (15)		
			13.6.3. Plane/drone attack.	13.6.2. Damage to the reactor.	Asset	Possible	Critical	Extreme (15)	13.6.1. Security measures on access to all critical machinery spaces. 13.6.6. Guarded personnel. 13.6.7. Reactor room is secured. 13.6.8. Strong radiation in the reactor room. 13.6.9. Reactor inside hull.	Rec 163. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements. Rec 164. Proper security and access control measures on board and at the port are to be developed in communication with regulators.

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 165. External threats are to be further evaluated and protocol to be developed in cooperation with the regulator and regulation to be developed. Rec 166. Consider further flying object study and strength of hull in way of reactor.
				13.6.3. Breach of reactor barrier or damage to the reactor.	Asset	Possible	Critical	Extreme (15)		
				13.6.4. Leakage of Helium/fuel.	Overall	Possible	Critical	Extreme (15)		
			13.6.4. Caber attack.	13.6.1. Control of reactor/radioactive material.	Overall	Possible	Critical	Extreme (15)	13.6.1. Security measures on access to all critical machinery spaces.	Rec 163. Further study to be done on cyber security and pertinent certification to be issued in accordance with regulatory requirements. Rec 164. Proper security and access control measures on board and at the port are to be developed in communication with regulators.
			13.6.5. Unauthorised access.	13.6.1. Control of reactor/radioactive material.	Overall	Possible	Critical	Extreme (15)	13.6.1. Security measures on access to all critical machinery spaces. 13.6.5. Restricted area of operation. 13.6.6. Guarded personnel. 13.6.7. Reactor room is secured.	Rec 164. Proper security and access control measures on board and at the port are to be developed in communication with regulators. Rec 165. External threats are to be further evaluated and protocol to be developed in cooperation with the regulator and regulation to be developed.
				13.6.2. Damage to the reactor.	Asset	Possible	Critical	Extreme (15)		

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.6.6. Sea mines.	13.6.2. Damage to the reactor.	Asset	Possible	Critical	Extreme (15)	13.6.7. Reactor room is secured.	Rec 164. Proper security and access control measures on board and at the port are to be developed in communication with regulators. Rec 165. External threats are to be further evaluated and protocol to be developed in cooperation with the regulator and regulation to be developed. Rec 168. Reactor(s) location(s) are dropped object, to be further analyzed considering threat from dropped containers, sabotage, RPG/missile attack, plane/helicopter crash etc.
				13.6.3. Breach of reactor barrier or damage to the reactor.	Asset	Possible	Critical	Extreme (15)		
				13.6.4. Leakage of Helium/fuel.	Overall	Possible	Critical	Extreme (15)		
13.7	Nuclear Waste Storage, Handling, & Disposal		13.7.1. General Comment.	13.7.1. Exposure of humans	Injury	Possible	Moderate	High (9)		Rec 126. If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank.

No.: 13	**Name:** Nuclear Technology Hazards								
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 169. Vessel design is to consider on board radioactive waste storage, monitoring and disposal. Procedures are to be developed, and security protocols are to be in place. Rec 170. Further study to be done on detailed plan of handling of radioactive material at the end of ship life, before the end of ship lifetime, or normal operation and during maintenance e.g., hull, reactor core, piping, heat exchangers, pumps, any other exposed material. Rec 171. Further study is to be done on the impact of radioactive waste handling to ports.
13.8	Radiological Leakage		13.8.1. Degradation of system components. **Comment:** fatigue, loads, flooding etc.	13.8.1. Leakage of radiological material.	Injury	Possible	Major	Extreme (12)	13.8.1. Biological shielding.	Rec 173. Radiological shield design to consider marine loads, environment, space confinement, vibration, motion, flooding etc. in design and proper inspection and maintenance plan to be developed
				13.8.2. Loss of material property.	Overall	Possible	Moderate	High (9)		
				13.8.3. Fatigue.	Asset	Possible	Moderate	High (9)		
			13.8.2. High temperature.	13.8.1. Leakage of radiological material.	Injury	Possible	Major	Extreme (12)	13.8.1. Biological shielding.	Rec 173. Radiological shield design to consider marine loads, environment, space confinement, vibration, motion, flooding etc. in design and proper inspection and maintenance plan to be developed
				13.8.2. Loss of material property.	Overall	Possible	Moderate	High (9)		
				13.8.3. Fatigue.	Asset	Possible	Moderate	High (9)		

No.: 13	**Name:** Nuclear Technology Hazards									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			13.8.3. Concrete cracking.	13.8.1. Leakage of radiological material.	Injury	Possible	Major	Extreme (12)	13.8.1. Biological shielding. 13.8.2. Radiation monitoring.	Rec 126. If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank. Rec 172. Considering the marine application of biological shielding, further study to be done on the possible use of polymers as an additional level of shielding survivability. Rec 173. Radiological shield design to consider marine loads, environment, space confinement, vibration, motion, flooding etc. in design and proper inspection and maintenance plan to be developed
				13.8.2. Loss of material property.	Overall	Possible	Moderate	High (9)		
				13.8.4. Radiation exposure.	Injury	Possible	Moderate	High (9)		
			13.8.4. Vibration - Global Hazards (see 4.3)							
13.9	Control system		13.9.1. General Comment.							Rec 174. The control system is to be redundant duplicate and developed based on Defense in depth principle

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)	
Design Intent:		
Description: Nuclear Technology Hazards - Small Modular Reactor		
Associated Drawings:		

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
14.1	General Comment		14.1.1. General Comment.							Rec 131. In a marine propulsion, availability of power plants is of high importance, considering the proposed NPP system is a compact integral system, followings are to be considered: 1. The reliability and availability of the NPP are to be further analyzed and defined, based on the operational needs of the ship, regulation, owner and operator requirements. 2. RAM (Reliability, Availability, Maintainability) analysis is to be performed with design development. 3. Detailed inspection maintenance plan for the entire nuclear system and its supporting systems is to be developed considering radiation exposure and risk and criticality of the NPP.

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
14.2	Uncontrolled Reaction		14.2.1. Failure of all shutdown rod and the redundancy.	14.2.1. Overheating, reactor oscillation, dropper effect.	Overall	Unlikely	Major	High (8)	14.2.1. Major safety critical system is redundant or triple redundant and independent. 14.2.2. The system will stabilize by itself due to design. Doppler effect kick in. 14.2.3. Injection of poison, killing of neutrons. 14.2.4. Triple redundancy safeguard (1 pseudo-passive, 2 active systems). 14.2.5. Design is such that no release of radioactive nuclei will occur.	Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 158. Control and monitoring systems in case of emergency may require more monitoring time than normal marine practices and are to be further studied with the regulators and the technology providers. Rec 174. The control system is to be redundant duplicate and developed based on Defense in depth principle
				14.2.2. Uncontrolled chain reaction. **Comment:** Oscillation, not explosion	Overall	Unlikely	Critical	Extreme (10)		

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			14.2.2. Failure of drum and the redundancy.	14.2.1. Overheating, reactor oscillation, dropper effect.	Overall	Unlikely	Major	High (8)	14.2.2. The system will stabilize by itself due to design. Doppler effect kick in. 14.2.3. Injection of poison, killing of neutrons. 14.2.4. Triple redundancy safeguard (1 pseudo-passive, 2 active systems). 14.2.5. Design is such that no release of radioactive nuclei will occur.	Rec 53. Develop a robust Emergency Shutdown (ESD) protocol considering (i) the motion of the ship (ii) normal operation (iii) emergency and (iv) conditions beyond emergency scenarios. Install high-reliability, redundant control systems for critical components to manage extreme marine conditions (e.g., capsizing, severe listing, flooding, etc.). Regularly train the crew on these procedures and conduct simulation drills. Rec 158. Control and monitoring systems in case of emergency may require more monitoring time than normal marine practices and are to be further studied with the regulators and the technology providers. Rec 174. The control system is to be redundant duplicate and developed based on Defense in depth principle
				14.2.2. Uncontrolled chain reaction. **Comment:** Oscillation, not explosion	Overall	Unlikely	Critical	Extreme (10)		
			14.2.3. Security & External Threat - Nuclear Technology Hazards (see 13.6)	14.2.1. Overheating, reactor oscillation, dropper effect.	Overall	Unlikely	Major	High (8)	14.2.1. Major safety critical system is redundant or triple redundant and independent. 14.2.2. The system will stabilize by itself due to design. Doppler effect kick in. 14.2.3. Injection of poison, killing of neutrons.	

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
									14.2.4. Triple redundancy safeguard (1 pseudo-passive, 2 active systems). 14.2.5. Design is such that no release of radioactive nuclei will occur.	
				14.2.2. Uncontrolled chain reaction. **Comment:** Oscillation, not explosion	Overall	Unlikely	Critical	Extreme (10)		
14.3	Magnetic Bearings		14.3.1. Loss of Power.	14.3.1. Loss of magnetic bearings.	Asset	Possible	Major	Extreme (12)	14.3.1. Back up battery. **Comment:** UPS for the essential systems of the reactor. 14.3.2. Catcher bearings. 14.3.5. Electrical power supply has enough redundancy to maintain power.	Rec 176. Bearing individual components of the rotating machines should have a FMECA.
			14.3.2. Electromagnetic interference.	14.3.1. Loss of magnetic bearings.	Asset	Possible	Major	Extreme (12)	14.3.2. Catcher bearings. 14.3.3. Shielding filter. 14.3.4. Core protection with shielding.	Rec 175. The electrical system is designed to block electromagnetic pulse. Rec 176. Bearing individual components of the rotating machines should have a FMECA.
			14.3.3. Electromagnetic pulse. **Comment:** Lightning	14.3.1. Loss of magnetic bearings.	Asset	Possible	Major	Extreme (12)	14.3.3. Shielding filter. 14.3.4. Core protection with shielding. 14.3.6. Software control to keep shaft aligned.	Rec 176. Bearing individual components of the rotating machines should have a FMECA.
			14.3.4. Short circuit.	14.3.1. Loss of magnetic bearings.	Asset	Possible	Major	Extreme (12)	14.3.5. Electrical power supply has enough redundancy to maintain power.	Rec 176. Bearing individual components of the rotating machines should have a FMECA.

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
14.4	Helium Leakage		14.4.1. Crack in the heat exchanger.	14.4.1. Helium Leakage in water side of heat exchanger.	Overall	Possible	Major	Extreme (12)	14.4.1. Venting of helium. 14.4.2. Helium reservoir pressure tank. 14.4.3. Pressure monitoring inside compartment B and pumping/removal of Helium.	Rec 177. In case of helium leakage detections and maintenance approaches are to be further developed .
				14.4.2. Helium leakage in barrier C.	Overall	Possible	Major	Extreme (12)		
				14.4.3. Brayton cycle inability to operate.	Overall	Possible	Moderate	High (9)		
				14.4.5. Maintenance, Live - Maintenance and Inspection (see 9.1)						
14.5	Power Availability		14.5.1. No additional risk identified.							
14.6	Operation		14.6.1. No additional risks identified.							
14.7	Inspection/Maintenance		14.7.1. Maintenance, Live - Maintenance and Inspection (see 9.1)							
			14.7.2. Maintenance, Shutdown - Maintenance and Inspection (see 9.2)							

No.: 14 | **Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
14.8	Safety System		14.8.1. No additional risks identified.							
14.9	Escape & Evacuation		14.9.1. General Comment.							Rec 88. Emergency protocol in case of accident related to nuclear system or radiation leak are to be developed considering nuclear exposure hazards. 1. Develop detailed evacuation and shelter protocols for radiation incidents, with muster stations and escape routes designed to minimize exposure. Equip the vessel with sufficient shelter areas to protect crew in radiation emergencies, ensuring proper training and access to emergency supplies. 2. Emergency evacuation and escape study to be conducted for all spaces for all modes of operation considering risk of radiation exposure. 3. Consider impact on port and surrounding and appropriate emergency plan in consultation with local authority and regulator to be developed and implemented. 4. Emergency plans are to be practiced regularly. Crew and other emergency responders are to be trained considering radiation possibility exist.

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 126. If the crew is contaminated with radiation above exposure limit, consider following: 1. Consider providing space, equipment including special type of shower for decontamination and primary treatment of contaminated person 2. Plans and procedure are to be developed on how to transport contaminated person to hospital 3. Water from the decontamination facility is to be directed to a special storage tank.

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
14.10	Harbor Operation		14.10.1. Partial load of reactor.							Rec 105. Considering ship power needs vary considerably depending on operation (low/ partial/full power etc.) and typically reactors operate on constant heat generation mode following are to be considered: 1. A detailed study for reactor design is to be conducted to accommodate ship load variation requirement. 2. Impact of load variation may produce higher demand on control system and are to be consider in design for various control system component for reactors 3. Load variation may produce higher fatigue load on reactors, their components and system, which need to be considered in design. 4. Requirements for load testing of NPP to be developed considering maritime regulation for engines and load variation 5. In case reactors cannot manage load variation for Balance of Power (BOP) an appropriate provision is to be provided to manage extra energy generated that is not needed for ship powering need. Rec 109. Electrical load analysis and power simulation load analysis at the detailed design stage is to be conducted for all modes of ship operation.

No.: 14	**Name:** Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology)									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			14.10.2. Emergency Shelter - Nuclear Technology Hazards - Impact on Ports (see 15.2)							

Title: Nuclear-Powered Container Carrier		**Company:**	**Method:** HAZID
No.: 15	**Name:** Nuclear Technology Hazards - Impact on Ports		
Design Intent:			
Description: Nuclear Technology Hazards - Impact on Ports			
Associated Drawings:			

No.: 15	**Name:** Nuclear Technology Hazards - Impact on Ports									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
15.1	General Recommendation		15.1.1. General Comment.							Rec 171. Further study is to be done on the impact of radioactive waste handling to ports. Rec 178. International regulations are to be developed on international travel either by IMO, NRC or IAEA. Special consideration on passage through canals such as Panama, Suez, Singapore straights. Rec 179. Further study is to be done if the reactor runs on partial load mode and a large amount of heat has to be dissipated and the impact on the marine environment e.g., increases in water temperature. All systems are to be dimensioned so that the vessel can operate globally.
15.2	Emergency Shelter		15.2.1. General Comment.	15.2.1. Harbor Operation - Nuclear Technology Hazards - Small Modular Reactor (HolosGen Technology) (see 14.10)						Rec 54. An emergency shelter plan is to be considered and whether there are any port restrictions. Rec 180. Port of Refuge and Shelter law is to be further study as in emergency port of refuge can be questionable. Rec 181. Further study is to be done on the potential of contamination in a port environment and the consequences for the local community.

No.: 15	**Name:** Nuclear Technology Hazards - Impact on Ports									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
			15.2.2. Seismic event - Global Hazards (see 4.9)							

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 16	**Name:** Nuclear Technology Hazards - Ship Recycling & Salvage	
Design Intent:		
Description: Ship Recycling & Salvage		
Associated Drawings:		

No.: 16 — **Name:** Nuclear Technology Hazards - Ship Recycling & Salvage

Item	Hazard/Top Event	Comments	Threats	Consequences	Matrix	UL	US	UR	Barriers	Action Items
16.1	General Recycling and Salvage Comment.		16.1.1. General Comment.	16.1.1. Radiation exposure.					16.1.1. Inventory of Hazardous Materials (IHM).	Rec 2. Considering radioactivity, end of life disposal is to be considered from beginning of the ship design to facilitate safe handling, removal and disposal of any parts, equipment and material that might be contaminated with radioactive material. Rec 3. Considering new materials and chemicals due to nuclear technology, Inventory of Hazardous Materials (IHM) is to be maintained, and any additional risk is to be studied and understood.

No.: 16	**Name:** Nuclear Technology Hazards - Ship Recycling & Salvage									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 18. Marine salvage operations are to be considered from the initial stage of design. Design need to consider removal of reactor during salvage operation Detailed operational procedure are to be developed for salvage company to follow to protect environment, crew/people from radiation exposure etc. Salvage operations based on the ship designs and the dose rates (radioactivity) are to be further investigated and proper procedures and training instructions are to be developed for the salvage crew. Further study to be done on risk control options in place for active safety management during salvage process. Rec 36. In order to manage the core which has spent fuel, alternate options on how to remove the core before it arrives to the shipyard such as using special purpose barge or other alternate methods are to be considered to minimize the risk in the dry dock/salvage/scrape yard area. Rec 180. Port of Refuge and Shelter law is to be further study as in emergency port of refuge can be questionable.

No.: 16	**Name:** Nuclear Technology Hazards - Ship Recycling & Salvage									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 182. Considering restrictions in nuclear technology disposal at the ship end of life it is necessary to consider which yard will be chosen and whether the removal of the ship will be in one or two stages (removal of the reactor in one shipyard and dismantling of the ship in another one). Further, special consideration should be given to the disposal of radioactive materials. Rec 183. Design to consider the possibility of a reactor transferred to another ship/location. Rec 184. Further study is to be done on how the reactor will stay in place in case of the salvage process and radiation is contained.
			16.1.2. Grounding - Global Hazards (see 4.4)							
			16.1.3. Hull splitting and sinking - Global Hazards (see 4.8)							

Title: Nuclear-Powered Container Carrier	**Company:**	**Method:** HAZID
No.: 17	**Name:** Finance Risk & Liability	
Design Intent:		
Description: Financial Risk		
Associated Drawings:		

No.: 17	**Name:** Finance Risk & Liability									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
17.1	General Financing Hazard		17.1.1. General Comment.							Rec 10. The Reactor and its systems are to be designed to meet the design life of the ship (typically 30 years), considering the possibility to install/reuse for another project are to be further investigated to improve economics. Rec 27. Further study is to be done for long-term fuel availability, licensing etc. Rec 28. Design aspects for the external risk issues are to be considered. Rec 29. Considering there is no rule and regulation which defines Liability for nuclear power ships. The following are to be considered: 1) Further rules and regulations are to be developed in cooperation with shipowners, P&I club, and regulators, etc. 2) Responsible parties for liabilities are to be defined by regulatory procedure

No.: 17	**Name:** Finance Risk & Liability									
Item	**Hazard/Top Event**	**Comments**	**Threats**	**Consequences**	**Matrix**	**UL**	**US**	**UR**	**Barriers**	**Action Items**
										Rec 127. At the design stage a detailed analysis for installation, removal and maintenance of the reactor modules is to be conducted. The study should include the financial analysis of all supporting vessels needed during the maintenance process. Rec 185. Further study to be done on the P&I contract.

Appendix IX – Detailed Regulatory Gap Analysis

No Gap or Changes needed to address Nuclear Power
Small Gap or Minor Change to address Nuclear Power
Medium Gap or Some Challenging Change to address Nuclear Power
Large Gap or Many Challenging Changes to address Nuclear Power

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
Sustainability and Emissions Regulations	EU 'Fit-for-55' FuelEU Maritime	- Not explicitly listed as a technology considered as zero-emissions	- No gap, however, the policy encourages technology development and deployment of emission-reducing technical solutions.	- This package sets an emission target for 2030 so its effect on marine nuclear energy is likely to be minimal	- Package does not include nuclear energy, but does promote zero-carbon solutions so can act as a stepping stone for future legislation to include nuclear energy
	EU Emissions Trading System (ETS)	- Nuclear power as energy source is not directly mentioned - Only focused on tank-to-wake emissions, does not incorporate emissions from production	- No gap, however, the policy encourages technology development and deployment of emission-reducing technical solutions.	- Nuclear energy is specifically mentioned as restricted from credit usage	- Credit restriction makes future investment a barrier
	US Clean Air Act	- Regulates air pollution and hazardous air pollutants such as radionuclides and any other radioactive pollutants. - May be referred to or used for maritime nuclear applications.	- No gap, however, this encourages technology development and deployment of emission-reducing technical solutions in the U.S.	- There are restrictions for radionuclides, but explicitly states that the NRC regulations supersede the act relevant to nuclear activities	- Deferment to NRC regulations makes regulation compliance simpler

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
	US Clean Water Act	- May be referred to or used for maritime nuclear applications.	- No gap, however, the policy encourages technology that reduce pollutants, including radiological material and high-level radioactive waste	- Alteration of radiological integrity of water and other radioactive materials/waste are defined as pollutants and unlawful to discharge into navigable waters	- Pollutant control is a normal process so effect would neutral
	US Marine Protection, Research, and Sanctuaries Act	- May be referred to or used for maritime nuclear applications.	- No gap, however, the policy encourages technology that reduce pollutants, including radiological material and high-level radioactive waste	- Act requires plan for removal or containment of disposed nuclear material for container leaks or decomposition in order to grant permit	- Additional step in permitting, but expected so effect would be neutral
	EU Energy Taxation Directive (ETD)	- Shipping sector fully exempt from directive - Member states independently implement national policy	- May not directly suggest nuclear solutions, but drivers for carbon-free energy on land can promote land-based nuclear developments and later impact nuclear solutions for ships as well.	- Although not applicable to shipping sector, land-based incentives for nuclear energy may promote its development and later impact nuclear solutions for ships as well.	- Tax exemption can make the technology attractive for investment
	IMO Strategy on Reduction of GHG Emissions 2023	- Does not specifically apply to nuclear reactors or enforce their use on vessels. - May need to be modified or updated to consider nuclear energy	- Facilitates the adoption of zero-emission energy solutions for ships over time, increasing demand for nuclear power all around	- Important driver to research, develop, and implement new technologies for sustainability and decarbonisation.	- Package does not include nuclear reactors, but does promote zero-carbon solutions so can act as a steppingstone for future legislation to include nuclear energy
	MARPOL Annex VI EEDI, EEXI, CII & DCS	- No explicit provision in IMO regulations and guidelines for the direct use of a nuclear carbon	- May form the framework to include nuclear power solutions in fleet	- In general, international consensus on updating codes of safety for nuclear-powered	- Stringent emissions reduction accounting through these mechanisms generally support the

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
		factor in EEDI, EEXI, CII and DCS - Provision for well-to-wake emissions considerations should be taken into account in these instruments - Minor gap to cover direct use of a nuclear as considered for carbon factor	decarbonisation strategies in the future	vessels is a major effort. This includes the provision of nuclear produced alternative fuels and nuclear propulsion in index calculations, as well the update of the administrative codes such as ISM, ISPS, STCW or other Hazardous Materials Codes to accommodate the new technology for merchant shipping.	research, development, and adoption of carbon-free technology solutions.
Nuclear Fuel Standards [including supply chain, manufacturing, recycling, and disposal]	Boiler and Pressure Vessel Code (BPVC) Section III – Rules for Construction of Nuclear Facility Components, Division 3	- Covers materials, design, fabrication, examination, testing, quality assurance, and required overpressure protection for nuclear facility components, including containment systems for transportation and storage of spent nuclear fuel and high-level radioactive material. - May not specifically apply to the transport and storage of spent nuclear fuel and high-level radioactive material on the ship from which it was produced. - May be referred to in marine specific standards - Additional modifications or updates may be needed to address technical integration of nuclear technology with ship structures and systems	- Standard equipment design for transport and storage of materials may be applicable with minor changes to include use on ships.	- Existing standards for nuclear-related structures, systems and components can be used or leveraged for different applications, including merchant nuclear propulsion.	- Existing nuclear codes and standards can contribute to the adoption of the technology for non-conventional purposes.

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
	ASTM International Set of Technology Standards for Fuel and Fertile Material Specifications and Spent Fuel and High-Level Waste	- May be referred to in marine specific standards	- Standard equipment design for transport and storage of materials may be applicable with minor changes to include use on ships	- Fuel quality standards may be unique according to the type of reactor, the country of Licence or location, as well as the arrangements and location of used fuel or radioactive waste management.	- Existing nuclear codes and standards can contribute to the adoption of the technology for non-conventional purposes.
Marine Design Standards	SOLAS Chapter VIII & Resolution A.491	- Applicable to pressurised water reactors for propulsion only. - Outdated and should be updated, modernised, and applicable to more types of advanced reactors	- Existing international code for nuclear-Powered Vessels (no need to develop from scratch) can form the basis of an updated international code.	- Existing SOLAS Ch VIII and A.491(XII) were specifically produced to support development of nuclear-powered vessels at the time of the 1960s through 1980. However, nuclear technology and marine standards have modernised since these were developed. While they form a useful precedent to build upon, Resolution A.491(XII) is generally obsolete and careful consideration is needed to update the Code with consideration of various types of reactor technology.	- Updating existing maritime regulations for implementing nuclear propulsion technology can be easier to manage than organizing the effort to develop from scratch. The existence of SOLAS Ch. VIII and A.491(XII) generally contribute to the productive discussion of the re-adoption of nuclear technology for merchant shipping.
Nuclear Reactor Design Standards	Boiler and Pressure Vessel Code (BPVC) Section III – Rules for Construction of Nuclear Facility Components	- Requirements needed for the packaging and transportation of radioactive materials by offerors and carriers - Not applicable to the management of nuclear material	- Standard equipment construction rules may form the basis of an update applicable to marine construction	- Existing standards for nuclear-related structures, systems and components can be used or leveraged for different applications,	- Existing nuclear codes and standards can contribute to the adoption of the technology for non-conventional purposes.

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
		handling on marine vessels - May be referred to by other codes or standards or updated to include onboard handling of nuclear material	and verification practices	including merchant nuclear propulsion.	
Transportation & Handling [of Nuclear Material, including Radioactive Waste]	IAEA - SSR Part 6 Regulations for the Safe Transport of Radioactive Material	- Establishes the general guidelines for the management of radioactive waste resulting from nuclear reactor operations. - Not applicable to the management of nuclear material handling on marine vessels	- Existing standards and regulations applicable to land-based nuclear power plant uses may form the basis of updated or new codes specific to nuclear-powered vessels	- Regulations directly sponsored by the IMO	- The IMO and IMDG being directly involved allows for a smoother transition by existing shipowners
	IMO International Maritime Dangerous Goods (IMDG)	- Establishes the Nuclear Waste Management Organisation (NUMO) and regulates the geological disposal of high-level radioactive material.	- Provides precedent of managing nuclear material as ship cargo	- Applicable to materials unirradiated and irradiated from thermal reactors only	- Directly applicable to nuclear uptake and eases the design process
	Council Directive 2011/70/Euratom	- Requirements for licences to transport, nuclear substances, recordkeeping as well as requirements for the design and certification of packages, special form radioactive material and other prescribed equipment - Not applicable to the management of nuclear material handling on marine vessels	- May be referred to by other codes or standards or updated to include onboard handling of nuclear material	- Controls transboundary shipments of waste and spent fuel - Has exemptions for shipments of spent fuel from research reactors back to home country where fuel was supplied	- Effect on uptake would be neutral as industry would refer to these standards for European nuclear operations.
	US 10 CFR 71 – Packaging and Transportation of Radioactive Material	- Establishes requirements for the packaging, preparation for shipment, and transportation of licenced nuclear material as well as the procedure for NRC approval of shipment	- Land-based regulations could be referred to by marine standards or updated to include activities in marine environment	- Covers shipment so there is tangential regulations to the maritime industry	- Effect on uptake would be neutral as standard is typical

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
	US 10 CFR 110 – Export and Import of Nuclear Equipment and Material	- Framework for management of source materials, byproducts, and processed products. Additionally, there is coverage for the installation and operation of radiation-monitoring devices.	- May be referred to or updated to include marine nuclear propulsion use cases.	- International shipping is limited to type B packaging as designated by the NRC	- Effect on uptake would be neutral as industry would not apply standard as is
	US DOE O 461.1 C Packaging and Transportation for Offsite Shipment of Material of National Security Interest	- Applicable to Cargo only. - May be referred to in marine standards or updated to include specific provisions for nuclear maritime operations.	- May be referred to or updated to include marine nuclear propulsion use cases.	- There is an equivalency for ensuring consistency with this regulation and the Nuclear Propulsion Act by way of the Deputy Administrator for Naval Reactors	- Link to the Nuclear Propulsion act allows streamlining for future vessels
	US 10 CFR 835 - Occupational Radiation Protection	- Related to the supervision and control of shipments of radioactive waste and spent fuel.	- May be referred to for use in marine applications.	- Does not contain comments specific to marine, but applicable as a radiological document	- Effect on uptake is neutral as this would be a standard document to follow
	UK Health and Safety at Work etc Act 1974 – Ionising Radiations Regulations 1999	- Establishes expanded regulations for the control of radioactive material and the disposal of its waste.	- No gap as directly applicable to marine	- Transport is explicitly defined to include seas and waterways	- Would likely restrain uptake unless planned for minimally crewed vessel
	US Nuclear Waste Policy Act	- Provides safety requirements for facilities that manage radioactive waste before disposal, including the associated transport of radioactive material.	- May be used or referred to by marine operators.	- Specifically states that act does not affect the Marine Protection, Research, and Sanctuaries Act of 1972 Section 224 regarding seabed disposal now repealed	- Act originally covered seabed disposal, but later repealed this option. Possible to restrain uptake with less disposal options allowed.
	49 CFR Part 173 Subpart I - Class 7 (Radioactive) Materials	- Sets requirements for the storage, segregation distances, hazard care, and contamination control of radioactive materials. - May be referred to in marine standards or updated to be	- No gap as specific to marine application	- Extensively covers hazardous waste as a marine pollutant and marine portable tanks	- Extensive documentation regarding marine pollutants likely contributes to uptake

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
		applicable to nuclear marine applications			
	Japan Reactor Regulation Act	- Requirements needed for the packaging and transportation of radioactive materials by offerors and carriers - Not applicable to the management of nuclear material handling on marine vessels - May be referred to by other codes or standards or updated to include onboard handling of nuclear material	- May be referred to by other codes or standards or updated to include onboard handling of nuclear material	- Explicitly prohibits disposal of waste at sea and allows for comment from Japanese Coast Guard regarding law enforcement	- Neutral or contribution to intake with explicit regulations in place to follow
	Japan Act for Final Disposal of High-Level Radioactive Waste	- Establishes the general guidelines for the management of radioactive waste resulting from nuclear reactor operations. - Not applicable to the management of nuclear material handling on marine vessels	- No gap as regulatory agency and geologic disposal is on land - May be used or referred to by marine operators.	- Does not mention marine or marine application	- Would likely have a neutral effect on uptake as its marine tangential
	Canada Packaging and Transport of Nuclear Substances Regulations, 2015	- Establishes the Nuclear Waste Management Organisation (NUMO) and regulates the geological disposal of high-level radioactive material.	- May be referred to by other codes or standards or updated to include onboard handling of nuclear material	- Refers back to the IMDG for marine applications	- Commonality to the IMDG would contribute to uptake as a streamlined process
	IMO International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC)	- Requirements for licences to transport, nuclear substances, recordkeeping as well as requirements for the design and certification of packages, special form radioactive material and other prescribed equipment	- No gap as nuclear propulsion is specifically excluded	-	

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
		- Not applicable to the management of nuclear material handling on marine vessels			
	Act on Protective Action Guidelines Against Radiation in the Natural Environment	- Applicable to cargo only. - No gaps to allow nuclear marine applications	- May be referred to by marine standards or updated to apply to nuclear marine applications.	- No direct mention to marine application or international shipping and acts more of a guideline for larger regulation on each article	- Neutral effect on uptake, but would be helpful as reference material for those looking into Korean laws
	IMO - International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium, and High-Level Radioactive Wastes on Board Ships (INF)	- Framework for management of source materials, byproducts, and processed products. Additionally, there is coverage for the installation and operation of radiation monitoring devices.	- No gap as specific to marine application Requires Ships Carrying INF Cargo to have an emergency plan to address the procedures to be followed in case of an incident involving the INF cargo	- Explicitly made for nuclear materials and waste and is extensive in standards for shipping	- Neutral or slightly contributes to uptake as standards are in-depth for operators to follow
	Council Directive 2006/117/Euratom	- Applicable to Cargo only. - May be referred to in marine standards or updated to include specific provisions for nuclear maritime operations.	- May be referred to in marine standards or updated to be applicable to nuclear marine applications	- Directive is without prejudice to rights and obligations under international law for maritime vessels, among other things	- Union requirements concurrent to internation law may restrict uptake for those wanting to enter the EU market, if significantly different from original country
	UK Environmental Permitting (England and Wales) Regulations 2010	- Related to the supervision and control of shipments of radioactive waste and spent fuel.	- May be referred to in marine standards or updated to include marine applications	- Regulation is applicable to sea adjacent to England and Wales to the territorial sea by strict definition Does not apply to offshore platforms Extensively covers nuclear regulation	- Large amount of information in one document for regulation related to the marine environment and nuclear applications would contribute to uptake

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
				including a reference to the nuclear installations act of 1965	
Quality Assurance	Boiler and Pressure Vessel Code (BPVC) Section XI – Rules for Inservice Inspection of Nuclear Power Plant Components	- Applicable for the examination, operational testing, inspection, repair, and replacement of components specific to light water-cooled nuclear power plants. - Not applicable to all types of reactor technology	- May be referred to in marine standards or updated to be applicable to maritime operations	- Applicable mostly to light-water cooled nuclear plants, but makes no mention of marine or marine applications	- May contribute to uptake by operators using light-water cooled reactors
	ASME NQA-1 – Quality Assurance Requirements for Nuclear Facility Applications	- Provides a standard for carrying out quality assurance programmes through siting, design, construction, operation and decommissioning of a nuclear power plant. - Not applicable to marine facilities.	- May be referred to in marine standards or updated to be applicable.		
	US 15 CFR 744.5 - Restrictions on certain maritime nuclear propulsion end-uses	- Summarises prohibitions of shipping using nuclear propulsion without licencing.	- May be applicable to nuclear marine applications today.	- Directly written for maritime nuclear propulsion	- Explicit directive likely to contribute to uptake
	IMO - International Safety Management Code (ISM)	- Provides administrative structures for basic safety management to shipping companies and shipowners to protect the operation of ships and prevent pollution. - May be used by marine operators - Does not include specific provisions for nuclear marine applications.	- No gap as specific to marine application	- No references to nuclear technology or operations	- Might restrict marine operators wanting to integrate nuclear technology
	ASME OM – Operation and Maintenance of Nuclear Power Plants	- Provides requirements for testing and examination of components to assess operational suitability, including responsibilities,	- May be adopted by maritime regulators or updated to include	- There are multiple regulations set in place for shipping that could	- Shipping regulation is a standard and would likely have neutral uptake

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
		methods, intervals, criteria, corrective action, qualification, and documentation.	nuclear marine applications.	be tangentially applicable	
Licencing, Nuclear Administration and Liability	Japan Nuclear Emergency Act	- Establishes the regulations regarding response measures for nuclear disasters to protect personal property and prevent the loss of life and personal injury.	- May be referred to or updated to include nuclear marine applications.	- Includes some references to nuclear-powered vessels of foreign origin entering Japan and Japanese nuclear-powered vessels entering foreign waters	- Regulation would likely have neutral uptake as compensation is a standard to be expected
	Canada General Nuclear Safety and Control Regulations	- Establishes the general requirements with respect to licence applications and renewals, exemptions, obligations of licencees, prescribed nuclear facilities and equipment and information, contamination, record-keeping, and inspections.	- No major gaps for nuclear marine applications.	- Contains explicit directives for marine application regarding disposal and pollution	- Explicit regulation is likely to contribute to uptake
	Canada Administrative Monetary Penalties Regulations	- Lists violations that are subject to administrative monetary policies, the method and criteria by which the penalty amounts will be determined, and the manner in which notices of violations must be served.	- Not specific to marine applications. May be referred to in marine standards or updated to include nuclear marine applications.	- There are no references to the marine or maritime industry	- Emergency procedures are laid out in Japan's Reactor Regulation Act so this would likely have neutral uptake
	Canada Class I Nuclear Facilities Regulations	- Requirements for site preparation licence applications, personnel certifications, record-keeping and sets timelines for regulatory reviews.	- Not specific to marine applications. May be referred to in marine standards or updated to include nuclear marine applications.	- There are no references to the marine or maritime industry	- Lack of regulation is likely to restrict uptake

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
	Canada Class II Nuclear Facilities and Prescribed Equipment Regulations	- Requirements for licence applications, certification of prescribed equipment, radiation protection and record-keeping.	- May be adopted by maritime regulators or updated to include nuclear marine applications	- Directly applicable to the maritime industry with penalties clearly laid out	- Marine law expressed would likely have neutral uptake
	Euratom Treaty	- Original treaty that established the Euratom and lays out the baseline regulations for all Euratom members to follow and build upon.	- Not specific to marine applications. May be referred to in marine standards or updated to include nuclear marine applications.	- There are no references to the marine or maritime industry	- Lack of regulation is likely to restrict uptake
	Korea Nuclear Safety Act	- Establishes the framework for nuclear activities in Korea that are enforced by the NSSC -Encompasses broad regulations over all aspects of nuclear power on land	- Not specific to marine applications. May be referred to in marine standards or updated to include nuclear marine applications.	- There are no references to the marine or maritime industry	- Lack of regulation is likely to restrict uptake
	Japan Atomic Energy Basic Act (AEBA)	- Generalises objectives for research and development, as well as the usage use of nuclear energy -Encompasses broad regulations over all aspects of nuclear power on land	- Euratom regulations could be updated or referred to include marine applications of nuclear power.	- There are no references to the marine or maritime industry	- Would likely have neutral effect unless amended to include marine applications
	UK Energy Act 2004	- Sets regulations relating to the civil nuclear industry and radioactive waste -Encompasses broad regulations over all aspects of nuclear power on land	- May be referred to or updated to include nuclear marine applications	- Includes article for notification of entry and departure of foreign nuclear-powered vessels	-
	Canada Nuclear Non-proliferation Import and Export Control Regulations	- Regulations for a licence application to import or export controlled nuclear substances, controlled nuclear equipment, or controlled nuclear information, in addition to exemptions from	- May be used as a framework for new or updated maritime regulations or may be updated to include nuclear marine applications	- Does not reference the marine or the maritime industry, but does have guidelines regarding heavy water usage and production which could be applicable if these	- Would likely have neutral effect unless amended to include marine applications

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
		licencing for certain import and export activities. - Not specific to maritime		sorts of processes were planned onboard a vessel	
	Convention on Nuclear Safety (CNS)	- Convention that allows for accountability by other convention signatories	- Not directly related to marine, but could be expanded upon	- Does no reference the maritime industry	- Contribute as safety mechanisms would allow for reassurance to operators
Risk / Safety / Environmental Assessment	Council Directive 2014/87/Euratom - Nuclear Safety Directive	- Establishes a community framework for the safety and the reduction of safety risks of nuclear installations.	- May be used by marine standards or updated to specifically include nuclear marine applications.	- Does not make any references to the marine or maritime industry, but does refer back to international regulation which can be tangential to existing Euratom marine legislation	- Directive would mostly be reference material leading to neutral uptake unless amended
	US CFR 62 - Criteria and Procedures for Emergency Access to Non-Federal and Regional Low Level Waste Disposal Facilities	- Establishes requirements to submit a request to the NRC for the emergency disposal of low-level radioactive waste.	- Land-based disposal activity not specific to marine applications.	- There are no references to the marine or maritime industry	- Would likely have neutral effect unless amended to include marine applications
	US 10 CFR 76 – Certification of Gaseous Diffusion Plants	- Establishes requirements that will govern the operation of certain portions of specific plants, that are leased by the United States Enrichment Corporation.	- Not applicable to marine applications. May be used as a reference when considering marine nuclear applications.	- Requires transport plan for ship special nuclear material of low strategic significance	- Would likely have neutral effect as could be substituted with other regulation
	Canada Nuclear Substances and Radiation Devices Regulations	- Requirements for the licencing and certification of nuclear substances and radiation devices, use of radiation devices and record-keeping.	- Not applicable to marine applications, but may be referenced by marine standards or updated to include nuclear marine applications	- There are no references to the marine or maritime industry	- While other legislation might substitute and alleviate concerns, lack of inclusion for marine application might restrict uptake

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
	Canada Radiation Protection Regulations	- Regulations that define the 'as low as reasonably achievable' (ALARA) principle and regulations for radiation dose limits, action limits, and requirements for labelling and signage, and reporting.	- May form a framework to develop maritime regulations or may be updated to include nuclear marine applications	- There are no references to the marine or maritime industry	- While other legislation might substitute and alleviate concerns, lack of inclusion for marine application might restrict uptake
Security and Safeguards	IAEA Treaty on the Non-Proliferation of Nuclear Weapons (NPT)	- Establishes international agreement on the peaceful use of nuclear material and establishing national safeguards to nuclear material. - Does not address the issue of a mobile nuclear power plant operating over multiple jurisdictions but will be important to consider for operational arrangements of nuclear-powered merchant ships.	- National safeguards would be applicable to nuclear material on ships or used for ship propulsion. Establishes a useful framework of international collaboration for continuous accounting and safeguarding nuclear material.	- The movement of an operating nuclear reactor, such as that used for merchant nuclear propulsion, between states of the NPT treaty requires clear interface between nations on how safeguards are implemented and transferred between jurisdictions.	- Neither contributes nor restrains the uptake of merchant nuclear marine ships but offers important precedent to international agreement on nuclear materials.
	IAEA - Convention on the Physical Protection of Nuclear Material (CPPNM)	- Establishes legal obligations regarding the physical protection of nuclear material used for peaceful purposes during international transport, the criminalisation of certain offences involving nuclear material, and international cooperation.	- While the framework in place is important to provide continued accountancy of nuclear material and safeguards at all times, it is not yet clear how the movement of commercial reactors on ships may be restricted by the NPT.	- Outlines strict restrictions on allowance of vessels into State waters carrying nuclear materials not signatories to the agreement	- Might restrict uptake to organisations whose host country is not a signatory to the law
	IMO - International Ship and Port Facility Security (ISPS)	- Focuses on establishing security measures for Governments, ports and shipping companies. - Does not include nuclear applications, but does not pose	- Not specific to maritime, but may form a framework for maritime regulations or may be updated to	- Only one reference to nuclear attacks but otherwise no other mentions to nuclear facilities	- Might restrict marine operators wanting to integrate nuclear technology

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
		gap for nuclear marine applications	include nuclear marine applications		
	US 10 CFR 37 Physical Protection of Category 1 and Category 2 Quantities of Radioactive Material	- Establishes guidelines on the security of Category 1 and Category 2 radioactive material from theft or diversion.	- No gap as specific to marine application	- There are no references to the marine or maritime industry	- Guidelines would be reference material leading to neutral uptake unless amended
	US 10 CFR 73 – Physical Protection of Plant and Materials	- Establishes requirements for the establishment creation and maintenance of a physical protection system and arrangement for special nuclear material in transit and the plants at which they are used.	- Does not include maritime requirements but may be referred to by maritime regulations.	- Only allows for equipment to be shipped by container ships when transported over sea	- Would likely have neutral uptake unless plans for other arrangements would need to be established
	UK Energy Act 2008	- Regulates the security of equipment, software and information relating to nuclear matters.	- Does not include maritime facilities or applications. May be used as basis for new maritime regulations or updated to include specific requirements for marine applications.	- There are no references to the marine or maritime industry	- Extensive documentation regarding nuclear equipment, if adapted to the maritime industry, would likely contribute to uptake
	Korea Act on Physical Protection and Radiological Emergency	- Framework for the physical protection of nuclear materials and nuclear facilities, radiation disaster prevention measures, and supplementary provisions via local governments and special institutions.	- Not specific to nuclear marine applications but may be used as basis for new or updated maritime regulations.	- There are minor references to foreign vessel owners and accidents regarding ships transporting nuclear material	- Will likely need amendments to include marine usage of nuclear material likely restraining uptake
	Korea Nuclear Security Regulations	- Defines security-related information requirements and general obligations for applications	- Not applicable to marine applications.	- There are no references to the marine or maritime industry	- Will likely need amendments to include marine usage of nuclear material likely restraining uptake

Subject	Guidance/Code/Standard Title	Comment on Code/Standard - Gaps	Comment on Code/Standard - Benefits	General Comments	Contribute / Restrain uptake of Nuclear for Merchant Shipping
	Convention on Early Notification of a Nuclear Accident	- Convention legislated to establish mechanisms for signatories to report accidents that may result in a nuclear release that will affect another country	- Can be applied to marine nuclear systems	- There are no references to the marine or maritime industry	- Act not specific to onshore reactors so could be applied offshore
	Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (CACNARE)	- Convention that allows for signatories to request assistance from the IAEA or other nations if there is a nuclear accident or radiological emergencies	- Directly applicable to marine nuclear systems	- There are no references to the marine or maritime industry	- Act not specific to onshore reactors so could be applied offshore
	Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (Joint Convention),	- Convention to address the issue of spent fuel and radioactive waste on an international scale - Establishes a peer review system for spent fuel management	- -Directly applicable to marine nuclear systems	- There are no references to the marine or maritime industry	- Act not specific to onshore reactors so could be applied offshore

Appendix X – Development of Nuclear Technology and An Inventory of Nuclear-Powered Vessels

1. Classification based on design generation over time

Nuclear power plants have evolved significantly over time, with their designs categorised into four distinct generations:

Gen I (1950s–1970s): The Dawn of Nuclear Power. These initial reactors were experimental – proofs-of-concept that paved the way for civilian nuclear energy production. While not always commercially focused, these prototypes were essential for demonstrating the potential of harnessing the atom.

Gen II (1960s–1990s): Commercialisation and Reliability. This generation marked a shift towards economic viability. Dominant designs include PWRs, known for their dependable operation; BWRs, prised for their relative simplicity; and advanced gas-cooled reactors, utilizing graphite as a moderator. Gen II plants established nuclear energy as a reliable power source.

Gen III / III+ (1990s–2020s): Safety and Innovation. Building upon Gen II successes, these reactors incorporate significant safety enhancements, greater fuel efficiency, and streamlined construction processes. This includes evolutionary improvements in existing technologies and advances like the AP1000 reactor, with its passive safety systems.

Gen IV (2030 and beyond): The Future is Now. A collaborative global effort, the Generation IV International Forum (GIF) leads the advancement of these groundbreaking reactor concepts. The goal: reactors that are safer, more sustainable, produce less waste, and are resistant to proliferation. Six technologies are in focus:

- PWR
- GFR
- LFR
- MSR
- SFR
- VHTR / HTGR

While Gen III PWRs have long provided compact, reliable power for navies, Gen IV reactors offer the potential for even more efficient operation. Higher energy outputs, greater fuel longevity, and potentially smaller reactor footprints could revolutionise maritime power systems.

2. Nuclear-Powered Vessels

Current nuclear Navy projects focus on enhancing stealth, endurance, and weapons capabilities. Projects like the US Navy's development of the '*Columbia Class*' ballistic missile submarines and the planned successor to the Virginia-class attack submarines involve cutting-edge nuclear reactors offering improvements in efficiency, safety, and power. Although not military vessels, Russia continues to lead the development of nuclear-powered icebreakers, with the '*Arktika Class*' being the latest, aimed at ensuring year-round navigation in the Arctic region.

This inventory underscores the evolving landscape of nuclear-powered vessels, highlighting the blend of technological advancement and complex challenges that define past, present, and future projects.

Military Nuclear-Powered Vessels

The USS *Nautilus* (SSN-571) is known as a revolutionary vanguard of the nuclear navy. Its commissioning in December 1954 marked a watershed moment in naval history. As the world's first operational nuclear-powered submarine, it shattered conventional notions of speed, range, and underwater endurance. Powered by its S1W light water reactor (using HEU), the *Nautilus* logged 513,000 miles over 25 years of service, all while conducting 2,500 dives.

Figure 25. USS Nautilus (Source: https://en.wikipedia.org/wiki/USS_Nautilus_(SSN-571)#/media/File:Nautiluscore.jpg)

The reactor on the USS Nautilus was light-water moderated, highly enriched in U-235 core, which allowed for a compact size. This reactor design was known as the first-generation submarine reactor S1W. The S1W was followed by the Aircraft carrier A1W reactor design used on the USS *Enterprise* (CVN-65), commissioned in 1961. The A1W plant was designed for surface ships and used two PWRs to power one ship propeller shaft through a single-geared turbine propulsion unit (Ragheb, 2011). Along with the *Enterprise*, the USS *Long Beach* (CGN-9), the first nuclear-powered cruiser, was commissioned into service in 1961. There was a total of nine nuclear-powered cruisers, all using PWRs, which are shown in Table 19. All nine ships were decommissioned in the 1990s (O'Rourke, 2008).

The nuclear-powered cruisers were decommissioned because of their higher cost, higher demands for strict training, and larger size in comparison to traditional cruisers. Other designs were considered for marine propulsion in the US Navy but were eventually phased out in an effort to standardise the nuclear navy.

Table 19. Previous US Navy nuclear-powered cruises (O'Rourke, 2008).

Hull Number	Name	Entered Service	Decommissioned
CGN-9	Long Beach	1961	1995
CGN-25	Bainbridge	1962	1996
CGN-35	Truxton	1967	1995
CGN-36	California	1974	1999
CGN-37	South Carolina	1975	1999
CGN-38	Virginia	1976	1994
CGN-39	Texas	1977	1993
CGN-40	Mississippi	1978	1997
CGN-41	Arkansas	1980	1998

General Electric Company's S1G Intermediate Flux Beryllium Sodium Cooled Reactor was the first liquid metal reactor developed for use on a US submarine. In the first two years of operation, The NS Seawolf submarine initially used this sodium cooled reactor, which was replaced in 1959 by a PWR to standardise the fleet.

Today, nuclear power is used primarily for submarine fleets, while only the US and France operate nuclear-powered aircraft carriers, and the Russian Navy operates a nuclear-powered battle cruiser. Current Naval uses of nuclear power are listed in Table 20. Arrangements are underway for the Australian Navy to acquire nuclear-powered submarines from the US and grow their nuclear Navy out into the 2030's and 2040s (US White House Briefing Room, 2023).

Table 20. Current naval use of nuclear power

US Navy	• 73 Submarines (55 Attack, 18 Ballistic/ Guided Missile) • 11 Aircraft Carriers
Russian Navy	• 21 Submarines (13 Attack, 8 Ballistic/ Cruise Missile) • 1 Battlecruiser
China	• 14 Submarines (9 Attack, 5 Ballistic)
British Navy	• 10 Submarines (6 Attack, 4 Ballistic)
France	• 9 Submarines (5 Attack, 4 Ballistic) • 1 Aircraft Carrier
Indian Navy	• 1 Submarine

The *NS Savannah* was a nuclear merchant vessel built in 1959 by the US Navy meant to as a national showpiece, carrying both cargo and passengers and not expected to be highly profitable. It represented the peaceful uses of nuclear power and demonstrated the US's innovative goals. The 22,000-ton Savannah was powered by a 74 MWe low enriched uranium (LEU) PWR and was very popular for giving tours of its engineering spaces during port calls [Ragheb, 2011]. The reactor occupied the centre of the ship and required a clear overhead for overhead crane refuelling. The ship was retired in 1970 because of its limited need and role.

Just a few years later, in 1968, Germany commissioned the *Otto Hahn* cargo ship and research facility, with a total weight of 15,000 tons. It successfully completed 126 voyages, covering around 650,000 nautical miles over a period of 10 years while visiting 33 ports in 22 nations and having transported 750,000 tons of cargo, all without facing any technical difficulties. However, due to high operational costs, the decision was made to convert its propulsion system to diesel in 1982 (Hirdaris, et al., 2014; Marcus & Mirsky, 2021).

The 8,000-ton Japanese *NS Mutsu* was the third civilian vessel put into service in 1972. The ship was supposed to perform its first test run at the pier in Ōminato, however, local protests led to change in the program, forcing the officials to test the ship in the open ocean. In 1974, a small deficiency in shielding allowing neutrons and gamma rays to escape was identified. Despite no significant radiation exposure, it evolved into a political matter, with local fishermen preventing her from returning to port for over 50 days. According to (Ishida, et al., 1993), *NS Mutsu* was removed from service in 1995 due to technical, commercial, and political pressures.

Sevmorput, a Russian nuclear-powered cargo ship, is the only merchant vessel that is still in service. The ship powered by a single KLT-40 reactor with the power of 135 MWt was put into service in 1989. The reactor core contains 150.7 kilograms of 30-40 percent enriched uranium (Diakov, Dmitriev, Kang, Shuvayev, & von Hippel, 2006). Upon commencing merchant service, the Sevmorput sailed toward the Soviet Far East by passing through the Mediterranean and around Africa. However, it was denied docking at Nakhodka, Vostochny, Magadan and Vladivostok due to protests. The workers also refused to load/unload the ship out of concern for potential radiation leaks stemmed from the Chernobyl disaster just a few years earlier. The vessel primarily operated along the Murmansk-Dudinka route, with several voyages to Vietnam during the early 1990s. The Sevmorput was in service until 2007. It went through a two-year refit and refuelling of the reactor before putting again into service in November 2015. Ever since, it has primarily been chartered by the Russian Ministry of Defence for the transportation of cargo linked to the enhancement of military infrastructure in the Arctic region.

Contrary to the *NS Savannah*, Russian Nuclear Ice Breakers have proven successful since they can operate for long periods without refuelling, have high power levels for breaking ice up to 3-m thick, and can stimulate the economy by opening up trade routes. After the introduction of the '*Lenin* Class' in 1959, a series of larger icebreakers known as the 23,500 DWT '*Arktika Class'* ships were launched in 1975. These robust vessels were equipped with two 171 MWt OK-900 reactors, providing 54 MW at the propellers, and are still in use today in the deep Arctic waters. The *Arktika* was the first surface ship to reach the North Pole. *Taymyr* is a nuclear-powered icebreaker with a shallow draft commissioned in 1989 and is still in service. It is the first of two similar vessels that are powered by a single 171 MWt KLT-40M reactor.

Table 21. Some key characteristics of merchant nuclear ships

Ship name	Vessel type	Country	Reactor type	Output (MW)	Commissioned	Decommissioned
Savannah	Cargo	USA	PWR × 1	80	1962	1977
Otto Hahn	Ore Carrier cargo-passenger	Germany	FDR × 1	38	1968	1982
Mutsu	Container	Japan	PWR × 1	36	1972	1996
Lenin	Icebreaker	Russia	PWR × 2	159 × 2	1959	1989
Arktika	Icebreaker	Russia	OK-900A × 2	171 × 2	1975	In service
Sovetski Souz	Icebreaker	Russia	OK-900A × 2	171 × 2	1989	2014
Let Pobedy	Icebreaker	Russia	OK-900A × 2	171 × 2	2007	In service
Vaygach	Icebreaker	Russia	KLT-40M × 1	171	1989	In service
Taimyr	Icebreaker	Russia	KLT-40M × 1	171	1989	In service
Sevmorput	Cargo	Russia	KLT-40M × 1	135	1988	In service

The Sturgis is a floating nuclear power plant which is different from the above-mentioned ships as it did not use nuclear power for propulsion. The Sturgis was a barge designed as a source of power in coastal areas, particularly for remote locations. The US Army used a Liberty ship, the *SS Charles H. Cugle*, as its platform. The propulsion equipment of the ship was removed and a 45 MWt, 10 MWe, LEU PWR was installed. The *Sturgis* was used to supply power on the Gatun Lake in way of the Panama Canal from 1968 to 1975, due to a severe drought in Panama (Hirdaris, et al., 2014; Marcus & Mirsky, 2021). The *Sturgis* was also used during the Vietnam War to provide additional power to the region enabling the passage of several thousands of US military ships. It was returned to the US in 1976-1977 for decommissioning, as the Army realised that further operation of the Sturgis was impractical. The *Sturgis* was the only FNNP in the world until 2019. In December 2019, the Russian 70 MWe *Akademik Lomonosov*, a FNNP, started its operation by supplying power in the port of Pevek, Chukotka, Russia.

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