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Nuclear propulsion for merchant ships: a path to sustainable maritime energy

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ABSTRACT

This study critically assesses the potential of nuclear propulsion, particularly small modular reactors (SMRs), as a transformative solution for decarbonizing merchant shipping. Combining high power density, long endurance, operational speed, and near-zero greenhouse gas emissions, SMR-powered vessels could deliver major efficiency gains and long-term cost stability. Drawing from historical experiences and recent innovations, the analysis evaluates technical performance, environmental impact, and socio-economic feasibility. Key adoption barriers include high capital investment, complex operational demands, and persistent safety concerns. Comparative energy system analyses and experimental insights highlight the necessity of rigorous regulatory oversight, robust safety culture, and public trust. The study identifies a collaborative funding model involving government, academia, non-profits, and defense sectors as critical for early deployment. It advocates for a unified international governance framework to ensure safe navigation, environmental protection, and equitable liability positioning nuclear propulsion as a promising yet challenging pathway to sustainable maritime operations.

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Nuclear powered vessels; emission control; marine vessels

Introduction

Overview

More than 80% of global goods are transported by sea (Zis et al. 2020; Li, Liu, and Wang 2022), making shipping the cornerstone of international trade. The interconnectedness of global trade, national prosperity, and economic growth relies heavily on an efficient and secure maritime sector (Xing et al. 2021). With growing global concerns over pollution and climate change, the maritime industry which known for its environmental impact, now faces the urgent challenge of drastically cutting and ultimately eliminating greenhouse gas (GHG) emissions. Over the past decade, the International Maritime Organization (IMO) has implemented ambitious strategies to reduce GHG emissions from maritime transport. One of the key targets set by the IMO is to cut carbon emissions by at least 40% by 2030, compared to 2008 levels and net-zero emissions by 2050 (T. I. M. Organization, 2018; IMO 2022; The International Maritime Organization 2023). In response to these regulations and to achieve CO_2 emission reductions, various alternative energy sources such as solar, wind, biofuels, and natural gas have been explored. Among potential solutions, nuclear power stands out as the only technology capable of meeting these goals (Hansson et al. 2020; T. I. M. Organization 2021; International Maritime Organzation n.d.). Nuclear-powered ships offer a cleaner and more sustainable alternative to conventional fossil fuel-powered vessels by significantly reducing greenhouse gas emissions and air pollutants (You and Lee 2022; Liu et al. 2024). Additionally, adopting nuclear energy for ship propulsion eliminates the risk of maritime oil spills, which remain a persistent environmental concern (Freire and Andrade 2015). This technology is particularly advantageous for vessels that spend extended periods at sea, as it eliminates the need for frequent refueling while ensuring carbon-free energy production. Although nuclear energy for commercial vessels has yet to be extensively

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studied and evaluated, notable advancements have been made in its application at land-based facilities (Anh et al. 2023; Duong et al. 2023).

However, the viability of nuclear power at sea has been demonstrated, with over 700 reactors successfully operating in the harsh conditions of the world's oceans (Parker 2013). Naval reactors have demonstrated superior operational reliability compared to conventional diesel engines. Additionally, nuclear propulsion offers greater design flexibility due to the compact nature of nuclear reactors, which require significantly less space than traditional fuel systems (Carlton, Smart, and Jenkins 2011). The reduced need for refueling further enhances the operational flexibility of nuclear-powered vessels, allowing for extended voyages with minimal logistical constraints. Among various reactor types, pressurized water reactors (PWRs) have emerged as the most successful, favored for their simplicity, safety, and compact design. These attributes make nuclear propulsion particularly appealing for merchant ships, as it maximizes cargo capacity by freeing up valuable space that would otherwise be allocated for fuel storage. Despite this, no nuclear-powered commercial vessels are currently in service due to existing reactor technologies being unsuitable for civilian maritime applications. To overcome this, new technologies must be developed, and the regulatory framework must be updated to accommodate these advancements.

For nuclear power to be a feasible option for shipping, new technologies must meet some essential criteria (Pieroni, Facer, and International Atomic Energy 2006; IAEA 2014; Bhattacharyya, El-Emam, and Khalid 2023):

- The emergency planning zone around the reactor should be minimal, ideally confined within the ship's hull, making commercial insurance possible and allowing ships to dock at ports.
- The nuclear power system must be inherently safe, with passive safety mechanisms that meet or exceed the highest international standards for security and safeguards.
- Nuclear propulsion that satisfies these criteria could revolutionize large-scale maritime transport. According to the Fourth IMO GHG Study (2020), over 12,500 ships including container ships, tankers, bulk carriers, cruise ships, and refrigerated vessels could benefit from adopting nuclear propulsion.

Researchers have examined the potential of nuclear energy for various ship types, including ultra-large ore carriers, container ships, icebreakers, and tankers (Namikawa et al. 2011; Hirdaris et al. 2014). Nuclear propulsion has proven particularly beneficial for icebreakers, addressing challenges such as limited fuel availability, high power requirements, and extended operations in Arctic regions (Khlopkin and Zotov 1997).

Nuclear as marine fuel

According to the IMO, the shipping industry currently contributes between 2.7% and 3.3% of global CO_2 emissions annually. This figure positions the shipping sector as the sixth largest contributor to anthropogenic emissions when compared to individual countries. If no measures are taken to address this issue, emissions could rise significantly, potentially reaching between 12% and 18% of the total allowable CO_2-induced greenhouse gas emissions under the International Energy Agency's 450 ppm stabilization scenario by 2050 (IPCC 2023). This suggests that, compared to 2007 levels, emissions from shipping may increase by 6% to 22% (925–1058 Mt of CO_2) by 2020, and by 119% to 204% (1903–2648 Mt of CO_2) by 2050 (Wang et al. 2021; Lee 2022).

Medium- to long-term solutions indicate that hydrogen still encounters barriers to onboard implementation. In addition, no current technology can completely eliminate emissions or provide major CO_2 reductions. For example, while natural gas presents a viable option for the medium term, its success depends on the development of robust port infrastructure. Meanwhile, renewable energy sources such as solar and wind can only supplement a portion of the energy needs for oceangoing vessels and are mainly suited to auxiliary propulsion. Fuel cells, especially when powered by hydrogen, offer a highly efficient energy production method. However, limited hydrogen availability and its low volumetric energy density suggest that widespread adoption of this solution may require significant time.

With the global merchant shipping fleet boasting a total power capacity of approximately 410 GWT equivalent to about one-third of the world's nuclear power plants, the potential for implementing nuclear technology in this sector is increasingly viable. The U.S. and U.K. Navies (MNAG (Maritime Nuclear Application Group) 2022) have pioneered programs in water reclamation technologies since the 1950s, focusing on producing PWR systems. These advancements have become highly respected and specialize in branches of maritime applications. Yoo et al. (2024) conducted a study on the Passive Residual Heat Removal System (PRHRS) for nuclear-powered ships, exploring the use of seawater as an alternative heat sink to dissipate residual heat. The findings revealed that the majority of the residual heat generated by the reactor core is effectively removed through seawater cooling. This demonstrated the successful operation of the Seawater-Cooled PRHRS (SWC-PRHRS), which functions autonomously without requiring operator intervention or an external water supply, ensuring reliable heat dissipation and enhanced reactor safety. By using specialized operational procedures, these programs excel at recording safety data, which has guided the commercial maritime sector's adoption of advanced reactor technologies. However, modern naval reactors are not typically suited for civilian applications due to the stringent safety protocols required. Low-enriched uranium-fueled naval reactors would likely not be viable for broad maritime applications due to the extensive regulatory and safety requirements. Beyond the necessity to address climate change, the renewed interest in nuclear-powered vessels for the merchant marine is driven by several factors:

- Energy security which diversify fuel sources, reduce reliance on fossil fuel import/export markets, and enhance resilience against onboard power disruptions.
- Mitigating volatile fuel costs that uranium prices can help stabilize fuel costs.
- Transition to a hydrogen economy to prepare for a future hydrogen economy is essential.

Unlike hydrocarbon-based combustion, nuclear fission does not involve chemical reactions, which means it can provide energy without generating greenhouse gas emissions. As highlighted by Sathaye et al. (Sathaye et al. 2011; Nicholson and Heath 2021; Snyder 2024), the lifecycle greenhouse gas emissions from fossil fuels far exceed those associated with nuclear power. This comparison is generally applicable to most renewable energy technologies, including solar panels, though hydropower and wind-assisted technologies (like wind turbines) stand out as exceptions. The difference lies in the fact that nuclear energy, while low in direct emissions, does produce some indirect emissions across its fuel cycle. These emissions are primarily associated with the energy released during uranium fission. The main sources include the kinetic energy of fission fragments, beta and gamma radiation, and neutron release. Additional emissions also occur from auxiliary processes such as nuclear plant construction, uranium mining and milling, facility decommissioning, and the management of depleted fuel.

Nuclear-powered ships have been in operation for over 50 years, primarily within the international naval sector and the Russian icebreaker fleet. Since the launch of the first nuclear submarine, approximately 700 nuclear reactors have been utilized at sea across various vessels. While the safety records of the Russian nuclear fleet have raised some concerns (Olgaard 2001; Reistad, Hustveit, and Roudak 2008), it is estimated that the Western world, mainly led by the U.S. Navy, has accumulated more than 6,200 reactor-years of operational experience involving 526 nuclear reactor cores. Fu et al. (2022) conducted a comprehensive risk assessment of nuclear-powered icebreakers operating independently, in escort missions, and within convoys in ice-covered waters. This analysis integrated Failure Mode and Effects Analysis (FMEA) and the Functional Resonance Analysis Method (FRAM) to evaluate potential risks. The study highlighted that the Emergency Core Cooling System (ECCS) accumulators play a crucial role in supplying water to the reactor, effectively limiting core damage while cooling overheated and partially degraded core components. These safety measures ensure a stable water supply during an accident, maintaining sufficient cooling within the reactor core. As a result, they prevent the formation of a molten pool at the reactor's base, thereby mitigating the risk of core meltdown and vessel erosion. This, in turn, significantly reduces the likelihood of radioactive material release, enhancing overall reactor safety. Despite the successful deployment of traditional nuclear reactor technologies, the commercial shipping industry has largely overlooked the potential use of Small Modular Reactor (SMR) technology onboard ocean-going vessels. The SMRs are designed to produce between 10 and 300 megawatts of electrical power (MWe), while microreactors are compact systems capable of generating up to 10 MWe. Both reactor types are intended to be manufactured in a controlled factory setting using standardized designs. This approach aims to enhance cost efficiency by leveraging economies of scale and streamlining the licensing process, ultimately making nuclear energy more accessible and economically viable. In summarization, the SMRs in maritime applications can be:

- Unlike conventional ships that rely on heavy fuel oil (HFO) or marine diesel, SMRs utilize nuclear fission to produce electricity. This results in zero carbon emissions, making them a compelling solution for shipping companies seeking to minimize their environmental impact and comply with stricter emissions regulations.
- Require significantly less fuel to generate the same amount of power as traditional fossil fuel-based systems. Their long operational lifespan without the need for frequent refueling not only lowers fuel costs but also reduces port downtime, improving overall vessel efficiency.
- Designed to withstand harsh maritime conditions, SMRs offer enhanced resilience against extreme weather and operational challenges. As self-contained units, SMR eliminate the need for storing or transporting large quantities of fuel, minimizing the risk of spills, explosions, or other hazardous incidents. This makes them particularly advantageous for vessels operating in ecologically sensitive or remote regions.

Contribution of this paper

This paper opens with an overview of current nuclear propulsion technologies for commercial marine applications, followed by a summary of an industry-led consortium's work on evaluating a commercially viable design for merchant ship. The paper examines both historical and recent advancements in the field, details the core features of SMR technology, and discusses the rationale behind key design decisions. The experimental cases are also analyzed in detail to discuss the pros and cons of applying nuclear power to merchant vessels. Additionally, it briefly identifies areas for further research and development, emphasizing long-term challenges that must be addressed to integrate nuclear propulsion into commercial shipping. The risks associated with nuclear-powered cargo vessels are analyzed to propose possible solutions for risk mitigation. Furthermore, the regulatory framework is outlined and analyzed to propose solutions for the adaptation of commercial nuclear vessels.

This research offers an in-depth evaluation of nuclear propulsion as a viable energy source for commercial vessels, considering environmental, technical, and societal aspects. By comparing various alternative energy systems, it addresses critical knowledge gaps, particularly as the maritime industry strives toward carbon-neutral operations. The insights gained are highly relevant for marine engineers, naval architects, and key stakeholders, such as large shipyards and shipowners, who are exploring sustainable energy options for the future of shipping.

Materials and methods

Nuclear powered vessels from literature

As of 2025, there are limited nuclear-powered merchant ships in regular commercial operation. While several nuclear-powered ships have been built, including icebreakers and submarines for naval or specialized purposes, the use of nuclear power in commercial shipping remains highly limited due to economic, regulatory, and public perception challenges. The NS Savannah (U.S. Department of Transportation Maritime Administration 2017) (United States), Mutsu (SASAKI 1969) (Japan), Otto Hahn (Rogan et al. 2008) (Germany) and Sevmorput (Rissanen et al. 1996) (Russia) were among the few nuclear-powered merchant ships ever constructed. To date, four nuclear-powered merchant ships have been constructed, all initiated as government-led projects. These vessels were primarily developed for research and technological demonstration rather than for purely commercial operations. Only Russia's Sevmorput, a nuclear-powered container ship and icebreaker (The Monterey Institute of International

Studies 1998; Sokov 2001), is occasionally used in Arctic routes, but it is an exception rather than part of mainstream commercial shipping. Most nuclear-powered vessels today are military submarines or Russian icebreakers, primarily operating in the Arctic. Nuclear-powered icebreakers offer significant technical and economic advantages over their fossil fuel-driven counterparts, particularly in polar operations. These advanced vessels can break through ice up to three meters thick and operate continuously for several months without requiring refueling. This extended endurance allows for prolonged navigation along the Northern Sea route, keeping it accessible for up to ten months each year. Nuclear propulsion has proven indispensable for operations in the Russian Arctic, where extreme conditions exceed the limits of traditional icebreakers. Nuclear-powered ships are uniquely suited to these harsh environments, as it can break through ice up to 3 meters thick and operate without the logistical complications of frequent refueling. This capability has extended Arctic navigation from just two months to ten months annually and enables year-round operation in the Western Arctic.

The icebreaker Lenin (Polunichev 1994), the world's first nuclear-powered surface vessel (20,000 DWT), led the way in Arctic navigation (Prishchepa 2019), operating for 30 years and receiving new reactors in 1970. Following its success, Russia introduced a fleet of larger vessels, including six 23,500DWT Arktika-class icebreakers, starting in 1975 (Energy Futures Initiative 2017). These robust ships, powered by dual reactors that generate 56 MW at the propellers, are deployed in the deep Arctic waters. The Arktika, notably, became the first surface ship to reach the North Pole in 1977, marking a significant milestone in polar exploration.

A preliminary search on ScienceDirect was conducted to investigate research and publications focused on nuclear-powered vessels for merchant shipping. Three distinct keyword searches were performed: 'nuclear powered merchant ship,' 'nuclear cargo vessels,' and 'commercial maritime nuclear reactor.' The first search resulted in 1,015 hits, the second in 7,768, and the third in 1,113, demonstrating a substantial body of research on the subject. Furthermore, a noticeable upward trend in the number of publications is evident, with research output progressively increasing over time. Figure 1 illustrates the annual growth in research activity related to nuclear-powered vessels, spanning from 2001 to 2025. This increasing interest underscores the growing recognition of nuclear power as a viable energy source for merchant ships.

The significant rise in research over the years highlights the growing need to explore nuclear-powered energy for cargo vessels as a potential alternative to traditional fuel sources in the future. This trend reflects a heightened awareness of the importance of adopting new energy solutions to meet global environmental standards and reduce reliance on fossil fuels. Analyzing publication trends reveals that nuclear-powered vessels are gaining substantial attention. This review offers valuable insights into the evolving field of nuclear-powered research and its potential role in advancing sustainable energy technologies.

The nuclear reactor is typically situated centrally within the ship's structure. In this design, the propulsion system is positioned at a considerable distance from the reactor, making mechanical propulsion less suitable. The thermal power necessary for the nuclear reactor is calculated based on the propulsion power of a reference vessel. Nuclear marine propulsion utilizes a nuclear reactor to generate the heat

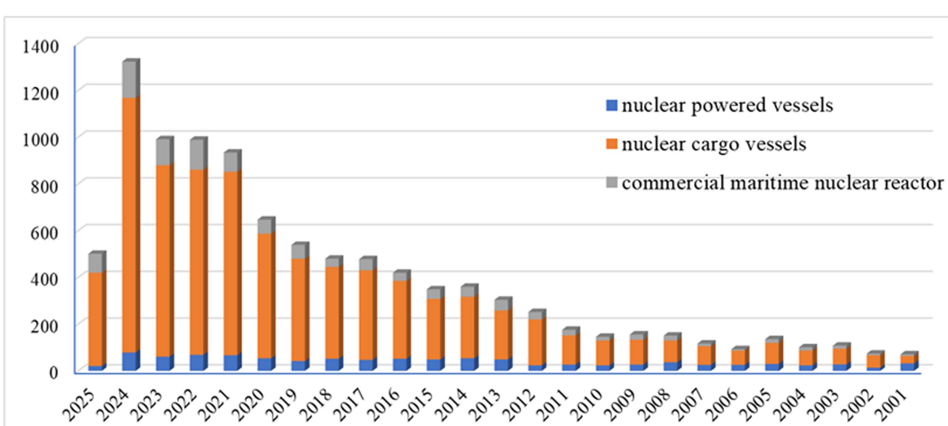

Figure 1. Number of studies related to nuclear powered merchant ship.

required for powering a ship. Fundamentally, the reactor heats water to produce steam, which drives a turbine. This turbine then transmits power to the ship's propeller either via a gearbox or through an electric generator and motor system (Figure 2).

A nuclear reactor is a core device which designed to initiate and control a sustained nuclear chain reaction. Nuclear reactors are commonly categorized based on several key factors (Kiesinger 2019):

- Type of nuclear reaction: for example, fission or fusion;
- Moderator material: such as graphite, water, or none;
- Coolant type: options include water, liquid metal, gas, or molten salt;
- Application: for example, electricity generation, marine propulsion, neutron radiation sources, or research purposes; and
- Technology generation: spanning from Generation I to Generation IV systems.

The global merchant shipping fleet has a combined power capacity of approximately 410 GWT, which is about one-third of the total capacity of the world's nuclear power plants. This comparison makes the exploration of nuclear technology integration in the maritime sector a plausible consideration. In addition to addressing climate change, the renewed interest in nuclear-powered vessels for merchant shipping is influenced by several other driving factors:

- Reduce reliance on the fossil fuel import/export market, and enhance resistance to power disruptions aboard ships.
- Less sensitive to fluctuations in uranium prices compared to fossil fuels.
- Preparing for the transition to green shipping economy.

Unlike hydrocarbon-fueled combustion, nuclear fission involves no chemical reactions, offering a potential source of energy that is free from greenhouse gas emissions.

This observation also applies to most renewable energy technologies, such as photovoltaic systems, with the notable exceptions of hydropower and wind-based technologies like wind turbines. The key difference is that the nuclear fuel cycle is not entirely emission-free. During uranium fission, various forms of energy are released, including the kinetic energy of charged fission fragments, beta and gamma radiation, as well as neutron energy (Lamarsh and Baratta 2012). Additional emissions may occur during various stages, including the construction of nuclear plants, uranium mining and milling, plant decommissioning, and the depletion of fuel.

Supercritical water-cooled reactors (SCWRs) (Figure 3) have emerged globally in recent decades as a promising advancement in nuclear technology by its numerous advantages. The main advantages can be listed up as significantly higher thermal efficiency with approximately 45% (Naidin 2009) compared to the 33% typical of current light water reactors. SCWRs (Schulenberg et al. 2005) also feature a relatively simple

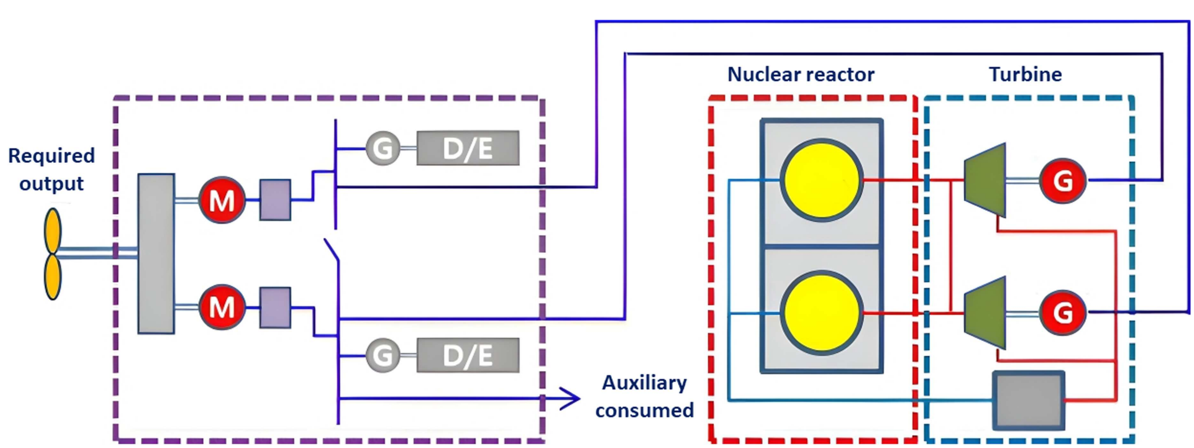

Figure 2. An example of schematic diagram of nuclear-powered vessel for merchant ship.

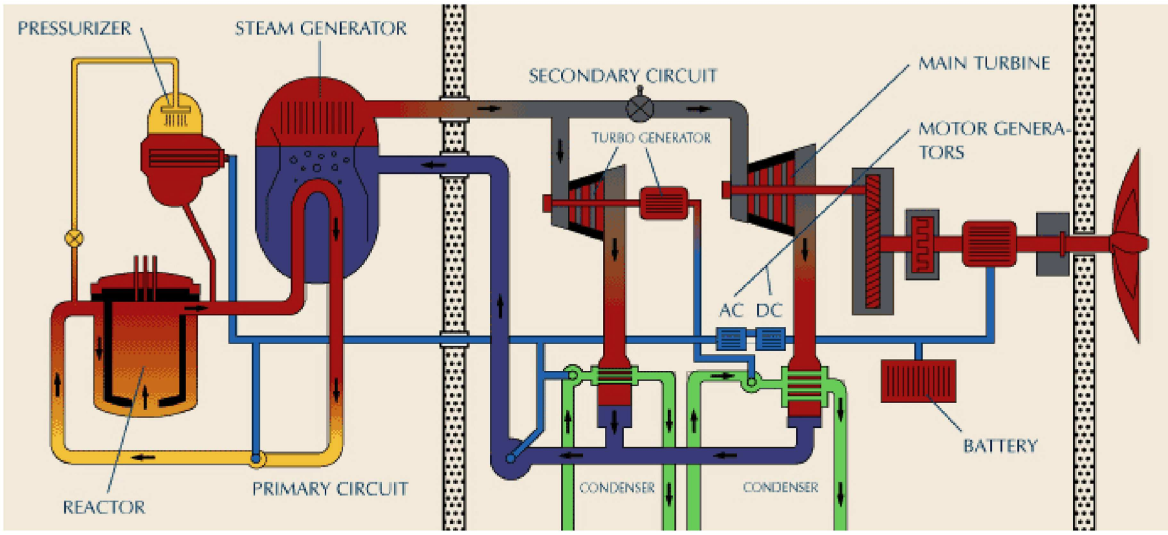

Figure 3. Typical pressurized water reactor technology (Rahman et al. 2020).

plant design and high-power density, which can streamline construction, reduce investment costs, and ultimately enhance reactor economics.

SCWR designs are generally divided into two main types (Schulenberg and Leung 2023): (i) the pressure-vessel type and (ii) the pressure-tube type. The pressure-vessel concept was initially introduced in Japan and later adopted by the Euratom partnership. Meanwhile, the pressure-tube concept, known as the Canadian SCWR, was first proposed by Canada. Although these two designs differ in structure, they share several key characteristics, such as external pressure and temperature ranges, steam cycle selection, material properties, and heat transfer features (Boungiorno 2003).

Thus, the standard marine nuclear propulsion system typically employs a PWR with two main circuits: the primary loop and the secondary loop. In the primary loop, pressurized water flows through the reactor core, circulating via pumps and pipelines and passing through steam generators, along with other systems designed for safe operation. The secondary loop, separate from the primary, channels steam generated by the steam generator to power the ship's turbine generator. This steam drives the primary propulsion turbine, which, in turn, rotates the propeller. Once the steam exits the turbine, it condenses back into water and is pumped by a feed pump to the steam generator, ready for recirculation.

In the primary circuit of a PWR based marine nuclear power plant, high-temperature, high-pressure water functions simultaneously as the reactor coolant and neutron moderator. Circulated by the main pump, the coolant enters the reactor core, where it absorbs the thermal energy released from nuclear fission. The heated water then exits the core and passes through the U-shaped tubes of the steam generator (primary side), where it transfers its energy to the feedwater in the secondary loop, which flows outside the tubes (secondary side). After relinquishing its heat, the primary coolant is re-pressurized by the main pump and redirected back into the core, allowing the process to repeat. This continuous circulation establishes a closed-cycle system, which is fundamental to the safe and efficient operation of marine nuclear propulsion.

In the secondary circuit of a PWR-based nuclear power plant, heat from the steam generator is utilized to produce steam. This steam converts thermal energy into mechanical and electrical power. The secondary system consists of both main and auxiliary steam turbines, along with the secondary section of the steam generator. It also includes essential support systems and equipment designed to ensure safe operation under both normal and fault conditions.

The main steam turbine serves as the central element of the power cycle. Steam produced in the evaporator exits from its upper section and is directed through the main steam pipe into the turbine's high-pressure cylinder, passing sequentially through the main valve and control valve that regulate its flow and drive the turbine blades. After expansion in the high-pressure stage, the partially expanded steam is routed through an intermediate steam–water separator and then enters the low-pressure cylinder, where it delivers additional mechanical work. After leaving the turbine, the exhaust steam flows into the condenser. In this unit, it is cooled by circulating water and condensed back into liquid form. The condensate is then pumped to a low-pressure heater, where it is gradually warmed and deaerated. Next, it passes through a high-pressure heater for further heating. Finally, the heated water is returned to the steam generator as feedwater, completing the closed cycle.

Kang, Lee, and Lim (2024) conducted research on SMRs as carbon-neutral energy solutions to address the intermittent nature of renewable energy, particularly in South Korea. The study highlighted that the SMART reactor integrates advanced design features aimed at improving safety, reliability, and economic viability. Throughout the standard design approval process, the detailed design was finalized with these innovative features, and key technologies underwent validation. The reactor's design incorporates inherent safety mechanisms and passive safety systems to further enhance operational safety and dependability.

The SMART reactor core (Figure 4) consists of 57 fuel assemblies, designed based on the well-established 17×17 fuel array utilized in commercial PWRs. These assemblies contain uranium dioxide (UO_2) ceramic fuel rods, ensuring reliable performance. The reactor employs slightly enriched uranium

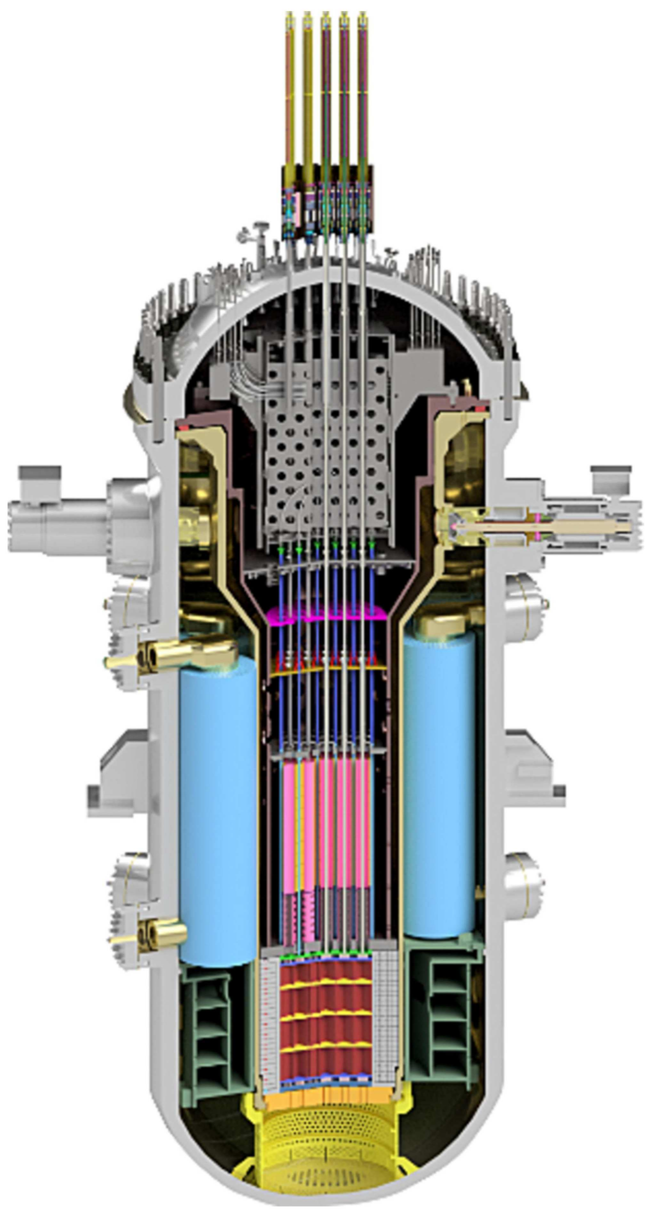

Figure 4. SMART reactor (Kang, Lee, and Lim 2024).

oxide with an enrichment level below 5.0 weight percent, supplying the necessary reactivity to support a continuous operational cycle of 30 months.

In nuclear-powered icebreakers, a compact integrated layout is frequently adopted, wherein all major components of the reactor coolant system, along with their connecting pipelines, are contained within the reactor pressure vessel. In this configuration, the entire primary circuit operates inside the vessel, incorporating the reactor core, control rod assemblies, steam generators, main circulation pumps, and pressurizing units. Such integration not only streamlines the flow path of the primary loop but also enhances the system's inherent safety characteristics. Within the secondary circuit, feedwater absorbs heat from the high-temperature, pressurized coolant in the primary loop as it passes through the secondary side of the steam generator (evaporator), generating saturated steam that is subsequently directed to drive the turbines.

Naval reactors are designed to be highly compact, with cores that feature exceptionally high power densities (Rechard et al. 1996). These cores typically occupy about 1 cubic meter of space and can generate power densities of up to 200 MW per cubic meter. To handle such significant power output, effective heat removal from the core is critical. This is typically achieved by maximizing the heat transfer surface area, or in some cases, by using liquid metal as a coolant instead of water. The adoption of water-cooled and water-moderated reactors was a key milestone in the advancement of this technology in the Soviet Union (Gladkov 1993). Before this breakthrough, various reactor designs, including those using graphite moderation, had been extensively tested.

Experimental trials and full-scale vessel tests have been conducted to evaluate the feasibility of nuclear-powered merchant ships (see Table 1). Efforts to develop these ships began in the 1950s, but the concept has yet to achieve commercial viability. The NS Savannah U.S.-built with 22,000 tons vessel launched in 1962, operated for only eight years. Despite its technical success, the ship proved economically impractical; its 74 MW reactor generated 16.4 MW for propulsion. Germany's Otto Hahn, a 15,000 tons cargo ship and research vessel, logged 650,000 nautical miles over 126 voyages without any technical issues. Powered by a 36 MW reactor that delivered 8 MW to the propeller, it was converted to diesel in 1982 due to high operational costs. Japan's 8,000 tons Mutsu, introduced in 1970 with a 36 MW reactor providing 8 MW to the propeller, encountered substantial technical and political obstacles and was ultimately deemed unsuccessful. All three ships used reactors fueled with low-enriched uranium (3.7–4.4% U_{-235}).

In 1988, Russia introduced the NS Sevmorput, a 61,900 tons vessel equipped for both cargo and ice-breaking operations, powered by a KLT-40 reactor, the same model used in large icebreakers providing 30 MW to the propeller from a 135 MW reactor. By 2003, it had only required a single refueling. Russian Arctic nuclear vessels, by this time, had amassed over 250 reactor-years of operational experience. Plans were also underway for a new, more powerful 110 MW icebreaker with a 55,600 DWT capacity, as well as dual-draft icebreakers with a capacity of 32,400 DWT and 60 MW output at the propellers.

Nuclear-powered propulsion systems offer a promising future option for specific segments of ocean shipping (Eide, Chryssakis, and Endresen 2013), with the potential to significantly reduce air emissions and enable faster transport of high-value cargoes (Hirdaris et al. 2014).

While some naval nuclear reactor programs were motivated by ambitious visions and long-term strategic benefits, their sustained development has ultimately depended on economic viability. During operation, thermal cracking was observed in several critical components, including the piping connecting the reactor to the pressurizers, the internal headers supplying purified water to the reactor coolant pumps, and the internal shells of pump flow chambers. These issues necessitated extensive analytical and experimental investigations of propulsion and test reactor systems, with particular emphasis on monitoring thermal and mechanical strain parameters. Corrosion-related degradation was also reported, often associated with deviations from prescribed primary water chemistry conditions. For instance, excessive salt concentrations in steam-generator feedwater were linked to failures in certain steam-generating tubes and other associated components. Furthermore, cumulative radiation exposure progressively increased the force required to actuate reactivity control mechanisms by the end of the reactor's designed service life. Operational experience additionally demonstrated that abrupt pressure fluctuations in the primary circuit could damage semi-enclosed internal structures not originally engineered to withstand full coolant pressures, as exemplified by the failure of a partition within the reactor coolant pump of an icebreaker.

Table 1. List of typical experiment on nuclear vessel.

No.	Reference	Time	Country	Ship name	Type	Fuel element	Power output (MW)	Target	Limitation	Insights gained
1.	(Vessel 1991; Seaborg et al. 1968)	1962 – 1972	USA	Savannah (21,800 tons, cargo capacity of 10,000 tons and 60 passengers)	Container	Nuclear containment with length of 15.24m and diameter of 10.67m	80	A test vessel and research laboratory were utilized to examine the design, functioning, and crew requirements of nuclear systems for maritime application.	- Faced challenges related to the generation of large volumes of radioactive waste. However, this issue was effectively addressed through minor modifications to the system, ensuring improved waste management and operational efficiency. -Due to the significant cost associated with its construction and operation, the vessel was decommissioned after just ten years of service.	- Low enrichment uranium is employed; - Fuel rods is used; - Effective management becomes increasingly challenging when multiple enterprises are involved in the design process, particularly at critical interface points, where coordination issues are often amplified.
2.	(Freire and Andrade 2015)	1962	Germany	Otto Hahn	Ore Carrier	Core include 12 square, 4 corner fuel elements. The corner element includes 12 fuel pins, 2 fuel pin with UB4	38	A research vessel is specifically designed to gather valuable insights and operational experience for the development of future nuclear-powered transport ships. Its primary objective is to test and refine the technologies, safety protocols, and operational procedures necessary for the successful integration of nuclear propulsion systems in commercial shipping.	- primarily served as demonstrators of nuclear propulsion technology; however, their development overlooked economic feasibility, including operational and capital costs. As a result, despite achieving technical success, they were ultimately abandoned when decision-makers at the time deemed discontinuing the projects to be more financially advantageous. - Despite being technically sound, the Otto Hahn encountered limitations in its operational routes due to regulatory challenges. For instance, it was barred from entering certain ports due to concerns about nuclear	- The completed guidelines on building and operation of nuclear-powered merchant vessels should be established. - Military institutions and universities tend to receive greater recognition and credibility compared to private enterprises. As a result, forming a joint venture that integrates military expertise, academic research, and commercial interests may be challenging but offers a stable and strategic path forward.

Table 1. (*Continued*)

No.	Reference	Time	Country	Ship name	Type	Fuel element	Power output (MW)	Target	Limitation	Insights gained
									safety. Given the high operating costs, the ship's nuclear reactors were eventually removed in 1979.	
3.	(Khlopkin and Zotov 1997)	1988	Sevmorput	Soviet Union	Icebreaker	Cluster type, 5.8 mm of outer diameter, 53 fuel pin, core of heat transfer is 233 m (Li, Liu, and Wang 2022)	135	A nuclear-powered Lighter Aboard Ship (LASH) vessel is designed for cargo transport and icebreaking operations in remote Arctic regions, combining the ability to handle containerized freight with the capability to navigate through thick ice-covered waters	Major nuclear disasters, such as the Chernobyl incident, fueled public opposition to nuclear-powered vessels. As a result, the NS Sevmorput faced protests and resistance when attempting to dock at certain ports.	equipped with a third-generation naval reactor developed in the former Soviet Union, stands as the only nuclear-powered merchant ship to achieve economic success.
4.	(Nakao 1974)	1972	Japan	Mutsu	Cargo	Fuel composed 112 fuel rods and 9 burnable poison rods. The fuel rod with length of 1040 mm and diameter of 10.53 mm	36	A prototype nuclear-powered commercial vessel is being developed to transport specialized cargo while also serving as a platform for crew training in the operation of nuclear propulsion systems	- Encountered significant interface management challenges due to the design and construction being contracted to two separate companies, leading to coordination difficulties and integration issues. -Due to the technical and political challenges it faced, the reactor aboard the Mutsu was deactivated in 1992. The vessel was then repurposed as an ocean observation ship, powered by diesel engines	The media plays a crucial role in shaping public acceptance, with public perception often influenced by the perceived benefits any added risks should be offset by clear advantages. It is essential to highlight the tangible benefits of nuclear energy to the public while minimizing misinformation through effective education and outreach.

Overall, while nuclear cargo vessels have demonstrated feasibility in niche settings, the economic, logistical, and public perception challenges encountered by the NS Savannah, Otto Hahn, and Mutsu illustrate the broader obstacles to widespread commercial viability. The Sevmorput's enduring performance suggests that nuclear-powered vessels may hold value in specific roles, particularly where harsh environments justify the added infrastructure and regulatory requirements of nuclear technology in maritime operations. The nuclear-powered cargo vessels may hold promise in specialized roles, such as Arctic shipping, but face substantial barriers to broad commercial adoption due to operational costs, complex regulations, and societal concerns surrounding nuclear energy. In conclusion, nuclear-powered reactors can sustain energy production for up to 10 to 20 years, enabling merchant vessels to operate for extended periods without the need for refueling. Additionally, uranium used in conventional light water reactors contains approximately 156,000 times the energy of coal, making it an exceptionally dense energy source. This high energy density eliminates the need for large fuel storage, allowing ships to travel faster and allocate more space for cargo. One of the key advantages of nuclear propulsion is its lack of greenhouse gas emissions, which can significantly reduce the maritime industry's environmental impact. Currently, shipping contributes approximately 2.7% of global carbon dioxide emissions, 4–9% of sulfur oxides, and 15% of nitrogen oxides. Nuclear-powered vessels have been proposed as a viable alternative to mitigate these emissions and enhance sustainability in maritime transport. However, the widespread adoption of nuclear propulsion in merchant shipping faces significant challenges. The high economic costs associated with nuclear-powered vessels, along with concerns about operational safety, hinder their implementation. In the event of a collision or technical failure, nuclear-powered ships could pose severe risks, including potential radiation leaks that may endanger crew members and harm marine ecosystems. These safety and economic concerns have so far limited the feasibility of nuclear propulsion in commercial shipping.

Risk associate to nuclear-powered vessels

Before uranium can be used in a nuclear reactor (CEA 2016), it must go through several stages, including mining, milling, conversion, enrichment, and fuel fabrication. These processes form the 'front-end' of the nuclear fuel cycle. Unirradiated uranium fuel emits very low levels of radiation (Chaplin 2015), with potential exposure risks primarily affecting individuals directly involved in the front-end activities, such as mining and processing, or during the placement of fresh fuel into the reactor core. Risk mitigation (Nuclear Regulatory Commission 2008) generally follows standard safety protocols outlined in domestic occupational health regulations. However, a notable gap exists: fissile material used for non-military purposes, such as naval propulsion, is exempt from international safeguards. This creates a potential area of concern that must be addressed.

Nuclear safety risks during the operation of a vessel can arise from two primary scenarios:

- The crew may be exposed to radiation due to an internal incident, such as a reactor malfunction.
- The crew may be exposed to radiation from external events, like grounding, collisions, or missile attacks, which could lead to reactor issues and the release of radioactive materials.

The European Maritime Safety Agency (EMSA) (Maritime and Agency 2024) has identified key concerns in the maritime sector, including regulatory gaps and oversight, flooding, vessel sinking, capsizing, collisions, grounding, improper maintenance and training, technological licensing, and compliance with non-proliferation treaty requirements. Additionally, EMSA highlights external risks such as piracy, hijacking, terrorist attacks, and other security threats. It also addresses deficiencies in shipyard licensing, technical capabilities, and the effectiveness of regulatory frameworks in maritime operations. A major focus is placed on variations in maritime practices and their impact on nuclear reactor safety, material handling, and regulatory enforcement. These challenges require further study to enhance risk assessment and develop additional safeguards for mitigating key hazards. Based on the findings, EMSA recommends refining existing safety measures and incorporating advanced strategies where necessary. Addressing these challenges requires collaboration between regulatory bodies and industry stakeholders to ensure safer and more sustainable maritime operations. Moreover, EMSA emphasizes the importance of enhancing research into safety risks associated with different vessel types, including chemical tankers, container ships, bulk carriers, and cargo vessels. The study also underscores the need for interdisciplinary cooperation among technical, economic, and environmental experts to create a more robust risk management framework. By adopting best practices, refining maritime safety policies, and strengthening enforcement mechanisms, the industry can better prevent accidents and improve overall security. Establishing clear safety standards, technological innovations, and enhanced crisis response protocols will contribute to a more resilient and sustainable maritime sector.

Lye et al. (2024) introduced the concept of probabilistic safety assessment (PSA), discussing its recent advancements and outlining potential future research directions in risk assessment of nuclear vessels. The historical evolution of PSA, particularly in relation to nuclear safety, is examined, including an overview and assessment of various methodologies used in this type of analysis. The author identifies six key areas for future research initiatives: multi-unit PSA for small and micro modular reactors; analysis of functional failures in passive systems; application of physics-enhanced machine learning for risk assessment; human reliability analysis in multi-unit nuclear reactor contexts; effective risk communication strategies; and conducting risk analysis that addresses uncertainties in scenarios with limited data. Olgaard (2001) examined the potential risks associated with Russian nuclear-powered vessels, including submarines, cruisers, and icebreakers. Among the most critical hazards are criticality accidents, particularly during refueling or defueling processes when spent nuclear fuel remains in the reactor. Such incidents pose a threat to both active and decommissioned submarines. Additionally, fires and explosions have led to catastrophic submarine losses, as seen in the Komsomolets disaster in 1989 and the Kursk tragedy in 2000.

Radioactive releases from a nuclear-powered vessel, depending on its location, could potentially affect third parties through contamination of air or sea. However, contrary to common assumptions, the security risks associated with these nuclear operations are relatively low. Once a nuclear reaction is initiated, the reactor fuel becomes intensely radioactive, creating a significant self-protective barrier; any attempt to remove the fuel would pose a severe risk to human health. Thus, security concerns are primarily centered on the possibility of hostile actions aimed at seizing or breaching the reactor. Although any radioactive release could lead to local radiation exposure and psychological distress among nearby populations, the actual physical harm would likely remain limited.

Even after the reactor is shut down and its nuclear fuel is removed, the propulsion system continues to emit residual radiation. The defueling process removes almost all fission products. More than 99.9% of the remaining radioactive materials are embedded within the structural alloys of the reactor components. The remaining 0.1% consists of radioactive corrosion and wear deposits. These deposits are activated by neutron exposure in the reactor core and are found along the internal piping systems. Refueling presents a particular safety challenge, as spent nuclear fuel retains fissile materials such as uranium−235 and plutonium, which vary based on the original composition and degree of fuel burn-up. While it is technically feasible to recover these materials through reprocessing, the intense radioactivity of spent nuclear fuel makes it exceptionally difficult to extract generally beyond the capabilities of unauthorized groups attempting such an operation.

In summary, nuclear-powered merchant ships come with unique risks that affect marine ecosystems, human safety, and regulatory frameworks. The major concern is the threat of radiological hazards and contamination accidents like collisions, groundings, or structural failures could release radioactive materials into the environment, with potentially lasting damage to oceans and coastlines. There is also the inherent risk of accidents or meltdowns involving nuclear reactors at sea, which could have devastating environmental and economic impacts if they occur. Managing radioactive waste from these ships presents additional logistical and safety hurdles, especially around secure storage, handling, and disposal.

Security risks are also high, as these vessels might be targets for attacks, sabotage, or piracy, demanding stringent security measures. Emergency response to nuclear incidents at sea poses another critical challenge; it requires specialized equipment and training, and in remote areas, response times could be worryingly slow. Operational risks are considerable too safe handling of nuclear reactors requires extensive training and oversight to avoid human errors that could lead to accidents.

On the regulatory side, existing maritime and nuclear laws still contain several gaps. These gaps may not fully address the unique risks associated with nuclear-powered ships. As a result, potential legal complications could arise, particularly in cases involving cross-border impacts. Public acceptance is also a significant factor. Many communities and stakeholders remain hesitant to support nuclear-powered vessels because of perceived safety and environmental risks. Such concerns may limit their adoption and deployment. In addition, any nuclear incident at sea could cause environmental impacts that extend across national boundaries. This situation would create diplomatic and regulatory challenges and require close international cooperation and coordinated response efforts. While nuclear propulsion offers a promising low-carbon option, managing its associated risks is crucial to supporting global sustainability and ensuring public confidence in this technology as part of maritime decarbonization. Addressing these risks will require well-developed international regulations, strict safety protocols, and a strong emphasis on emergency preparedness.

Risk assessment of nuclear-powered vessel

Initially, the primary risk factors are identified. Each factor is assessed for its risk sensitivity concerning human safety, environmental impact, ship integrity, and cargo security. Ultimately, the Risk Index is quantified using the Frequency Index and Severity Index, as detailed below:

$$\text{Risk Index (RI)} = \text{Frequency Index (FI)} * \text{Severity Index (SI)} \quad (1)$$

The Frequency Index (FI) measures how often damage occurs, while the Severity Index (SI) assesses the extent of that damage. The Risk Index (RI) is categorized into three levels: Low, medium, and high, based on the frequency and severity of the incidents.

The hazards are classified into four categories includes the reactor compartment, the balance of plant compartment, unlawful acts, and general arrangement. Thus, the risk mitigation process has been proposed as in Figure 5.

Nuclear powered vessels frequently encounter accident risks like collisions, fires or explosions, and machinery damage or failure during operations in ice-covered waters, whether navigating independently, escorting other vessels, or traveling in convoys. To systematically identify hazards for nuclear-powered vessels, the analysis can be divided into two key areas: first, conducting an analysis focused on navigational accident scenarios specific to nuclear-powered icebreakers, and second, performing a detailed analysis that addresses potential machinery damage or failure scenarios within the nuclear power plant systems. The risk assessment of nuclear-powered vessels can be carried out through 03 main steps (Garrick 1999; Agency 2001; Journal 2022):

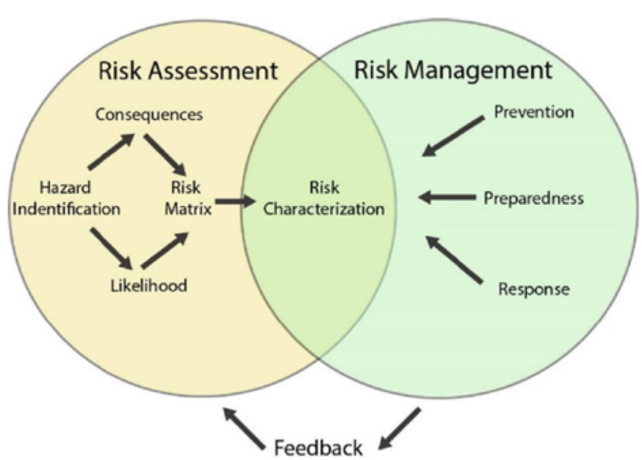

Figure 5. Risk mitigation process.

Step 1: Hazard identification of accident scenarios for nuclear-powered vessel

The first stage focuses on identifying potential accident scenarios for nuclear-powered merchant ship using the failure mode and effects analysis method (Alford and Lilly 2024). This method involves analyzing failure modes and their effects across various operational contexts, including independent, escort, and convoy operations. By categorizing different navigational hazards as failure modes, this analysis examines the causes, assesses the likelihood and severity of their outcomes, and evaluates the associated risk levels. The study identifies critical accident scenarios specific to icebreaker escort operations based on these risk assessments.

Step 2: Risk Analysis of Accident Scenarios

In the second stage, the functional resonance analysis method (Patriarca et al. 2020) is employed to model the progression of the identified accident scenarios in ice-covered waters. This approach identifies key functions and coupling changes within the accident scenarios, establishing critical accident paths as targets for risk reduction efforts.

Step 3: Analysis of risk control options (RCOs)

Building on the critical accident paths identified in step 2, this final step proposes specific RCOs aimed at reducing the risks associated with nuclear-powered icebreaker accidents in ice navigation. The targeted RCOs address the critical coupling paths to mitigate the risks in these scenarios, ultimately enhancing operational safety in ice-covered waters.

Adumene et al. (2022) identified essential research avenues to develop a comprehensive risk management framework aimed at enhancing the safety of nuclear-powered shipping. Key areas include the use of digitalization, resilient system design, and the internet of things (IoT). It also finds gaps in current knowledge and introduces a preliminary hybrid framework designed to incorporate hierarchical hazard structures within a fault-based risk aggregation model, supporting informed decision-making for nuclear-powered maritime operations. Guo and Wu (2023) addressed limitations tied to the dynamic properties and uncertain data in the risk systems of hinge joint structures within marine nuclear power plants (MNPP). To manage the challenge of divergent expert opinions in group decision-making, it introduces a new technique, the discrete aggregation method (DAM). DAM leverages fuzzy opinion aggregation, factoring in the degree of expert consensus to effectively resolve conflicting perspectives. Additionally, a hinge joint accident model is developed using the bow-tie (BT) approach for hazard identification, which is then integrated into a dynamic Bayesian network (DBN) model. Garrick and Christie (2002) examined the risk assessment for US nuclear power plants and showed that probabilistic risk assessment (PRA), also known as PSA, is a fundamental component of the nuclear power industry's global safety culture. However, risk assessment practices are currently evolving, with regulatory frameworks particularly in the United States not yet fully established to enable a risk-based licensing process. Though there is gradual progress on the regulatory front, it is often slow and challenging. In the U.S., the approach remains 'risk-informed,' largely maintaining standard practices but requiring risk assessments as an additional layer. This approach adds complexity and costs, especially as the nuclear power sector faces increased competition due to deregulation.

When a nuclear-powered vessel is set to begin operations, it is essential to focus on the functional connections prone to functional resonance. This requires a multi-faceted approach to ensure operational safety and effectiveness:

- As the merchant ship navigates through overseas regions, the ship management company must equip it with accurate navigation equipment and up-to-date charts to ensure safe passage. Continuous monitoring of the vessel's course, strengthening oversight, and providing well-planned sailing routes are critical responsibilities of the ship management company.
- Human factors are significant in maritime safety, with crew attentiveness being crucial to avoid accidents. Enhancing crew competence and maintaining a cautious approach throughout the voyage are essential steps for operational safety.

- Onboard maintenance requires intense human-machine interaction, particularly under demanding and dynamic conditions. To ensure system resilience, equipment combining both passive and active safety features should be prioritized. Fail-safe components, designed to remain in a safe state if failure occurs, should be operational and regularly inspected. In critical incidents, such as a coolant loss or collision, the reactor shutdown system must function reliably to promptly halt reactor activity. Safety drive mechanisms are designed to quickly halt the reactor, maintaining a subcritical state in emergencies.
- Use control rods that can be electrically inserted to shut down the reactor.
- Employ gravity or spring-loaded mechanisms to automatically insert rods into the core if the system loses power.
- Following principles of redundancy, independence, and diversity enhances system reliability. Automation in the control and activation of safety functions, especially using self-actuating devices, boosts the robustness of the safety system. Emphasizing passive and self-activated safety features helps limit risks associated with external systems, power failures, and human errors. This approach ensures the icebreaker's safety systems remain dependable under varied operational conditions.

For the safety systems installed in nuclear-powered vessel, it is crucial to continuously verify their availability and effectiveness to ensure proper functionality and prevent major disasters. In the event of a reactor failure, safety protection facilities and voltage stabilizers must be activated immediately to maintain effective cooling and pressure stability within the nuclear power plant. The emergency core cooling system provides water through accumulators to mitigate core damage and cool any overheated or partially compromised core components. This proactive measure guarantees sufficient water flow into the reactor core, preventing the formation of molten material at the bottom and averting potential core melt and erosion of the reactor vessel, which effectively limits the release of radioactive materials.

Additionally, timely actions must be taken during an accident to prevent nuclear leakage from the vessel while ensuring the core remains adequately cooled. Strategies to mitigate severe accident consequences focus on minimizing core damage and reducing radiation exposure. In the face of severe accidents, it is vital to keep personnel away from compartments adjacent to the reactor containment and other high-radiation areas to limit exposure. Furthermore, measures should be implemented to protect the crew from radiation exposure, especially those living in nearby areas. Depending on the radiation levels present, additional protective actions, such as establishing shelters or administering iodine prophylaxis, may be necessary to safeguard personnel.

In nuclear-powered ships, the high initial cost of a reactor makes it likely that only a single unit will be installed, capable of generating sufficient power for both propulsion and auxiliary systems. To ensure operational safety, a backup propulsion system is essential in case of reactor failure, enabling the vessel to return to port and maintain critical emergency functions. A combination of diesel generators and batteries is considered the most effective solution. While diesel generators can supply adequate power for propulsion and cooling the reactor's decay heat similar to land-based nuclear plants as a secondary backup system is still required. Incorporating a hybrid nuclear-battery system offers several advantages. Batteries not only provide backup power in the event of total failure but also assist with load leveling, reducing peak demand and allowing for a downsized reactor with lower thermal output. This integration enhances both efficiency and safety.

The design of secondary safety systems should follow key engineering principles:

- Employing different operating principles to prevent common-mode failures.
- Using multiple components and systems to protect against individual failures.
- Physically separating critical systems to avoid cascading failures.
- Ensuring systems default to a safe state in case of malfunction.
- Allowing periodic testing without disrupting normal operations.

Modern reactor designs are inherently safe, operating under-moderated with a negative reactivity coefficient. This means they automatically shut down in response to rapid load changes, turbine malfunctions, or loss of primary coolant, preventing catastrophic failures. Designers must also account for ship-induced accelerations, carefully calculating operational margins to align the reactor's stability with the vessel's expected movement and conditions. Regarding radiation containment, PWRs, including SMRs, rely on three fundamental barriers to prevent radioactive release: fuel cladding, the primary coolant circuit, and the containment structure. While concerns exist about radiation exposure through direct contact or inhalation of particles, extensive operational experience spanning over 800 reactor-years suggests that under normal conditions, the risk is minimal. In the maritime setting, the reactor compartment is reinforced with double bulkheads, a double bottom, and double hull protection to mitigate risks in the event of a collision or grounding. However, the probability of impact amidships is higher than at the stern, presenting a design challenge. Engineers must balance the risk of subjecting the reactor to excessive accelerations against the potential for collisions that could compromise the containment structure.

Regulations and guidelines

The existing international legal framework has been established through a series of conventions developed by the IMO and the International Labor Organization (ILO) (Stopford 2020). In 1981, the IMO adopted Resolution A.492 (XII), introducing the Code of Safety for Nuclear Merchant Ships (Breivik et al. 2013). However, this code has yet to be put into practice. In 2022, the UK regulation for merchant nuclear ship has been lunched (The Stationery Office Limited 2022). Currently, there is limited established standards exist for the design, operation, or development of nuclear-powered merchant vessels. Despite the fact that maritime transport of radioactive materials and nuclear waste from power plants has been ongoing for nearly five decades, the international legal framework regulating these shipments remains fragmented and lacks consistency (Breivik et al. 2013). Various international conventions and agreements offer some level of governance, but they often overlap or fail to comprehensively address all aspects of safety, security, and environmental protection (Suykens 2011). This regulatory patchwork creates challenges in enforcement and compliance, leading to potential gaps in the oversight of the transport of hazardous materials across global shipping routes. As a result, there is a growing need for a more cohesive and uniform policy that effectively governs the risks and complexities involved in such shipments.

Lye et al. (2024) researched to fill a crucial gap by analyzing current policies and critically evaluating how effectively they manage the environmental risks posed by nuclear-powered merchant vessels. By conducting deep analysis, the study highlights the limitations and weaknesses within the existing regulatory framework and investigates potential improvements. The ultimate aim is to strengthen the international community's capacity to address and minimize the risks of radioactive marine pollution from nuclear-propelled ships, particularly within the context of maritime decarbonization efforts. Lye et al. (2024) reviewed the regulatory gap for developing the maritime modular reactor in Korea. A cohesive and harmonized regulatory framework is crucial to ensure the safety, effective management of radioactive waste, and prevention of accidents related to nuclear-powered ships. Although initiatives by the International Atomic Energy Agency (IAEA) and the IMO are making progress, significant gaps persist particularly in the areas of maritime-specific risk assessments, emergency response procedures, and consistent cross-border regulations. Strengthening collaboration among regulatory authorities, launching pilot projects, and fostering open engagement with stakeholders will be essential to improve safety measures and support regulatory consistency. Public acceptance also plays a pivotal role, necessitating thorough environmental impact assessments (EIAs) and clear communication to build trust and align SMR-powered vessels with global sustainability goals. While challenges remain, these obstacles also open avenues for innovation and international cooperation.

These frameworks are primarily based on standards developed for nuclear-powered naval vessels. Their main goal is to minimize risks related to radiation exposure and environmental contamination. However, further improvements are required to fill existing gaps in design standards for commercial use. In particular, more detailed criteria are needed for the installation, operation, and decommissioning of reactors on merchant ships. Current guidelines also lack sufficient clarity regarding crew training and cybersecurity protections for reactor control systems. They provide limited guidance on how nuclear propulsion can be integrated with other sustainable technologies. To enable wider adoption, regulatory authorities should also address international concerns about port access for nuclear-powered ships. In addition, they need to develop comprehensive incident management frameworks and promote stronger international cooperation to harmonize regulatory practices worldwide.

The regulatory landscape governing nuclear-powered vessels presents three key challenges:

- The Safety of Life at Sea (SOLAS) Convention, Chapter VIII, which is adopted by IMO, established the Code of Safety for Nuclear Merchant Ships (Resolution A.491.XII) in 1981. This code is designed around PWRs, commonly used in naval applications. However, the emergency planning requirements for mobile, high-pressure reactors make them unsuitable for nearshore environments, rendering them commercially uninsurable and preventing port access. Without port calls, nuclear-powered ships are impractical. Therefore, IMO standards need to be revised to accommodate newer, safer nuclear technologies.
- Strict export control laws for naval nuclear propulsion in countries like the USA, UK, Russia, and China extend to all maritime nuclear propulsion systems, based on the same technologies referenced in Resolution A.491.XII. To enable the development of civil nuclear-powered ships, national export control regulations must be updated to distinguish between military and civilian applications, while maintaining robust security measures. Modernizing these rules would also drive innovation in shipbuilding and vessel ownership.
- Existing nuclear liability frameworks, such as the Vienna and Paris Conventions, exclude nuclear-powered ships, primarily due to concerns stemming from outdated reactor designs. Although the Brussels Convention of 1962 attempted to address this, it was never ratified. To make nuclear-powered ships commercially viable, a new liability convention is needed one that allows for insurability and accounts for the safety of modern nuclear technologies. With updated export controls and insurance frameworks, this revised convention could be implemented.

To effectively regulate nuclear-powered merchant vessels and mitigate their environmental risks, a comprehensive multilateral framework is essential. Such a framework would provide institutional guidance for the safe navigation of these ships, prevent and control marine pollution, and ensure timely, effective, and adequate compensation following nuclear incidents. Currently, the IMO is advancing international regulations for alternative marine fuels, including guidelines for fuels like liquefied natural gas, methanol, hydrogen, and ammonia. As nuclear power represents a decarbonizing alternative for ship propulsion, similar regulatory measures could be developed collaboratively by the IMO and IAEA. This partnership would address the prevalent fragmentation and inconsistencies in rulemaking and foster a cohesive approach to regulating nuclear-powered shipping.

Results and discussions

Nuclear-powered merchant ships have not been a focal point of serious discussion in naval architecture for nearly four decades. However, recent advancements in commercial shipping, including the demand for larger, faster, and more powerful vessels, have reignited interest in nuclear propulsion as a viable alternative. Modern ship designs now provide opportunities for high-speed maritime transport, potentially capturing a portion of the high-value goods market currently dominated by air freight.

One example is the proposed Fast-Ship (Vergara and McKesson 2002), a large monohulled vessel requiring 250 MW to operate via five gas turbine-waterjet units. Operational cost estimates for Fast-Ship highlight (N. Reactor and P. Design 1968) that fuel prices play a critical role, accounting for over a third of total operating expenses. In contrast, a nuclear-powered Fast-Ship (Ummah 2019) could mitigate fuel price fluctuations, saving approximately 5,000 tons of fuel per trip. These savings could be reinvested into additional cargo capacity, generating more revenue.

Nuclear propulsion offers a stable, cost-effective energy source, as nuclear fuel prices remain relatively low and steady, making it ideal for high-power, long-distance applications. Recent advances in nuclear technology indicate that modular nuclear reactors could be commercially viable within the next decade. For a Fast-Ship, an optimal design might feature two helium-cooled reactors, each driving a pair of 50 MW helium turbines connected to waterjet pumps, along with an additional 50 MW gas turbine. Although the initial construction cost of a nuclear-powered Fast-Ship would be higher, it would benefit from reduced fuel costs and potential for further cost, weight, and size optimizations. Gabbar, Adham, and Abdussami (2021) analyzed four distinct energy systems for marine vessels, evaluating their performance based on key metrics. These systems include: (i) Stand-alone fossil fuel-based energy system, (ii) Stand-alone nuclear energy system, (iii) Renewable and fossil fuel hybrid energy system, (iv) Nuclear-renewable hybrid energy system (*N*-R HES). The assessment was conducted using key performance indicators (KPIs) such as cost of energy (COE), net present cost (NPC), and GHG emissions. Findings suggest that the nuclear-renewable hybrid energy system (*N*-R HES) offers the most promising solution for the maritime industry by significantly lowering GHG emissions while enhancing economic viability.

Chandrasekar, Kumar, and Chelliah (2017) analysis highlights key considerations for nuclear-powered marine propulsion in comparison to conventional fuel-based systems. The average calorific value of typical marine fuel, such as hydrocarbon fuel oil, is approximately 40,000 kJ/kg. Based on this, the thermal output from the marine boiler of a reference ship is estimated at 29,170 kW(th), assuming negligible losses. Given that marine engines typically achieve a 50% efficiency in converting heat to propulsion work, an onboard nuclear reactor with a minimum capacity of 14.6 MW(e) would be required to achieve equivalent propulsion performance. The estimated overnight capital cost for SMRs, based on current technology, ranges between $5,000/kW(e) and $8,000/kW(e) (Mignacca and Locatelli 2020). This implies an additional investment of $73 million to $117 million per ship for the power source alone, excluding the cost of the vessel and necessary retrofits. Furthermore, converting an existing ship into a nuclear-powered vessel may not be feasible, necessitating the construction of new ships, leading to further capital expenditures. If the onboard modular nuclear reactor supplies electricity at a levelized cost of $0.08/kWh(e), the estimated operating expense related to energy consumption would be $1,126 per hour of voyage. However, this cost would not be incurred separately in a nuclear-powered vessel, making it financially advantageous. Additionally, a single ton of uranium fuel (O'Rourke 2011) can sustain a reactor for several years of operation, demonstrating the resource efficiency and long-term viability of nuclear propulsion as a pathway toward decarbonizing the maritime sector.

These advancements highlight nuclear propulsion's potential to transform high-performance maritime shipping by delivering long-term cost savings and operational efficiency. The widespread use of PWRs (Leverenz, Gerhard, and Göbel 2004) in both nuclear power generation and propulsion can be traced back to their early adoption, driven by water's advantageous properties as a coolant. Water effectively moderates neutrons, transfers heat efficiently, pumps readily, is chemically stable, widely available, and relatively inexpensive. PWRs have shown resilience and reliability in naval applications such as aircraft carriers and submarines. However, challenges arise when considering PWRs for merchant ship propulsion due to their large size and weight. Maintaining thermal efficiency requires high-pressure vessels and components, which are prone to in-service wear and degradation. Without significant simplifications, PWRs are also prohibitively costly for lower power outputs, particularly under 500 MWe per unit.

Boiling water reactors (BWRs) (Shiralkar 1981) once appeared to offer cost savings, yet they present difficulties for marine propulsion. The reactor's phase transitions, coupled with the ship's heaving motions, could destabilize power control. Additionally, BWRs require extensive shielding to manage radiochemical carryover, making them complex for marine use. Consequently, BWRs have not gained popularity in maritime applications.

The challenges currently associated with nuclear-powered merchant shipping suggest that prospective shipowners must be willing to take on the role of early adopters, possess strong financial stability, and commit to a long-term investment strategy. Given potential limitations in vessel acceptance and possible trade restrictions, shipowners must also be prepared to navigate significant risks in an uncharted market. However, if successful, the advantages of being a pioneer in this field could be substantial.

In traditional shipping, Protection & Indemnity (P&I) clubs provide coverage for third-party liabilities in the event of accidents. For a nuclear-powered fleet, however, a specialized trust or insurance mechanism would likely be necessary to address potential radiological pollution risks following a severe incident. Overall, the path to operationalizing nuclear merchant vessels remains complex and uncertain, requiring extensive regulatory, financial, and technological advancements before large-scale implementation can take place.

Gas turbine modular helium reactor

This plant design is conceptually similar to an aeroderivative gas turbine, but it utilizes a nuclear reactor in place of traditional fuel burners and operates within a closed helium cycle, resulting in a lower compression ratio. In this system, helium is heated by the nuclear reactor, then expands across the turbine blades, after which it is recompressed and recirculated to the hot side of the cycle. As the turbine rotates, it generates torque that can be directly transferred to a generator within the containment shell, allowing for direct electrical power generation.

To improve thermal efficiency beyond that of a simple cycle, a heat recuperate is included to capture leftover heat from the turbine exhaust, which in turn reduces the reactor's size. Additionally, a precooler and an intercooler decrease the power needed for compression. Figure 6 presents configurations of fuel reactors and practical components. The integrated closed recuperative (ICR) cycle stands out as the best option, closely resembling the nuclear adaptation of the Northrop-Rolls Royce WR–21 gas turbine (Colin 2003). This design achieves a low compression ratio of 2.7, using two compressors, and features a separate power turbine for enhanced reactor control and thrust in propulsion. With these design features, a nuclear plant could achieve a thermal efficiency of 47.6%.

Helium stands out as an ideal coolant for nuclear systems (Owston 2021; Zhou et al. 2023) due to its unique properties. As a monoatomic gas with low molecular weight, helium enables high efficiency at relatively low compression ratios, which minimizes the stress placed on turbine blades. Its high specific heat capacity, gas constant, and thermal conductivity allow for the design of compact and efficient components. Additionally, helium's low density and high gas constant enable high flow rates without encountering the Mach limitations often seen in traditional gas turbines (Figure 7).

Moreover, helium's chemical inertness is a significant advantage, as it reduces the potential for radioactivity within the turbine machinery, contributing to a safer and more stable operating environment in nuclear applications.

Pebble bed modular reactor

This reactor design is conceptually similar to the Gas Turbine-Modular Helium Reactor (GT-MHR) (Atijm 2002; LaBar 2002), but it features a pebble bed core, composed of thousands of 6 cm diameter

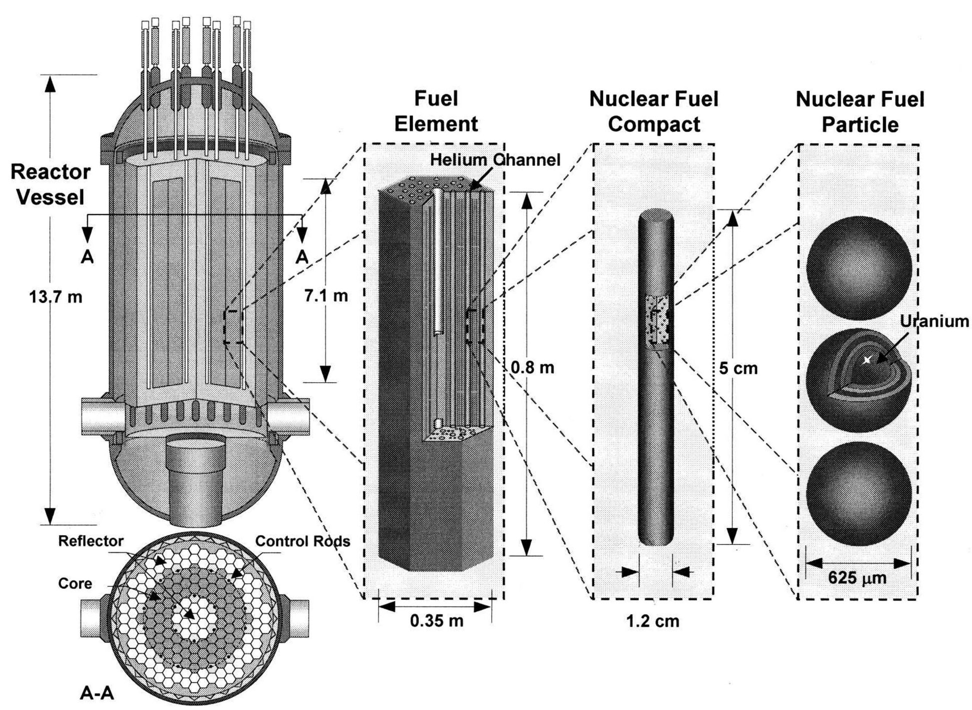

Figure 6. Nuclear fuel reactor and elements (Vergara and McKesson 2002).

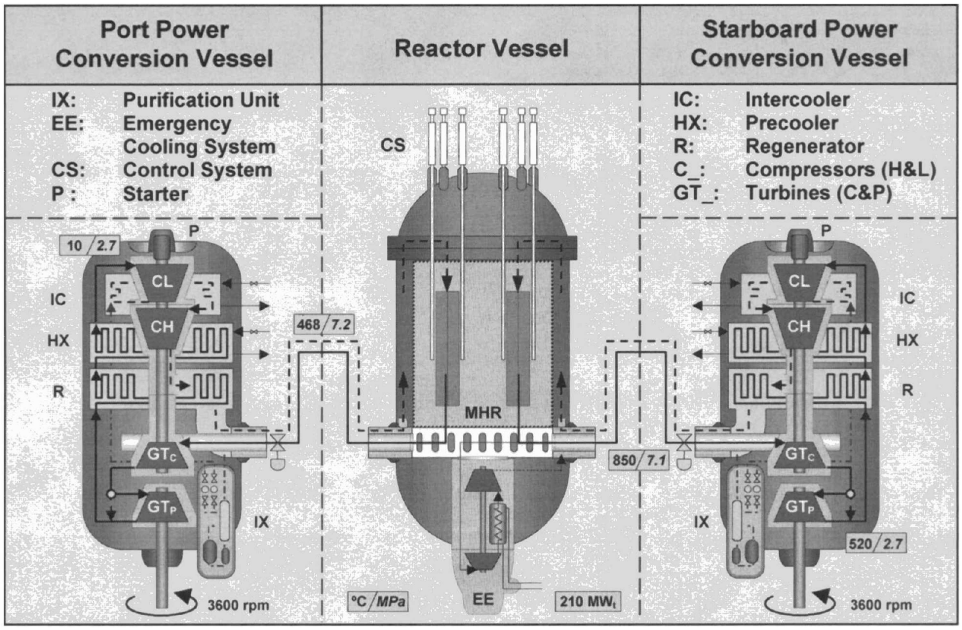

Figure 7. Gas turbine modular helium reactor module (Vergara and McKesson 2002).

graphite balls embedded with TRISO-coated uranium microparticles. This configuration is well-suited for power generation and allows for on-line refueling through a recharging and monitoring system, which could potentially support a reflected annular core design. However, this fueling method introduces additional complexities to the operation of a propulsion power plant and poses challenges to international safeguards for nuclear material control.

To manage the removal of fission heat, helium is injected into the reactor vessel (RV) at a pressure of 7.1 MPa from the primary containment vessel (PCV). The helium gas flows upward along the periphery of the RV and then descends, cooling the reactor's annular core. This efficient heat removal system is critical for maintaining optimal operating conditions and ensuring the reactor's safety.

Risk assessment

Nuclear power as a propulsion method in maritime transport offers a potential pathway to reduce carbon emissions, yet it also introduces significant environmental risks. Collisions, major mechanical failures, fires, explosions, or nuclear leaks from nuclear-powered merchant ships could have severe impacts on marine ecosystems. While recent studies on nuclear propulsion in merchant shipping have explored the technical, economic, and sociopolitical hurdles to its widespread adoption, there remains a notable gap in research from the perspective of international law. This gap underscores the importance of a more detailed analysis of the international regulatory framework addressing environmental risks linked to nuclear-powered vessels.

Although various international conventions, protocols, and agreements aim to regulate nuclear propulsion for merchant ships, this study’s critical analysis reveals that the existing framework has numerous limitations. These issues include challenges in applying nuclear convention principles, obstacles in ratifying specialized conventions specific to nuclear-powered ships, over-reliance on flag state regulation with inconsistent enforcement, and inadequate liability and compensation mechanisms for environmental damage. These regulatory shortcomings hinder the effective management of environmental risks posed by nuclear-propelled vessels.

Lesson learned

The first key point is that naval nuclear propulsion is entirely viable. All ships in this category used fuel rods, and aside from the NS Sevmorput, they operated with low-enriched uranium. Initial impressions are crucial, and because achieving complete success on the first attempt is often challenging, building prototypes becomes essential for gaining confidence.

Economic viability is the foundation for sustaining any project, meaning cost-effectiveness must be a core consideration. Of all nuclear-powered ships, the only one to achieve economic success was the NS Sevmorput, a third-generation nuclear vessel developed in the former Soviet Union. Earlier vessels, such as the NS Lenin, encountered significant problems, including the need to replace its reactor. This highlights the learning curve involved in nuclear reactor development. Additionally, project management can become problematic, especially when multiple organizations are involved in the design process, complicating collaboration at key interfaces.

Military institutions and universities generally command more trust than private companies. Therefore, a partnership that integrates military interests, academic research, and private-sector profit could be a challenging yet sustainable path forward.

Lastly, the media plays a critical role in shaping public perception. Public acceptance of nuclear energy depends largely on communicating the clear benefits it offers. Any additional risks must be justified by corresponding gains, and public skepticism can be addressed through education and efforts to reduce misinformation.

With the increasing recognition of nuclear power as a key solution for addressing climate change, SMRs are expected to play a pivotal role in the global energy transition. Their potential applications include: (i) replacing coal-fired power plants while enabling decentralized electricity generation closer to demand centers, (ii) serving as a reliable alternative to diesel in remote and mining regions, (iii) supplying high-quality steam to heavy industries as a cleaner substitute for fossil fuels, and (iv) facilitating large-scale hydrogen production and seawater desalination without carbon emissions. Across the world, various advanced SMR designs are under development, with some already nearing deployment. A major advantage of SMRs lies in their adaptability to cutting-edge design innovations and technologies. By integrating inherent safety features and passive safety systems, they offer substantial improvements in operational safety and reliability. When determining whether nuclear power is suitable for a specific vessel, several additional factors should be considered:

- Speed requirements
- Space constraints
- Emission regulations
- Limitations on oil handling
- Restrictions on ballast water
- Deck space availability
- Flexibility in operational needs
- Local fuel costs, availability, and quality

The following types of vessels could potentially benefit from nuclear power, and operators of these ships would be wise to explore the capabilities of uranium fuel. As always, a thorough economic analysis is essential for making the right propulsion system decision:

- Large container ships
- Automobile carriers
- Refrigerated cargo vessels
- Long-distance passenger ships
- Logistics support vessels
- Commercial submarines
- Bulk cargo carriers

Future prospects

With growing concern over greenhouse gas emissions from the use of fossil fuels in international air and maritime transport, combined with the strong safety record of nuclear-powered ships, it is likely that marine nuclear propulsion will receive renewed interest as a viable alternative.

The rising cost of fossil fuels, along with their environmental impact, has led to nuclear power being considered a potential solution for ships with high power demands. Meanwhile, fuel cells are emerging as a viable option for vessels with lower power needs, particularly those designed for coastal operations, where emissions from marine engines are facing increasing scrutiny. Historically, the use of nuclear power in commercial shipping has been limited to technology demonstrators and has not been seriously considered as a practical propulsion source due to concerns over risk, international politics, and reluctance to transfer proven naval nuclear technology to commercial operators.

Beyond the fundamental considerations, marine nuclear power plant highlights its advantages over alternative fuel-based propulsion systems:

- The entire power plant, including auxiliary systems and fuel, is small and lightweight as possible while meeting the vessel's operational range and power demands.
- The system is designed for straightforward maintenance, allowing for efficient servicing during short drydocking periods.
- The design minimizes the need for refueling, enabling the vessel to operate continuously along its intended service route without frequent fuel replenishment.
- The power plant is capable of adjusting to varying energy demands, including long-term fluctuations such as time spent at sea, in port, or in drydock, as well as short-term variations caused by maneuvering or cargo operations. This ensures optimal performance across different operational conditions.

In recent years, several high-speed ship concepts have emerged and gained significant attention. These designs feature advancements in naval architecture and offer innovative solutions to improve the efficiency of movement at the air-water interface. When an object moves at this interface, it generates a wave train that consumes energy, in addition to experiencing drag as it moves through the medium. A brief overview of these high-speed ship concepts highlights the technologies currently being explored to address these challenges.

Global trends predict a doubling of maritime trade over the next 20 years, alongside potential threats from global warming and the indirect economic impacts of fossil fuel-powered systems, especially as oil prices continue to rise. Increasing demand for rapid ocean transport of time-sensitive freight, combined with ongoing advancements in nuclear reactor technology, highlight the need for a more thorough analysis of the technology and economic prospects of nuclear power for commercial high-speed ships in the 21st century.

Nuclear power offers distinct advantages for such vessels, including speed, power, environmental sustainability, and economic viability. The persistent impact of high oil prices is expected to endure, regardless of OPEC's actions, as additional costs for oil-burning systems will likely be imposed due to future regulations aimed at reducing sulfur dioxide and greenhouse gas emissions. Moreover, a variety of emerging nuclear power technologies and reactor designs may lay the groundwork for a resurgence of commercial nuclear power and nuclear-powered merchant ships. Some of these concepts are briefly discussed here.

SMRs enhance safety through simplified system design and inherent safety features. They also employ passive safety mechanisms that reduce the likelihood of accidents. SMRs provide several important advantages, including greater operational flexibility and lower initial investment costs. With the global shift toward electrification and renewable energy integration, the demand for SMRs is expected to grow rapidly in the near future. In addition to power generation, SMRs can supply thermal energy for a range of carbon-neutral applications. These include seawater desalination, district heating, and hydrogen production.

However, the adoption of nuclear-powered ships will encounter numerous challenges in its early stages. One of the primary barriers is the exceptionally high initial investment, which is estimated to be up to three times the cost of conventional vessels. Additional financial burdens, including increased crew expenses, high insurance premiums, and significant decommissioning costs, are likely to make traditionally risk-averse and cost-conscious shipowners hesitant. Furthermore, port restrictions may limit the accessibility of nuclear-powered ships, making vessel types that can load and unload cargo offshore a more viable starting point.

Despite these socio-economic concerns, nuclear ships offer a key environmental advantage: zero GHG emissions during operation. Advances in nuclear reactor technology, particularly fast reactors, have demonstrated the ability to breed additional fuel and recycle spent fuel from conventional reactors. This innovation not only enhances fuel efficiency but also significantly mitigates the challenges associated with long-lived nuclear waste, extending uranium resources to support reactor operations for approximately 1,500 years while minimizing environmental impact.

Conclusions

Nuclear energy offers a promising alternative for powering merchant ships, especially large, high-speed vessels, as long as cost-effective designs are implemented. To mitigate public resistance, it is essential to communicate the risks and benefits of nuclear power well in advance. Effective management that follows best practices is crucial to building trust among internal stakeholders, thereby fostering broader public confidence. However, the high initial costs on the learning curve can deter private investors. Sharing development and production costs with non-profit organizations, such as universities and military institutions, may provide a viable funding model.

In the development of nuclear reactors for maritime applications, it is essential to evaluate market dynamics and niche demands to ensure compatibility with the requirements of prospective operators. Experimental evidence highlights that the successful deployment of nuclear energy in shipping is contingent upon the establishment of a comprehensive and reliable regulatory framework. However, the inherently global and mobile nature of maritime operations, coupled with the fragmented and often unpredictable character of international shipping regulations, introduces significant ethical and governance challenges. These factors collectively complicate the adoption of nuclear propulsion for commercial vessels and underscore the need to critically reassess its long-term feasibility within the sector.

Drawing from research, literature, and experimental insights, several key conclusions emerge:

- Constructing nuclear-powered merchant ships will remain unfeasible without significant reductions in life-cycle costs and infrastructure enhancements, which must demonstrate clear economic benefits over traditional vessels.
- Securing approval from port authorities and coastal states is a formidable challenge. Nuclear-powered vessels require a functional regulatory framework, including a designated flag state, homeport, and maintenance facilities. International agreements defining the rights and responsibilities of flag and port states are also necessary before expanding nuclear experiments.
- For niche markets like high-value cargo transport, nuclear propulsion could offer advantages by enabling faster speeds. It may also influence route selection, reducing political and security risks.
- Key stakeholders including ports, flag states, shipowners, and cargo operators could drive the next phase of nuclear-powered commercial vessels by establishing collaborative financial and organizational models. Such partnerships could centralize efforts to advance nuclear propulsion and facilitate its broader adoption.

While nuclear propulsion has clear benefits, it also presents substantial regulatory, economic, and operational obstacles. The study highlights that:

- Nuclear energy is a powerful potential energy source for commercial shipping.
- The benefits of nuclear power in shipping may outweigh the associated risks.
- Safety concerns are significant, and adapting nuclear power for commercial use poses considerable challenges.
- Decarbonization and emissions reduction are critical factors in favor of nuclear energy.
- Social and technological hurdles can be addressed using insights from naval ships.
- Nuclear power plants on ships could meet regional energy demands.
- Advances in alternative fuels may also provide viable options for maritime power.
- Cybersecurity is a key concern with nuclear technology in commercial shipping.

Risk assessments and engineering solutions affirm the technical feasibility of nuclear propulsion. However, with the maritime sector's prescriptive regulatory structure and fragmented nuclear regulations, success requires harmonized, performance-based standards across technological, regulatory, and organizational levels.

The IMO is increasingly focusing on alternative energy solutions in its current and future regulations to mitigate emissions from fossil fuel consumption. As part of the transition toward the IMO 2050 zero-emission strategy, several policy measures and initiatives can be implemented to facilitate the integration of nuclear power into the maritime industry:

- Establishing standardized port-entry regulations and inspection protocols for nuclear-powered vessels under IMO and IAEA frameworks will streamline operations and ensure regulatory consistency across international waters. National authorities should collaborate with these organizations to develop best practices for licensing, operation, and decommissioning of SMRs in maritime applications.
- Exploring the deployment of land-based nuclear reactors in coastal regions to generate green fuels and power for the shipping sector. This could involve utilizing existing nuclear facilities or repurposing decommissioned coal-fired power plants near major ports. Collaborative cost-sharing models, such as project financing and adjusted freight charges, should be established among nuclear industry stakeholders, shipping companies, and port authorities to ensure feasibility.
- Gradual integration of nuclear-derived green fuels with conventional hydrocarbon-based marine fuels as an initial step toward decarbonization. While full substitution may not be immediately achievable, developing hydrogen production and distribution infrastructure will be crucial to supporting nuclear energy's role in maritime shipping and achieving zero tank-to-wake GHG emissions. National and international decarbonization strategies should align with both nuclear and hydrogen energy programs.
- Public awareness and engagement initiatives are essential for fostering trust and acceptance of nuclear-powered shipping. Coordinated outreach efforts that highlight safety, environmental benefits, and economic viability can help overcome misconceptions and generate broader support for maritime SMRs.
- Developing policies for uranium import and export is critical for ensuring the fuel supply chain necessary to sustain nuclear-powered ships. Regulatory frameworks should facilitate the secure and efficient handling of nuclear fuel while complying with international safety and non-proliferation standards.

In countries open to nuclear-powered vessels, there is strong interest in future applications driven by political, technological, and societal factors. Key areas for future research include reactor placement on ships, optimal technologies, vibration mitigation, maintenance protocols, and crew training. This research provides a comprehensive assessment of nuclear propulsion for commercial vessels, addressing environmental, technical, and social considerations. Comparative analyzes of alternative energy systems further bridge knowledge gaps, especially as the industry moves toward carbon-neutral transportation. These findings are valuable for marine engineers, naval architects, and stakeholders, including large shipyards and shipowners, seeking sustainable energy solutions for the maritime sector.

Author contributions

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