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Review

Review of the Regulatory Challenges and Opportunities for Maritime Small Modular Reactors in Republic of Korea

Seon-Gon Kim [1], Sanghwan Kim [2], Jophous Mugabi [1,*] and Jae-Ho Jeong [1,*]

[1] Department of Mechanical Engineering, Gachon University, 1342, Seongnam-daero, Sujeong-gu, Seongnam-si 13120, Republic of Korea; tjsrhs5159@gachon.ac.kr
[2] Naval Ship Engineering Research Center, Korea Research Institute of Ships & Ocean Engineering, 32, 1312 Beon-gil, Yuseong-daero, Yuseong-gu, Daejeon-si 305-343, Republic of Korea; kimsh110@kriso.re.kr
* Correspondence: mugajoph@gachon.ac.kr (J.M.); jaeho.jeong@gachon.ac.kr (J.-H.J.)

Abstract: Small Modular Reactors (SMRs) offer transformative potential for maritime propulsion by providing significant benefits such as reduced emissions, enhanced fuel efficiency, and greater operational autonomy. However, their integration into the maritime sector presents complex regulatory challenges due to the convergence of nuclear and maritime laws. A unified, harmonized regulatory framework is essential to ensure safety, radioactive waste management, and accident prevention. While initiatives led by the International Atomic Energy Agency (IAEA) and International Maritime Organization (IMO) are progressing, key gaps remain, particularly regarding maritime-specific risk assessments, emergency response protocols, and cross-border regulatory harmonization. Enhanced collaboration between regulatory bodies, pilot projects, and transparent engagement with stakeholders will be critical to refining safety protocols and accelerating regulatory alignment. Public acceptance remains a vital factor, requiring rigorous environmental impact assessments (EIAs) and transparent communication to build trust and align SMR-powered vessels with global sustainability objectives. While challenges persist, they also present opportunities for innovation and international cooperation. By addressing these regulatory and public acceptance challenges through coordinated efforts and policies, SMR propulsion can become a cornerstone of a more sustainable, efficient, and technologically advanced maritime sector. Successful deployment will position SMRs as a key component of the global energy transition, driving progress toward low-carbon shipping and a greener maritime industry.

Keywords: nuclear powered vessels; Small Modular Reactors (SMRs); floating nuclear power plants; SMR licensing; regulatory challenges

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1. Introduction

The shipping industry is a major contributor to global greenhouse gas (GHG) emissions, consuming over 300 million tonnes of fossil fuels yearly, accounting for about 3% of total global emissions, and is expected to increase with the development of the global economies [1–3]. While other industries are taking radical steps to reduce their emissions, the maritime sector's share of global GHG emissions could increase significantly. To achieve net-zero emissions, a transformation of the entire global economy will be essential. With the pressing need to tackle climate change, the idea of zero-emission cargo ships has become increasingly relevant [4]. The International Maritime Organization (IMO) has set ambitious goals for the industry, aiming for net-zero marine GHG emissions by 2050, with interim targets for near-zero carbon emissions by 2030 and additional milestones for 2030 and 2040 [5] Achieving these targets will require a significant transformation in the maritime sector, focusing on developing vessels that can operate with net-zero carbon emissions. This shift towards green fuels and advanced technologies highlights the industry's commitment to clean energy and a sustainable future [6,7]. Optimizing resource use and improving ship operations through innovative fuel systems is essential to protect the planet. While progress has been made with eco-friendly fuels such as LNG, hydrogen, ammonia, biofuel, and methanol, GHG emissions remain a significant challenge. The reliance on fossil fuels persists, driven by the high production costs of alternative fuels, limited infrastructure, and competition from other industries [6–9]. As the global economy is expected to triple by 2050, fossil fuels—despite being heavily restricted—will likely continue to play a major role in the marine industry due to their high energy density (35.8 MJ/L) compared to alternative fuels [10], unless a viable solution is found. Nuclear power is emerging as a promising alternative, offering a much higher energy density (Uranium 235–3,900,000 MJ/kg) than other fuels [11,12]. This can significantly lower fuel costs and volume, improving the sustainability of maritime operations.

Nuclear-powered ships generate steam using onboard nuclear power plants to drive turbines [13,14]. The USS Nautilus, launched by the USA Navy in 1955 as the first nuclear-powered ship, demonstrated nuclear propulsion and influenced submarine technology in Russia, China, France, the UK, and India [15,16]. Civilian examples include the Soviet Union's Lenin, the first nuclear-powered surface ship, which served as an icebreaker for 30 years [17,18], and the USA NS Savannah, the first nuclear-powered merchant ship launched in 1959 [19,20]. As of 2023, Russia operates several nuclear-powered icebreakers, while only Russia's Sevmorput, commissioned in 1988, remains in service [21]. Table 1 summarizes the nuclear-powered vessels developed or under development in various countries.

Nuclear power provides maritime vessels, especially submarines, with extended operational capability by minimizing the need for refueling, which is particularly advantageous in remote areas like the Russian Arctic [22]. Its high energy output and zero GHG emissions reduce environmental impact and operational costs, helping to offset the initial investment [8,23]. Moreover, nuclear-powered engines are designed with robust safety measures to prevent radioactive leakage, making them reliable for long-term use. The emergence of Floating Nuclear Power Plants (FNPPs), particularly those utilizing Small Modular Reactors (SMRs), has also showcased the potential for nuclear energy in providing electricity, heating, and desalination services in offshore and remote locations. Countries such as Russia, Canada, China, and the USA are actively pursuing the development of marine-based SMR designs, with notable examples like Russia's Akademik Lomonosov, which has been operational since 2020 [24].

Despite the advantages, deploying civilian nuclear vessels presents significant challenges. Public opposition, driven by safety risks, regulatory hurdles, and concerns over nuclear proliferation, is a major barrier [6,8,13]. While nuclear technology can help reduce greenhouse gas emissions, its adoption in merchant shipping is limited due to high costs, equipment vulnerabilities, and risks of collisions or spills. Historical cases like the NS Savannah [19,20], Mutsu [25–27], and Otto Hahn [14] illustrate operational inefficiencies and safety issues, leading to their decommissioning. Additionally, the absence of nuclear-specific training within the Standards of Training, Certification, and Watchkeeping (STCW) framework underscores the need for regulatory reforms to prepare seafarers for these operations [28,29]. Addressing these issues will require policy alignment, enhanced safety protocols, and targeted training programs to support the sustainable adoption of nuclear technology in the maritime sector.

This review examines the regulatory challenges and opportunities surrounding maritime SMRs, including SMR-powered vessels and floating nuclear power plants. Addressing these challenges is essential to preparing the marine transport industry for the deployment of SMR-powered vessels, which presents complex licensing and regulatory hurdles crucial for ensuring compliance with rigorous safety, security, and environmental standards. Successful integration of SMRs into maritime operations will not only enhance industry resilience but also play a pivotal role in supporting global efforts to achieve net-zero emissions by 2050.

Table 1. Examples of global SMR nuclear-powered vessels (icebreakers and commercial ships).

Ship Name	Country	Operation Period/Status	Shipbuilder	Reactor Type & Capacity	Reactor Supplier	Fuel Type & Enrichment	Fueling Cycle	Primary Use	Critical Issues	Remarks	Ref.
NS Savannah	USA	1962~1972	New York Shipbuilding, Camden, NJ, USA	PWR74 MWt	Babcock & Wilcox, Akron, Ohio, USA	LEU, 4.5% enriched	3-year	Cargo/Passenger Ship	Commercially unsuccessful due to high operating costs and safety concerns.	World's first nuclear-powered merchant ship; now a museum.	[13,14]
Otto Hahn	Germany	1968~1979	Kieler Howaldtswerke, Kiel, Germany	PWR38 MWt	Siemens, Munich, Germany	LEU, approx. 4% enriched	2-year	Cargo Ship	Economic inefficiency and public opposition.	Converted to diesel propulsion in 1979.	[13,14]
Mutsu	Japan	1970~1992	Mitsui Engineering, Tokyo, Japan	BWR36 MWt	Mitsubishi Heavy Industries, Tokyo, Japan	LEU, approx. 5% enriched	2.5-year	Research Ship	Reactor shield leaks caused political controversy and redesign.	Decommissioned; reactor removed in 1995.	[25–27,30]
Lenin	USSR	1959~1989	Admiralty Shipyard, Saint Petersburg, Russia.	OK-150 PWR90 MWt → OK-900 PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 5% enriched	3-year	Icebreaker	Early reactor issues led to reactor replacement.	Retired in 1989; now a museum ship.	[15,21]
Arktika	USSR	1975~2008	Baltic Shipyard, Saint Petersburg, Russia.	OK-900A PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 4–5% enriched	3-year	Icebreaker	Reactor malfunction led to early decommissioning.	First surface ship to reach the North Pole; Arktika-class.	[15,21]
Sibir	USSR	1977~1992	Baltic Shipyard, Saint Petersburg, Russia.	OK-900A PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 4–5% enriched	3-year	Icebreaker	High maintenance costs, stopped operating in 1993.	Decommissioned; Arktika-class vessel.	[15,21]
Rossiya	USSR/Russia	1985~2013	Baltic Shipyard, Saint Petersburg, Russia.	OK-900A PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 4–5% enriched	3-year	Icebreaker	High operating costs.	Out of service since 2013; Arktika-class vessel.	[15,21]

Table 1. *Cont.*

Ship Name	Country	Operation Period/Status	Shipbuilder	Reactor Type & Capacity	Reactor Supplier	Fuel Type & Enrichment	Fueling Cycle	Primary Use	Critical Issues	Remarks	Ref.
Sevmorput	USSR/Russia	1988~Ongoing	Baltic Shipyard, Saint Petersburg, Russia.	KLT-40 PWR135 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, 14.1% enriched	3-year	Icebreaking Container Ship	Limited commercial success due to port restrictions.	Continues operation in the Arctic region.	[15,21]
Taymyr	USSR/Russia	1989~Ongoing	Wärtsilä, Helsinki, Finland	KLT-40M PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 14.1% enriched	3-year	Icebreaker	Long Arctic operations under extreme conditions.	Taymyr-class vessel.	[15,21]
Sovetskiy Soyuz	USSR/Russia	1990~2012	Baltic Shipyard, Saint Petersburg, Russia.	OK-900A PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 4–5% enriched	3-year	Icebreaker	Aging infrastructure.	Decommissioned in 2014; Arktika-class vessel.	[15,21]
Vaygach	Russia	1990~Ongoing	Wärtsilä, Helsinki, Finland	KLT-40M PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 14.1% enriched	3-year	Icebreaker	Long-term Arctic operations.	Taymyr-class vessel.	[21]
Yamal	Russia	1993~Ongoing	Baltic Shipyard, Saint Petersburg, Russia.	OK-900A PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, 14.1% enriched	3-year	Icebreaker	No major issues reported.	Active in Arctic missions; Arktika-class vessel.	[21]
50 Let Pobedy	Russia	2007~Ongoing	Baltic Shipyard, Saint Petersburg, Russia.	OK-900A PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 4–5% enriched	3-year	Icebreaker	Regular maintenance for Arctic operations.	Completed in 2007; Arktika-class vessel.	[21]
Arktika (New)	Russia	2024~Planned	Baltic Shipyard, Saint Petersburg, Russia.	RITM-200 PWR171 MWt	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, approx. 19.75% enriched	7-year	Icebreaker	Delays due to design challenges.	Construction began in 2013; completed in 2016.	[11]

Table 1. *Cont.*

Ship Name	Country	Operation Period/Status	Shipbuilder	Reactor Type & Capacity	Reactor Supplier	Fuel Type & Enrichment	Fueling Cycle	Primary Use	Critical Issues	Remarks	Ref.
Core Power MSR Vessels	UK	Expected 2030+	TBD	MSR	Core Power, London, UK	LEU with thorium options (planned)	3-year	Cargo ships/Offshore platforms	Conceptual design stage.	Expected operations post-2030.	[31]
Ulstein MSR Vessels	Norway/UK	Expected 2030+	Ulstein, Ulsteinvik, Norway	MSR	Core Power, London, UK	LEU with thorium options (planned)	3-year	Cruise ships/Cargo vessels	Conceptual design stage.	Expected operations post-2030.	[32]

2. Marine Nuclear Reactors: Design, Fuels, and Operational Principles

Marine nuclear reactors have evolved significantly to meet the increasing demand for high-performance naval propulsion systems, offering unparalleled endurance and efficiency. These reactors utilize advanced fuel compositions with high specific energy, allowing vessels to operate for over a decade without the need for refueling. A typical nuclear propulsion system used in a nuclear-powered vessel is illustrated in Figure 1. Naval reactors primarily employ specialized fuel compositions with high energy densities, which minimizes the frequency of refueling. The three main types of fuels used are uranium–zirconium (U–Zr) alloys, uranium–aluminum (U–Al) alloys, and metal–ceramic fuels. Naval reactors often use highly enriched uranium (HEU), with enrichment levels reaching up to 93% U-235. A typical fuel composition consists of 15% zirconium and 85% uranium, facilitating prolonged reactor operation [17,23]. The use of HEU allows for extended burn-up times, potentially enabling vessels to achieve an almost infinite operational range under optimal conditions. While HEU is standard in naval applications, its use in civilian ships is discouraged due to safety and security concerns [15]. Instead, civilian maritime SMRs generally utilize low-enriched uranium (LEU), with enrichment levels between 3% and 5%. Some advanced designs, such as micro-reactors, employ High-Assay Low-Enriched Uranium (HALEU), with enrichment levels from 5% to 20%, though its adoption remains limited due to regulatory challenges [15,33–35].

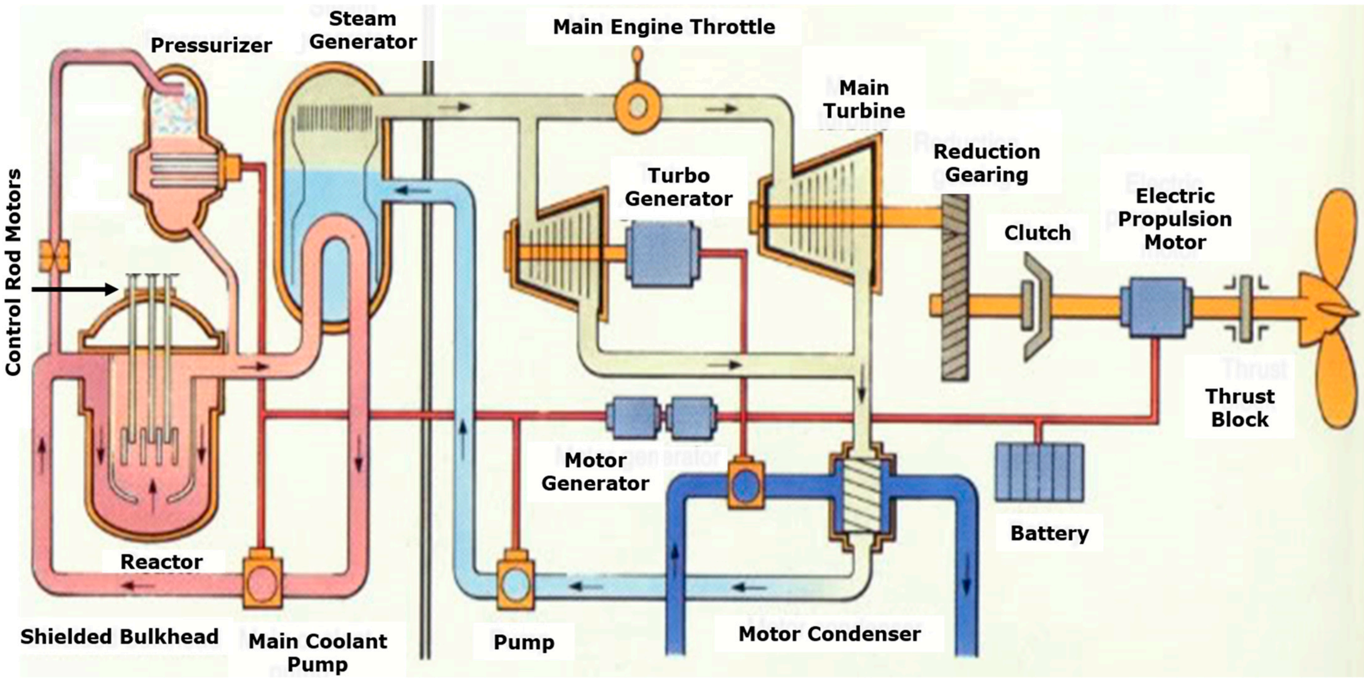

Figure 1. Schematic diagram of a typical pressurized water nuclear propulsion system used in a nuclear-powered maritime vessel [7].

Marine reactors generate heat through the process of nuclear fission, in which the nucleus of a fissile isotope, such as U-235, Pu-239, or U-233, absorbs a neutron and splits into smaller fragments as shown in Figure 2. This splitting releases a large amount of energy in the form of heat, along with two or three additional neutrons. The newly released neutrons induce further fission events, creating a self-sustained chain reaction. The heat generated during this process primarily results from the radioactivity of the fission products, such as cesium and strontium, which emit energy as they decay. To regulate the chain reaction, marine reactors utilize control rods composed of strong neutron absorbers like boron or cadmium. These rods are inserted between the fuel assemblies to control the availability of free neutrons. Withdrawing the rods increases the number of neutrons available for fission, raising the reactor's power output. Conversely, reinserting the control rods stabilizes or reduces the reactor's power. In emergencies, the rods can be fully inserted to rapidly halt the chain reaction, ensuring operational safety.

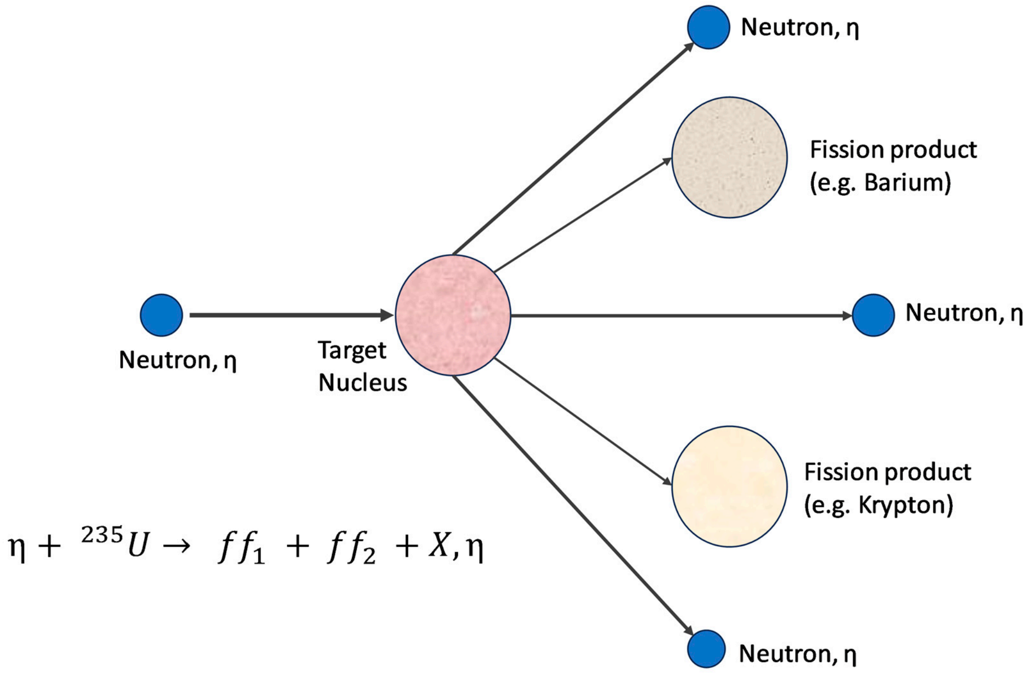

Figure 2. Illustration of a basic nuclear fission reaction.

Most marine nuclear reactors are thermal reactors, which rely on thermal neutrons to enhance fission efficiency [17,23]. The two most common types are Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs), illustrated in Figure 3. PWRs use a dual-circuit system where water circulates under high pressure (about 150 atmospheres) through the reactor core, absorbing heat and preventing boiling. This keeps the coolant liquid even at high temperatures (around 325 °C) [36–38]. This heat is then transferred to a steam generator, which produces steam for propulsion turbines. PWRs employ uranium dioxide (UO_2) fuel enriched to about 3–5% U-235 and utilize control rods for fission regulation. The separation of the primary and secondary circuits ensures that the radioactive primary coolant is isolated from the turbine system, reducing the risk of contamination. BWRs use a single-circuit design where water boils directly in the reactor core to produce steam, which then powers the turbine. With a lower operating pressure of around 75 atmospheres, the coolant's boiling point is about 285 °C [36,38]. BWRs, while simpler than PWRs, face contamination concerns due to radioactive steam in contact with turbine components, limiting their use in marine applications [30]. PWRs are preferred for nuclear-powered vessels because their self-regulating nature enhances safety by reducing neutron moderation and fission rates [23]. Although BWRs generate steam with 12–15% water vapor, resulting in slightly lower efficiency, they are easier to design and can handle variable power output. However, the need for shielding and maintenance of radioactive turbine components restricts BWRs' widespread adoption in marine settings.

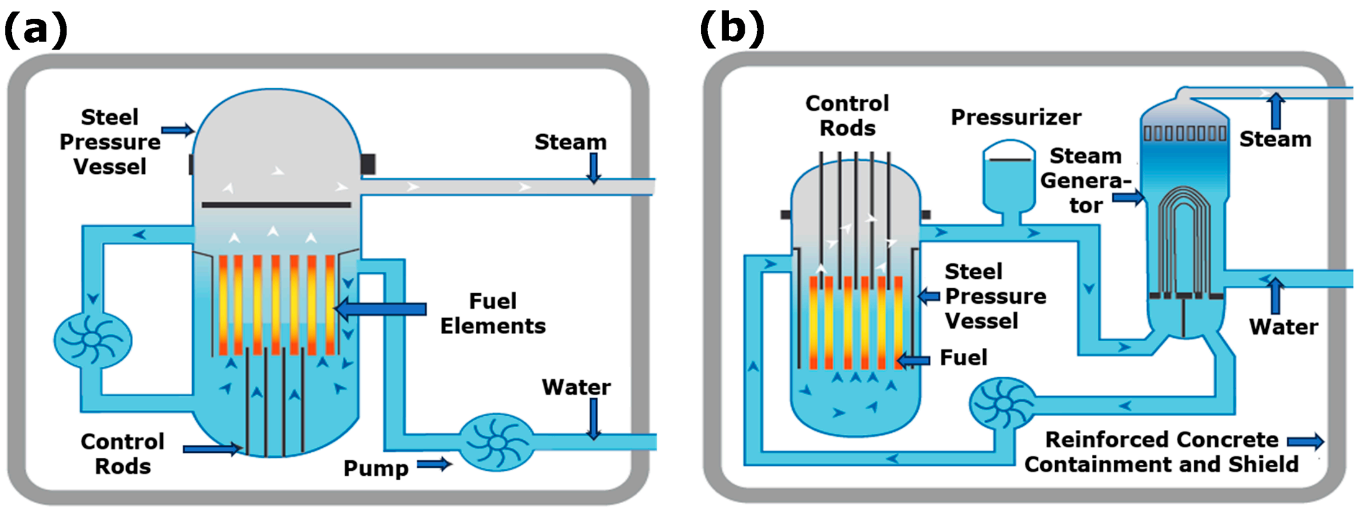

Figure 3. Schematics of a (**a**) boiling water reactor (BWR) and (**b**) pressurized water reactor (PWR) , extracted from World Nuclear Association [38].

Marine reactors incorporate multiple safety features to protect operators and ensure reliable performance. Heavy shielding, often made of lead, surrounds the reactor to protect personnel from radiation exposure. A typical marine reactor may contain over 100 tons of lead shielding, significantly increasing the ship's weight but ensuring crew safety. Advanced reactors are equipped with automated safety protocols that monitor the reactor's status and initiate shutdown procedures when necessary, ensuring continuous operation even in challenging environments [17].

Recent advancements in marine nuclear technology focus on improving reactor efficiency, extending operational lifetimes, and enhancing safety. New designs are exploring fast neutron reactors and molten salt reactors (MSRs) as potential alternatives to conventional thermal reactors [17,23]. Fast neutron reactors offer higher fuel efficiency by utilizing a broader range of isotopes for fission, while MSRs promise reduced waste production and improved safety due to their low-pressure operation and unique passive safety features [39]. Efforts are also underway to reduce reliance on HEU to mitigate nuclear proliferation risks, exploring the use of LEU with innovative designs that maintain performance while minimizing security concerns [15,33–35]. These advancements aim to enhance the sustainability of naval propulsion systems, reduce maintenance requirements, and further extend operational lifetimes, ensuring that marine nuclear technology continues to evolve in response to the needs of modern naval fleets.

2.1. Maritime Small Modular Reactors

Small and Medium-sized or Modular Reactors (SMRs) are nuclear reactors designed to be modular, scalable, and safer than conventional large reactors. According to the International Atomic Energy Agency (IAEA), SMRs are categorized based on their power output, with small reactors producing up to 300 MW electric (MWe) and medium-sized reactors generating between 300 and 700 MWe [40,41]. SMRs operate on the same principle as any nuclear reactor, initiating a chain reaction in the fissile material to generate heat. This heat is transferred to a power conversion system via a coolant to produce electricity. SMRs are gaining global interest for their modular design, which allows for easier construction, reduced costs, and faster deployment [42]. They feature enhanced safety measures, including passive safety systems and multiple safety barriers to prevent fission product release, even in extreme scenarios. This improved safety reduces the Emergency Planning Zone (EPZ) to the site boundary, enhancing emergency preparedness [43,44]. The advent of SMRs marks a significant leap in maritime nuclear propulsion, addressing environmental challenges and boosting energy efficiency. The smaller size and modular design of SMRs lower capital outlay per unit but result in higher specific costs per kWe compared to large reactors, at least initially [45]. The NuScale project, for instance, has been estimated as high as $20,139 per kW, nearing the $15,667 per kWe of the Vogtle plant, Waynesboro, Georgia, USA [46–48]. However, costs may decline with increased deployment and efficiency. The BWRX-300 SMR designed by GE Hitachi Nuclear Energy (Wilmington, NC, USA), aims to tackle these issues by offering up to 60% lower capital costs per megawatt compared to conventional SMRs, due to the over 50%, decrease in concrete building volume [49]. Despite the challenges surrounding the development and deployment of SMRs, several countries—including South Korea [50,51], the UK [52], the Czech Republic [53], and Poland [51,54,55]—are making significant strides in advancing SMR technology. Notably, Argentina's CAREM-25 (designed by the National Atomic Energy Commission, CNEA), a water-cooled SMR, is nearing completion [56,57], while the USA has certified an SMR design, setting an important benchmark for regulatory compliance [58,59]. These developments reflect the global momentum toward integrating SMRs into future energy frameworks, underscoring their potential to drive decarbonization and reliable electricity generation [60,61]. As international interest accelerates, SMRs are poised to become a key component of sustainable energy systems, helping nations meet ambitious climate goals and enhance energy security.

Currently, modular SMRs are primarily used in Floating Nuclear Power Plants (FNPPs), with operational examples in Russia and China (Table 2). FNPPs provide a reliable, low-carbon energy source for remote coastal areas, islands, and offshore installations, which traditionally relied on fossil fuels for power generation [24,62]. Russia's Akademik Lomonosov, the first SMR-based floating nuclear power plant, has been supplying electricity and heating to remote areas since 2019 [11]. With its success, Rosatom (Moscow, Russia) is now developing RITM series reactors for land and sea applications. China is also advancing FNPP technology with the ACP100S (China National Nuclear Corporation (CNNC), Beijing) and ACPR50S (China General Nuclear Power Group (CGN), Shenzhen, Guangdong) reactors for offshore energy, especially for oil and gas exploration [63,64]. Denmark's Seaborg Technologies (Copenhagen, Denmark) is collaborating with Samsung Heavy Industries (Seongnam, Republic of Korea) and Korea Hydro & Nuclear Power (Gyeongju, Republic of Korea) to develop Compact Molten Salt Reactors (CMSRs) [65]. In Canada, Prodigy Clean Energy (Montreal, QC, Canada) is partnering with NuScale Power (Portland, OR, USA) to create cost-effective offshore nuclear plants [61]. Additionally, Thorcon, based in the United States (Cheyenne, WY), plans to deploy a molten salt reactor in Indonesia by 2029 [42,66,67]. In South Korea, KEPCO (Korea Electric Power Corporation, Naju, Republic of Korea) is developing the BANDI-60S, an SMR designed for FNPPs [42,67] (Figure 4). This two-loop PWR has a thermal output of 200 MWt and an electrical output of 60 MWe, aimed at providing energy to remote locations like islands and offshore facilities. The BANDI-60S features a block-type design that improves safety by reducing large coolant pipe break risks. Partnering with Daewoo Shipbuilding & Marine Engineering (DSME) (Geoje, Republic of Korea), KEPCO targets niche markets with the reactor designed for a 60-year lifespan, a fuel cycle of 48–60 months, and a burnup rate of 35 GWd/t, ensuring sustainable energy for specialized settings [68]. Table 2 provides a summary of the various SMR-powered FNPPs being developed globally.

Table 2. Developments of floating nuclear power plants (FNPPs) to date in various countries.

Project/Vessel Name	Country	Reactor Type	Reactor Supplier	Fuel Type & Enrichment	Fueling Cycle	Primary Use	Shipbuilder	Status/Year of Commissioning	Ref
MH-1A Sturgis	USA	PWR (10 MW)	Martin Marietta, Bethesda, MD, USA	LEU, ~4% enrichment	2–3-year	FNPP (desalination)	Army Corps of Engineers, Washington, DC, USA	Operational from 1961 Retired (1976)	[69–71]
Akademik Lomonosov	Russia	2 x KLT-40S Modular PWRs (35 MW each)	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, 14.1% enrichment	3-year cycle	FNPP deployed to Pevek, Arctic region	Baltic Shipyard, Saint Petersburg, Russia.	Commissioned 2019	[72–74]
CNNC FNPP	China	ACP100 (125 MW Integrated PWR)	CNNC, Beijing, China	LEU, 4.8% enrichment	5–8 year	FNPP	China State Shipbuilding Corp. (CSSC), Shanghai, China	Commissioned 2022	[63,64,75]
CGN FNPP	China	ACPR50S (65 MW Modular PWR)	CGN, Shenzhen, China	LEU, 5% enrichment	5–8 year	FNPP	CSSC, Shanghai, China	Planned for 2025	[64,76]
Seaborg MSR Power Barge	Denmark	Compact MSRs (100 MW)	Seaborg, Copenhagen, Denmark	LEU with thorium options	12-year	FNPP	Likely DSME, Geoje, Republic of Korea	Expected by 2027	[65,77]
ThorCon Nuclear Reactor	Indonesia	Thorium MSR (500 MWt)	ThorCon International, Cheyenne, WY, USA	LEU (Molten Salt)	8-year (planned)	FNPP/Local power generation	DSME, Geoje, Republic of Korea (planned)	Planned for 2028	[42,66,67].
OPEB Floating Unit	Russia	2 x RITM-200M Integrated PWRs (50 MW each)	OKBM Afrikantov, Nizhny Novgorod, Russia	LEU, 14.1% enrichment	3-year cycle	FNPP	TBD	Planned for 2028	[11,77,78]
Kepco FNPP	Korea	BANDI-60S Modular PWR (60 MW)	Kepco E&C, Gimcheon, Republic of Korea	LEU, 14.1% enrichment	3-year cycle	FNPP	DSME, Geoje, Republic of Korea	Planned for 2029	[42,67,68,77]
NuScale FNPP	Canada/USA	NuScale SMR (60 MW per module)	NuScale Power, Portland, OR, USA	LEU, 4.95% enrichment	2-year cycle	FNPP	TBD	Planned for 2030+	[61]
Prodigy Clean Energy	Canada	NuScale SMR/MSR (various)	NuScale/Prodigy Clean Energy, Montreal, QC, Canada	LEU, 4.95% enrichment	2–5-year cycle	FNPP/Island power	TBD	Concept stage. Planned deployment by 2030	[61]

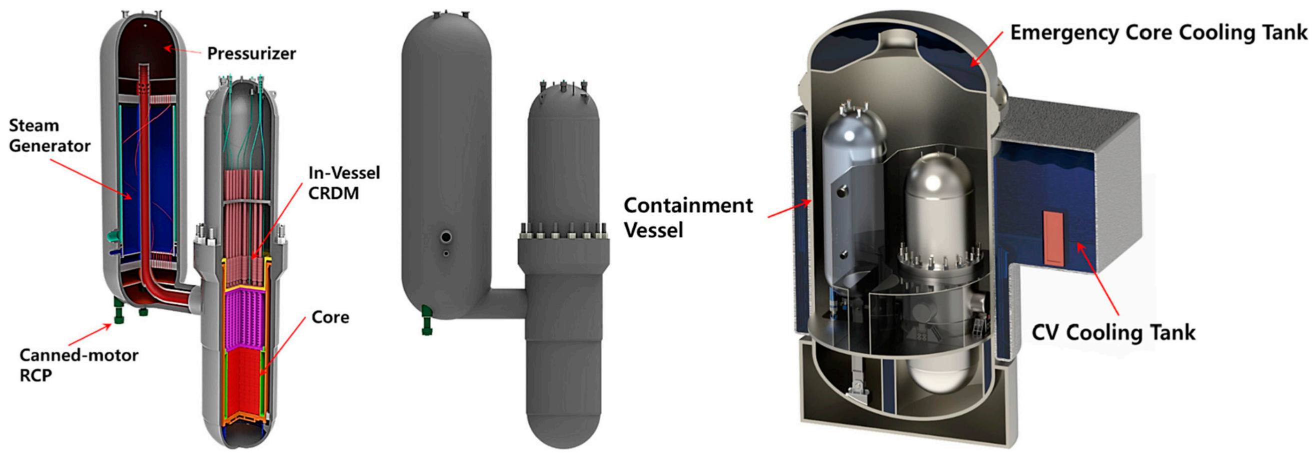

Figure 4. Configuration of the safety features of the BANDI-60S SMR to be used in floating nuclear power plants in South Korea, reproduced with permission from Elsevier B.V. 2024 [43].

2.2. Safety Features and Operational Efficiency of Nuclear-Powered Vessels

The history of nuclear-powered vessels reveals significant regulatory vulnerabilities, highlighted by incidents like the 1962 discharge of low-level radioactive waste by the NS Savannah, the 1968 Suez Canal passage denial for the Otto Hahn due to insufficient safety documentation, and the 1974 radioactive leak from the Mutsu during its maiden voyage [13]. These events underscored the need for stricter safety regulations and design improvements. A 1996 report from Denmark's RISO Research Institute (Roskilde, Denmark) noted 61 accidents involving nuclear-powered ships, mainly in Russia, including serious incidents like Loss of Coolant Accidents (LOCA) and reactor failures [17,79]. Among these, 20 incidents resulted in vessel sinkings, while the USA reported six incidents, including flooding and reactor issues. Figure 5 presents the incident cases involving nuclear-powered ships, showing a total of 61 accidents. Notable incidents further illustrate the risks of nuclear vessels, such as the 2000 Kursk submarine disaster, which killed all 118 crew members [80,81], and the 2003 collision of the USS Hartford with the USS New Orleans, which caused damage but no radiation leak [82]. The grounding of the USS San Francisco in 2005 resulted in one fatality, and the Fukushima Daiichi disaster in 2011 had wide-ranging implications for nuclear safety protocols, including maritime operations [83]. In 2012, a fire on the USS Miami caused extensive damage without radiation release, while a 2019 fire on the Russian submarine Losharik claimed 14 lives, raising concerns about the aging fleet [81]. The Otto Hahn incident specifically exposed gaps in the regulatory framework, leading to enhanced safety requirements for nuclear vessels, including clear compliance evidence with international standards for sensitive areas like the Suez Canal. This prompted more rigorous safety assessments, inspections, and increased oversight from maritime and nuclear regulatory agencies. The incident also fostered international cooperation on nuclear safety standards, promoting harmonization of regulations and best practices.

Currently, several small modular reactor (SMR) designs are in development, with growing interest in maritime applications. The Idaho National Laboratory predicts that by 2050, SMRs could make up 50% of new nuclear power plants. By 2035, they may replace 65–85 gigawatts of fossil fuels globally. The marine nuclear market, valued at $2.3 billion in 2022, is projected to grow at an annual rate of 8.8%, reaching $4.9 billion by 2031 [84]. Lessons from historical incidents continue to shape the safety features and operational efficiency of modern nuclear-powered vessels, driving advancements in technology and regulation.

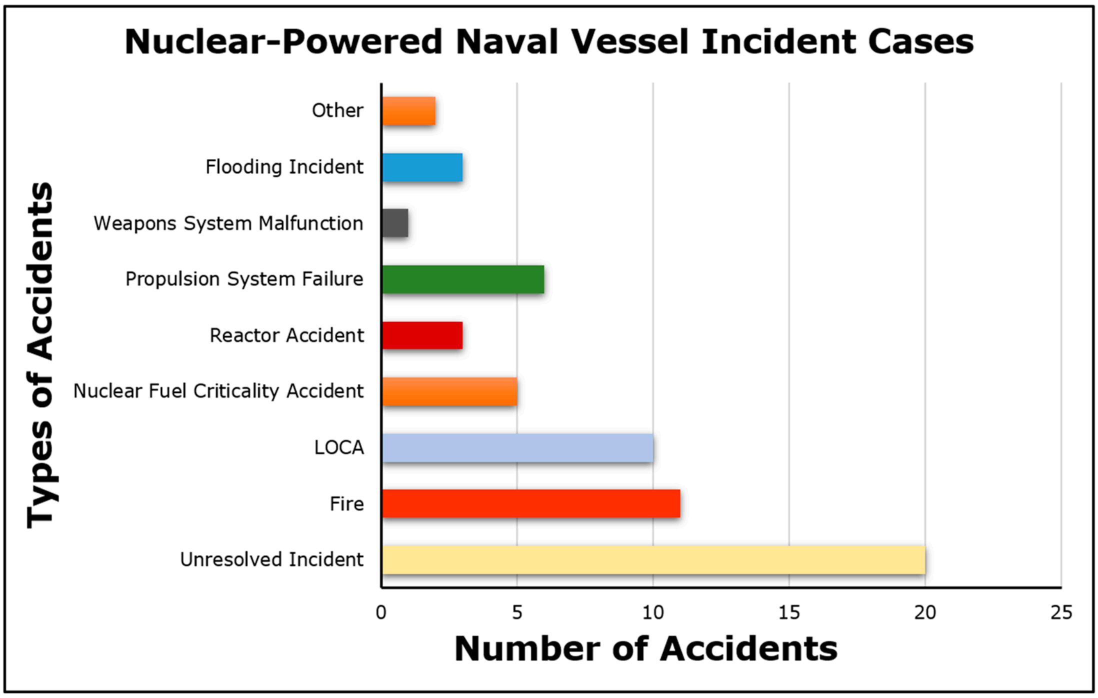

Figure 5. Nuclear-powered naval vessel incident cases. Data extracted from [79].

3. Regulatory Framework for Maritime SMRs and FNPPs in Korea

The deployment of SMRs and Floating FNPPs in Korea presents unique regulatory and licensing challenges due to their advanced technology, potential offshore deployment, and the necessity for strict compliance with safety, security, and environmental standards. Korea is actively developing a regulatory framework to guide the use of these reactors in maritime applications, ensuring alignment with both domestic and international requirements. This effort aims to balance technological innovation with robust oversight, addressing safety concerns while promoting sustainable energy solutions. The licensing process for maritime SMRs and FNPPs typically involves several sequential stages: submission of the design application, comprehensive safety analysis, environmental impact assessments, and a detailed review by regulatory bodies. While many countries' licensing frameworks for SMRs resemble those for larger nuclear plants, the unique characteristics of SMRs—such as their smaller size, modularity, and operational flexibility—require adaptations to existing regulations. To address this, Korea is advancing a technology roadmap focused on the development and regulation of nuclear-powered propulsion ships, divided into short-term and long-term phases, with initial efforts aimed at adapting existing laws for maritime reactors. Amendments to the Korean Atomic Energy Act may be necessary to tackle the specific challenges of ship propulsion reactors. The roadmap includes developing legal standards for the design, verification, and safety analysis of these reactors, emphasizing a phased approach that begins with domestic law reviews and extends to harmonization with international standards. This process will establish a legal basis for licensing nuclear-powered vessels while aligning regulatory practices with those governing conventional nuclear plants, tailored for maritime environments.

A recent study by Kim et al. [85] examined both domestic (Korean) and international regulatory frameworks related to nuclear-powered ships, highlighting essential safety considerations for ship propulsion reactors in Korea. This study also discusses regulations specifically aimed at marine vessels powered by more compact and integrated SMRs, which offer enhanced safety features compared to traditional nuclear ship reactors. The study recommends establishing a specialized licensing framework for these vessels, drawing on elements from the USA Nuclear Regulatory Commission (NRC) guidelines for SMRs, particularly the NuScale licensing case. This approach allows Korea to utilize international best practices while adapting them to local circumstances. It emphasizes that SMR-powered vessels incorporate enhanced safety features, including passive safety mechanisms that significantly reduce accident risks compared to conventional light-water nuclear ship reactors.

Maritime SMRs and FNPPs in Korea must adhere to multiple layers of national and international regulations. The Korea Institute of Nuclear Safety (KINS) plays a central role in ensuring compliance through safety evaluations based on Light-Water Reactor Safety Examination guidelines, which are heavily influenced by the USA NRC's NUREG-0800 framework. Additionally, marine reactors must comply with maritime-specific regulations established by the Ministry of Maritime Affairs and Fisheries, including adherence to the IMO's Safety of Life at Sea (SOLAS) Chapter 8 regulations for nuclear vessels, ensuring that licensing procedures align with global maritime safety standards.

Korea's regulatory strategy aims to harmonize domestic laws with international frameworks to facilitate the deployment of maritime SMRs. This harmonization is essential for streamlining regulatory approvals, enhancing international collaboration, and ensuring that Korean nuclear-powered vessels can operate in international waters without regulatory conflicts. The roadmap reflects Korea's commitment to global safety standards, integrating nuclear safety regulations from the IAEA and maritime law from the IMO to address critical areas such as radioactive waste management, accident prevention, and emergency response [15,86]. Figure 6 illustrates the considerations for establishing marine SMR licensing requirements.

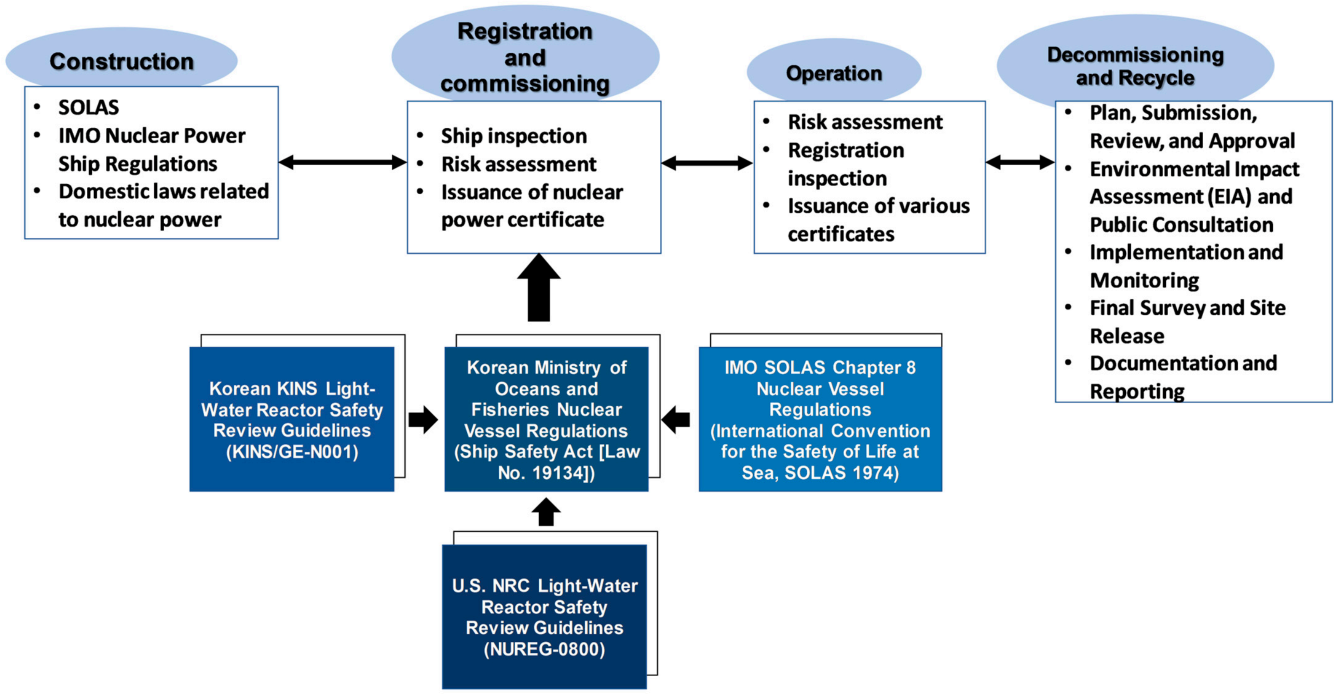

Figure 6. Considerations for the establishment of marine SMR licensing requirements, reused with permission from the Korea Society of Radiation Industry 2024 [85].

3.1. International Maritime Organization's (IMO) Regulations on Nuclear-Powered Vessels: Current Framework and Recommendations for Updates

The IMO regulates nuclear-powered vessels through Chapter VIII of the SOLAS Convention, which outlines essential safety requirements for their operation [20,87,88]. The Code of Safety for Nuclear Merchant Ships supplements these rules by establishing specific safety standards for nuclear-powered merchant vessels. However, these regulations need modernization to address emerging technologies, such as SMRs and FNPPs, which introduce new safety features and operational complexities.

3.1.1. Current Regulatory Framework

SOLAS Chapter VIII contains twelve rules governing the operation of nuclear-powered vessels. These rules apply to all nuclear-powered vessels, except warships (Rule 1), and require full compliance with the general provisions of SOLAS and additional guidelines outlined in IMO Resolution A.491(XII) (Rule 2). No exemptions from these rules are permitted (Rule 3). The regulations emphasize oversight by competent national authorities. For example, the reactor's design, installation, and operational standards must be approved by relevant authorities, accounting for radiation-related inspections (Rule 4). The installation of the reactor must reflect the ship's characteristics and navigational limitations (Rule 5). Authorities must ensure that no unexpected radiation hazards arise, either onboard the vessel or ashore (Rule 6).

Port operations for nuclear-powered vessels require comprehensive risk assessments to confirm that no radiation hazards will affect port states (Rule 7). These assessments must be shared with port states visited by the vessel. An operating manual detailing safety protocols is required to ensure safe operation (Rule 8), and inspections based on the risk assessment must be conducted annually (Rule 9). Nuclear-powered vessels must also carry a Nuclear-Powered Vessel Safety Certificate that is renewed annually (Rule 10). Port states have the authority to conduct special inspections following IMO/IALA safety recommendations (Rule 11). In the event of maritime accidents, the captain is required to notify neighboring countries to initiate emergency response protocols (Rule 12).

3.1.2. Recommendations for Regulatory Updates

The deployment of SMRs and FNPPs in the maritime sector necessitates significant regulatory updates to ensure these advanced technologies are safely integrated [12]. SOLAS Chapter VIII must be modernized to accommodate new reactor designs and operational features specific to commercial shipping. The following are recommended.

1. The chapter should introduce guidelines for passive safety systems, automated emergency shutdown mechanisms, and radiological protection protocols. Additionally, decommissioning standards tailored for merchant vessels should be integrated to address the unique lifecycle of these reactors.
2. The evolving nature of nuclear technology calls for close collaboration between the IMO and the IAEA to develop a harmonized regulatory framework [12]. Joint protocols are needed to address safety management, radioactive waste disposal, and emergency response drills. Port-entry protocols must be standardized to ensure smooth and compliant operations across international borders. Coordination between the two organizations will help align nuclear and maritime regulations, especially in managing cross-border operations and nuclear waste compliance.
3. Commercial shipping operations will need new training and certification programs to prepare civilian crews for managing nuclear-powered vessels, which are not currently included in the STCW framework [28,29]. Guidelines are also needed for refueling operations, remote maintenance, and radiological hazard management, all tailored for non-military environments. Furthermore, port-entry requirements should be updated to address varying national safety standards, ensuring streamlined inspections and defining rules for navigating sensitive areas, such as Arctic shipping routes and exclusive economic zones (EEZs).
4. Clear protocols for radioactive waste management are essential to prevent environmental risks. Offshore waste handling procedures must be established and spent fuel storage solutions implemented. Decommissioning processes should be integrated into the regulatory framework to ensure safe vessel dismantling and nuclear material disposal.
5. Enhanced safety and security measures are critical for mitigating risks, including radiation leaks, accidents, piracy, and security threats. Regulations should mandate physical security systems and cybersecurity protections to prevent unauthorized

access to reactor systems. Emergency shutdown procedures must also be established, along with international agreements for responding to radiological incidents at sea.

6. The introduction of nuclear-powered vessels also raises concerns about liability and insurance. New nuclear-specific liability conventions for commercial shipping should be developed, and public-private insurance models encouraged to manage the financial risks of nuclear accidents.
7. Environmental protection must remain a priority. Comprehensive environmental impact assessments (EIAs) should be conducted to evaluate risks associated with nuclear-powered vessels, particularly in ecologically sensitive areas. These assessments should include radioactive emissions monitoring and marine contamination evaluations, with continuous monitoring of FNPPs and nuclear-powered ships operating in international waters.

3.2. Korean Ministry of Oceans and Fisheries Regulations on Nuclear-Powered Vessels

To facilitate the deployment of maritime SMRs and align with international standards, Korean regulations must harmonize with the frameworks established by the IMO and the IAEA. Korea's regulatory approach should fully integrate global best practices in areas such as radioactive waste management, accident prevention, and emergency response. However, inconsistencies between Korea's regulations and international standards present challenges that need to be resolved to promote safer and more compliant operations [85,89].

3.2.1. Current Regulatory Framework for Nuclear-Powered Vessels in Korea

The Korean Ministry of Oceans and Fisheries governs the operation and regulation of nuclear-powered vessels through several articles. Article 2 defines key terms related to nuclear reactors, which establish the regulatory scope. Article 3 allows the Minister of Oceans and Fisheries to accept special equipment as compliant if it performs as effectively as the stipulated standards. Article 4 mandates that the hull structure and material be corrosion-resistant or appropriately treated. It also requires nuclear-powered vessels to adhere to standards related to steel structure, stability, compartmentalization, machinery, electrical systems, fireproofing, firefighting, lifesaving equipment, and other essential facilities. Article 5 outlines the approval process for reactor installations, requiring that reactor design, construction, inspection, and assembly be approved by the Minister. The approval must account for radiation inspection limitations and ensure that the installation is appropriate for the navigational conditions in which the ship will operate. Article 6 requires the preparation of safety documentation, including an assessment of radiation risks to the ship's occupants, food, and water supplies. The safety document, once approved, must remain up to date, and a safety evaluation report must be submitted to port authorities well in advance to allow for comprehensive safety reviews. Article 7 mandates the development of an operating manual for the nuclear facility, which must include operational protocols and procedures. This manual must be approved by the Minister of Oceans and Fisheries and kept current. Article 13 addresses the containment vessel requirements, stipulating that it must prevent leakage of radioactive materials in case of equipment damage. The article prohibits the use of safety valves that could release radioactive materials externally, requiring instead the installation of pressure equalization devices to protect the containment vessel from external pressure if the ship sinks. It also requires stop valves or check valves for any pipes penetrating the containment to prevent radioactive leakage.

3.2.2. Conflicts Between Korean Regulations and IMO Standards: Recommendations for Harmonization

Korea's regulatory framework for nuclear-powered vessels contains several conflicts with IMO standards, which can hinder effective alignment with international requirements and create operational challenges. One key conflict lies in terminology and definitions. Article 2 of Korea's regulations provides specific definitions for terms related to nuclear reactors, but these may not align with the broader terminology used by the IMO. Inconsistent definitions can lead to interpretation discrepancies between national and international authorities, complicating compliance. Harmonizing these definitions with those used by the IMO would ensure consistency and reduce ambiguity.

The reactor installation approval process outlined in Article 5 focuses primarily on national oversight by the Minister of Oceans and Fisheries, emphasizing radiation inspections. In contrast, the IMO encourages a more collaborative approval process involving multiple stakeholders, including international regulatory bodies. Korea should consider incorporating international stakeholders into the approval process to streamline installations and ensure compliance with both domestic and international standards. There are also discrepancies in safety documentation requirements. Article 6 mandates that safety documentation be submitted to port authorities, but the IMO requires standardized safety documentation recognized by multiple jurisdictions. Aligning Korea's safety documentation procedures with IMO guidelines would facilitate smoother port entry and inspections for nuclear-powered vessels in international waters.

Article 7 mandates the creation of an operating manual for nuclear vessels. However, the IMO emphasizes international best practices and comprehensive emergency protocols in operating manuals, which may not be fully captured in the Korean framework. Updating Korean operating manuals to reflect IMO standards would ensure they include comprehensive emergency procedures and best practices for handling maritime accidents. The containment requirements in Article 13 also present potential conflicts. The prohibition on external safety valves for containment vessels may differ from IMO-accepted safety technologies, which could offer more effective containment solutions. Korea should review and adopt internationally recognized safety technologies to allow for greater flexibility and compliance with evolving global standards.

3.2.3. Recommendations for Harmonizing Korean Regulations with International Standards (IMO and IAEA)

1. Harmonize Terminology: Align key definitions in Article 2 with IMO terminology to ensure clarity and reduce inconsistencies in interpretation between domestic and international authorities.
2. Collaborative Approval Process: Revise Article 5 to incorporate a collaborative reactor installation approval process, involving international stakeholders and regulatory bodies to ensure compliance with global safety standards.
3. Align Safety Documentation Procedures: Update Article 6 to ensure safety documentation follows IMO guidelines for standardized reporting, facilitating smoother port entry and regulatory inspections.
4. Update Operating Manuals: Modify Article 7 to incorporate international best practices and emergency protocols outlined by the IMO, ensuring comprehensive operational guidance for nuclear-powered vessels.
5. Adopt Flexible Containment Standards: Review Article 13 to incorporate internationally recognized containment technologies, allowing greater flexibility in safety solutions while maintaining high containment standards.
6. Strengthen Port and Waste Management Protocols: Develop standardized port-entry protocols for nuclear-powered vessels and align radioactive waste management practices with IMO and IAEA guidelines to facilitate smooth international operations.
7. Expand Crew Training Programs: Introduce training and certification programs for civilian crews that align with international maritime and nuclear safety standards, preparing them for the unique challenges of operating nuclear-powered vessels.
8. Enhance Emergency Preparedness: Establish international emergency response agreements to handle radiological incidents at sea, ensuring prompt and coordinated action between domestic and international authorities.

3.3. Analysis and Comparison of the USA SMR (NuScale) and the Korean (SMART) Licensing Cases

The NuScale SMR and the Korean SMART (System-Integrated Modular Advanced Reactor) are both integrated Pressurized Water Reactors (iPWRs), designed to offer compact, safe, and efficient nuclear power solutions. While both share modular designs, safety-focused features, and regulatory processes, each follows distinct codes, methodologies, and licensing procedures shaped by their respective national regulatory bodies. This section compares the key methodologies and regulatory approaches of NuScale and SMART, highlighting similarities, differences, and insights that can inform future regulatory alignment.

SMART, with a capacity of 100 MWe, received Standard Design Approval from the Korean Nuclear Safety and Security Commission (NSSC) on 4 July 2012—the first iPWR to achieve certification. SMART focuses on integrated reactor systems that improve safety through passive safety mechanisms, reduced components, and simplified maintenance [43]. In contrast, the NuScale SMR underwent an extensive licensing process with the USA Nuclear Regulatory Commission (NRC) between 2008 and 2020 [59,90]. The Pre-Application Review (PAR) conducted between 2008 and 2016 identified potential licensing issues early on. Following this, the NRC issued Design-Specific Review Standards (DSRS) in 2016 to facilitate a more streamlined design certification process. The formal Design Certification Application (DCA) review from 2016 to 2020 included more than 2000 Requests for Additional Information (RAIs) related to the design and 400 RAIs concerning Topical Reports (TRs), reflecting the extensive scrutiny involved in the USA regulatory framework. The licensing process for the NuScale SMR is illustrated in Figure 7.

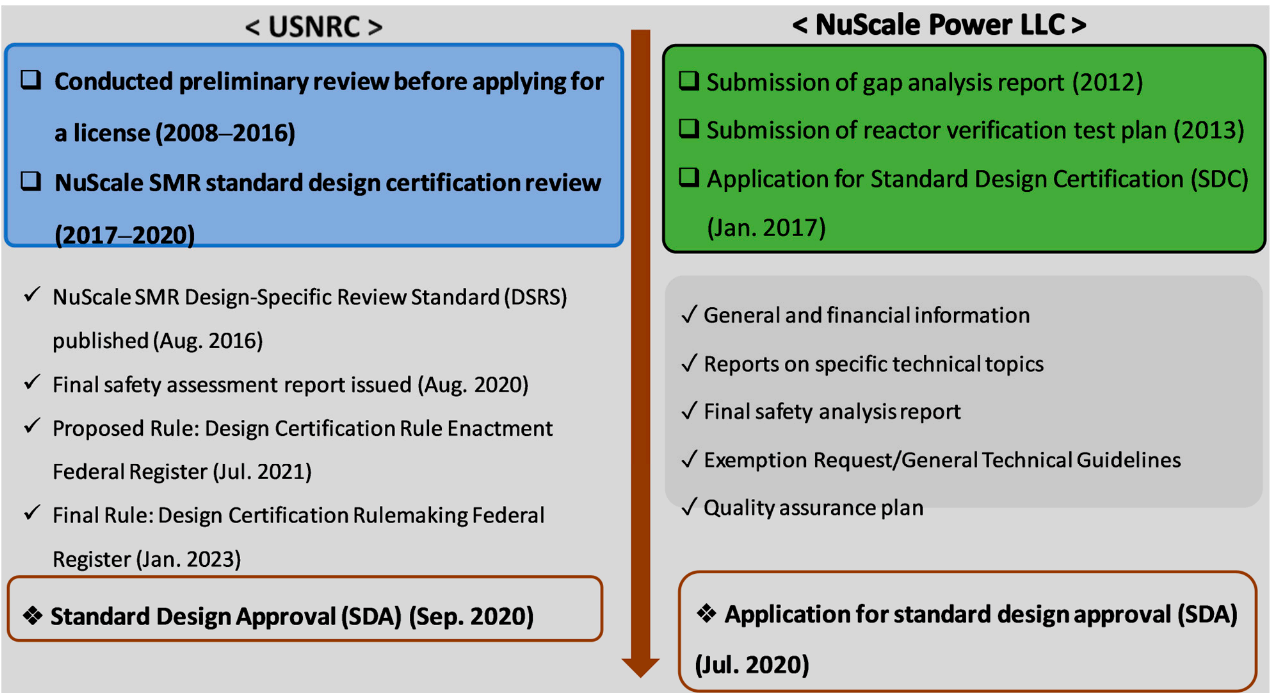

Figure 7. US SMR (NuScale) licensing process [90].

3.3.1. Codes, Methodologies, and Safety Features

Both NuScale and SMART utilized advanced codes and methodologies to assess and validate their reactor designs. However, there are key distinctions in their approaches: The NuScale SMR emphasizes accident prevention and mitigation in both transient and non-LOCA scenarios. Seven primary transient scenarios were evaluated, including reactivity anomalies, coolant flow reduction, radioactive release events, and heat removal issues. The RELAP5 code [91,92] was used extensively to model LOCA. Other analytical tools, such as SCANR (Subchannel Analyzer for NuScale Reactors) [93] and CASMO-5 [94], were employed to analyze neutron behavior and subchannel flow dynamics. Specific attention was given to control rod ejection accident analyses using tools like SIMULATE-3K [95] and RELAP5 [92] to ensure reactor stability during severe transients. The SMART reactor focuses on passive safety systems designed to operate without external power, enabling extended cooling and safety operations for up to 72 h. While SMART also evaluates accident scenarios, such as LOCA and transient events, its design relies heavily on natural circulation mechanisms to ensure safety. SMART's safety analysis integrates codes similar to those used internationally (e.g., RELAP5), but with customized configurations to match local regulatory needs.

NuScale employs several proprietary codes to perform system-level analyses, many of which are aligned with NRC-approved methodologies. However, proprietary restrictions sometimes limit public access to these codes. In contrast, SMART relies on more transparent methodologies, including internationally recognized tools like MARS-KS (Multi-dimensional Analysis of Reactor Safety) [92,96], which supports validation by both Korean and international regulatory bodies. The openness of SMART's methodology aids in fostering regulatory collaboration between Korea and international organizations.

3.3.2. Exemptions and Regulatory Flexibility

Regulatory exemptions play a crucial role in both the USA and Korean frameworks, particularly in addressing scenarios where standard requirements may not apply to SMR. In the United States, under 10 CFR 50.12, the NRC allows for exemptions when compliance would pose excessive difficulty or cost, or when such exemptions align with public safety and national security interests. This flexibility enables the NRC to permit exemptions that address conflicts with other regulatory requirements and to temporarily defer compliance when necessary. As a result, NuScale has successfully obtained several exemptions during its certification process to accommodate the unique design features of its SMR.

In contrast, Korea's licensing process, governed by the NSSC, offers fewer formal exemptions. However, there is some degree of flexibility through Article 3 of the Ministry of Oceans and Fisheries regulations, which permits the approval of alternative equipment that meets or exceeds the required safety standards. Despite this provision, Korea's regulatory framework could benefit from adopting a more collaborative exemption process similar to that seen in the USA. This approach would enhance the ability to adapt to the innovative aspects of modular reactor designs.

Additionally, the Canadian Nuclear Safety Commission (CNSC) provides a useful precedent with its REGDOC-2.5.2, which allows for alternative approaches to reactor design as long as they meet or exceed existing safety standards. By incorporating similar provisions into its licensing framework, Korea could offer greater flexibility for the deployment of small modular reactors. Such changes would not only facilitate innovation but also ensure that safety remains a top priority while adapting to the evolving landscape of nuclear technology [97].

3.3.3. Recommendations for Aligning Korean SMR Licensing with International Standards

To enhance the global competitiveness of Korean SMRs and streamline regulatory processes, Korea should focus on aligning its SMR licensing framework with international standards. This alignment will not only facilitate smoother international certification and operation but also strengthen safety and innovation within the industry. Key recommendations for achieving this include adopting internationally accepted safety standards and codes, which would promote transparency and consistency in safety assessments. By expanding the use of these codes and methodologies, Korea can facilitate joint regulatory reviews with bodies such as the USA NRC and the CNSC.

Additionally, Korea should introduce flexible exemption provisions similar to those found in 10 CFR 50.12 (NRC) and REGDOC-2.5.2 (CNSC). These mechanisms would allow Korean SMRs to adopt alternative safety approaches when appropriate, thereby enhancing innovation while ensuring that safety standards remain uncompromised. Enhancing collaboration with international regulatory bodies is also essential; Korea should encourage collaborative design reviews and joint licensing processes with the NRC and CNSC. This collaboration would enable Korea to leverage shared expertise, minimize redundant reviews, and ensure that they align with global safety expectations.

Furthermore, Korea should work with the IMO to standardize port-entry protocols and emergency procedures specifically for maritime SMRs. This initiative would ensure that vessels powered by Korean SMRs can operate seamlessly across international waters. Finally, incorporating both proprietary and public codes strategically will be beneficial. While proprietary codes can enhance efficiency, balancing their use with publicly accessible tools (similar to SMART's approach) will foster regulatory transparency and build international trust. By implementing these recommendations, Korea can significantly improve its SMR licensing process and strengthen its position in the global nuclear energy market.

3.4. Comparison of Russian Reactor Ship Regulations (NP-079-18) with Korean Maritime SMR Regulations: Key Insights for Harmonization

Russia's NP-079-18 regulation offers a valuable framework for comparison, as it provides comprehensive guidance on the operation, decommissioning, emergency preparedness, and emergency declarations for ships equipped with nuclear reactors. Approved under Russian Federal Law No. 170-FZ, "On the Use of Atomic Energy", NP-079-18 focuses on establishing protection plans for personnel in the event of nuclear or radiation accidents, applying to both operational and decommissioning phases of nuclear vessels, including FNPPs [98]. Korea can benefit by adopting and adapting aspects of NP-079-18 to ensure that its regulatory environment is sufficiently robust to handle the unique challenges posed by nuclear-powered ships. Harmonizing with Russian best practices will complement the alignment efforts with IAEA and IMO frameworks, enabling Korea to develop a comprehensive regulatory model for maritime nuclear reactors. A summary comparing the regulatory frameworks for SMRs in the USA and Korea with the Russian NP-079-18 is presented in Table 3.

Table 3. Comparative summary of NuScale, SMART, and Russian NP-079-18 regulatory frameworks.

Aspect	NuScale (USA)	SMART (Republic of Korea)	Russia (NP-079-18)
Regulatory Body	NRC (USA)	NSSC (Republic of Korea)	Rostekhnadzor (Russia)
Emergency Preparedness	Passive systems; collaborative response	Natural circulation; safety documentation	Precise action plans and real-time alerts
Exemptions and Flexibility	Available under 10 CFR 50.12	Limited flexibility; relies on IAEA standards	State control with fewer external reviews
Communication and Notification	Multi-stakeholder collaboration	Port authorities and national agencies	Notification within 15 min to emergency teams
Design Focus	Modular, scalable for urban/remote sites	Compact, targeted for smaller grids	Energy independence for Arctic and remote operations
Data Transmission	Real-time monitoring	Safety evaluations during port operations	Mandatory real-time data during operation

3.4.1. General Provisions and Regulatory Details of NP-079-18

In Russia, shipbuilding organizations are responsible for planning and preparing safety and protective measures during the construction and commissioning phases. Once the vessel becomes operational or enters the decommissioning stage, the captain and senior officers take responsibility for maintaining these measures. Standardized measurement plans must be collaboratively developed by the main engineering organization and the responsible authority, but each ship's plan is tailored to its specific operational conditions and design characteristics, with final approval granted by the ship's captain.

These action plans include design-basis and beyond-design-basis accident scenarios to ensure preparedness for a wide range of potential incidents. During the ship's construction, shipyards must have systems to transmit condition and radiation data to emergency response teams, with real-time data transmission required during the operation and decommissioning phases. The responsible authority oversees regular updates of these plans, ensuring they are reviewed at least every five years or sooner if operational changes necessitate revisions. Korean regulations should adopt similar measurement plan strategies, ensuring that safety plans are ship-specific while reflecting general design standards. Regular updates to these action plans, aligned with evolving IAEA and IMO recommendations, would maintain high safety standards and improve preparedness across a ship's lifecycle.

3.4.2. Measurement Plan Requirements and Safety Systems Documentation

NP-079-18 mandates that measurement plans must contain detailed information on personnel deployment, the status of safety-related systems, and the readiness of emergency equipment. Documentation of routine inspections, repairs, and the continuous monitoring of operational parameters is required. Personnel must log radiation data during both normal operations and potential accident scenarios. Additionally, the plan must include evacuation routes, procedures for managing personnel exposure, and protocols for issuing emergency warnings and coordinating communications during incidents.

Korea should incorporate comprehensive radiation monitoring and logging procedures into its maritime SMR regulatory framework, requiring routine inspections and personnel training for emergency scenarios. Establishing clear protocols for emergency communication (in coordination with national and international authorities) would align Korean regulations with NP-079-18 and IAEA standards, improving operational safety and accountability.

3.4.3. Emergency Preparedness and Declaration Protocols

Russia's NP-079-18 outlines detailed criteria for declaring an emergency preparedness state for FNPPs. An emergency state can be declared if safe operational limits are violated or if external impacts disrupt key safety systems. Specific criteria include exceeding radiation dose rates and the occurrence of design-basis accidents. Upon declaring an emergency, the captain or their substitute assumes responsibility for managing the response and implementing the action plan. The FNP administration must notify emergency response agencies within 15 min of the declaration, following an approved warning schedule. Precautionary measures are activated immediately to contain the situation and prevent escalation. Coordination with IAEA standards and relevant regional agreements ensures seamless collaboration between the vessel's crew, national authorities, and international bodies.

Korea's maritime SMR regulations should establish clear emergency preparedness criteria, including thresholds for radiation dose rates and protocols for accident declaration. Like the Russian model, Korea should require real-time notification to national and international authorities to ensure timely responses to emergencies. The inclusion of pre-approved warning schedules and collaboration protocols with IAEA and IMO frameworks would ensure smooth coordination during incidents at sea.

3.4.4. Recommendations for Harmonizing Korean Regulations with NP-079-18

To enhance regulatory alignment and improve safety protocols for maritime SMRs, Korea should adopt several elements from Russia's NP-079-18 framework:

1. Establish Collaborative Measurement Plans: Develop standardized measurement plans tailored to each vessel's specific operational conditions in coordination with shipbuilders and engineering organizations.
2. Implement Real-Time Data Transmission Requirements: Require real-time monitoring and transmission of radiation levels and operational data during the construction, operation, and decommissioning phases, ensuring quick responses to emerging risks.

3. Define Clear Emergency Preparedness Criteria: Incorporate detailed criteria for emergency declarations, including design-basis accidents and radiation dose thresholds. Develop action plans that comply with both IAEA standards and regional agreements for effective incident management.
4. Adopt Pre-Approved Communication Protocols: Introduce standardized warning schedules to guide emergency notifications and ensure coordination with national and international response agencies, modeled after NP-079-18′s 15-min notification rule.
5. Incorporate Regular Regulatory Reviews and Updates: Ensure safety action plans are reviewed every five years or earlier, reflecting operational changes and regulatory developments to maintain high safety standards.

4. Global Harmonization of Regulatory Standards for SMRs: Opportunities and Challenges

The global deployment of SMRs presents significant opportunities for harmonizing regulatory frameworks [45]. As international interest in SMR technology grows, consistent safety, security, and licensing standards are becoming increasingly essential to facilitate cross-border deployment and ensure public safety. The International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) are central in coordinating these efforts, offering guidance on licensing and establishing best practices for SMRs through initiatives that foster collaboration among member states. Key initiatives like the International Framework for Nuclear Energy Cooperation (IFNEC) and the Multinational Design Evaluation Program (MDEP) are vital for fostering collaboration between regulatory authorities and industry stakeholders.

MDEP, a project under the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD), coordinates regulatory reviews of new reactor designs across multiple countries [99]. This initiative enables regulators and industry participants to share technical expertise and align nuclear safety standards, promoting uniformity in design approvals and licensing processes. It is essential for facilitating information exchange among regulatory bodies, reducing redundant reviews, and enhancing the efficiency of SMR deployment across jurisdictions. The IFNEC serves as a collaborative forum that unites states and organizations to promote the safe and secure development of nuclear energy for peaceful purposes [100]. Established to encourage nuclear power use while addressing concerns related to nuclear waste and proliferation, IFNEC provides a platform for member countries to explore mutually beneficial approaches to nuclear energy, ensuring adherence to the highest standards of safety, security, and non-proliferation. The framework includes 34 participant countries, 31 observer countries, and several international organizations, such as the IAEA and the Generation IV International Forum. IFNEC operates through various working groups and committees that focus on infrastructure development, policy coordination, and technical cooperation. Its mission is to facilitate international collaboration, share best practices, and support the development of nuclear energy infrastructure in member countries.

4.1. IAEA's Nuclear Harmonization and Standardization Efforts

While progress in harmonization is being made, challenges remain, particularly in regulatory adaptation, public acceptance, and financing for SMR projects. To address these, the IAEA launched the Nuclear Harmonization and Standardization Initiative (NHSI), which seeks to unite policymakers, regulators, designers, and operators around common regulatory strategies [40,101]. NHSI focuses on fostering collaboration during the pre-licensing phase to develop consensus on technical and policy issues while advancing safety and security measures. However, current NHSI efforts encompass all SMR applications and do not give specific attention to maritime SMRs, which have unique regulatory challenges. These include marine environmental risks, navigation laws, international port regulations, and protocols for managing accidents at sea. Future NHSI initiatives would benefit from tailored strategies that address the specific needs of maritime SMRs, supporting their deployment in the maritime sector.

The IAEA has established an Agency-wide Platform on SMRs and Their Applications, providing a comprehensive resource for member states exploring SMR technology. Furthermore, the IAEA has reviewed over 60 safety standards relevant to SMRs and is preparing to release a detailed safety report that will guide the application of these standards to diverse SMR technologies, ensuring consistency in global regulatory practices.

4.2. Modular Design and Standardization Opportunities

The modular design of SMRs offers significant potential for streamlining licensing processes and reducing development costs. Standardizing reactor components and operational procedures across jurisdictions would accelerate regulatory approvals and enhance international deployment efforts. However, the benefits of modularity can only be fully realized through consistent regulatory frameworks across different countries. The IAEA's 'SMR-160' framework is an integrated approach that addresses safety, security, and non-proliferation concerns, aligning SMR regulatory practices across member states.

Additionally, the NEA, under the OECD, plays a critical role in promoting the safe, environmentally sustainable, and economically viable use of nuclear energy [102,103]. The NEA provides a platform for exchanging information and best practices related to nuclear regulation, with particular emphasis on SMR development.

4.3. Recommendations for Harmonizing Maritime SMR Regulations

To facilitate the deployment of maritime SMRs, regulatory frameworks must reflect the unique risks and operational challenges associated with nuclear-powered vessels. The following recommendations aim to align maritime SMR standards with global nuclear regulations:

1. Integrate Maritime SMR Standards into NHSI Initiatives: The IAEA's NHSI framework should include specific guidelines for maritime SMRs, addressing safety requirements related to marine environments, navigation laws, and port operations.
2. Harmonize International Port Regulations: Standardizing port-entry protocols and inspection procedures for nuclear-powered vessels under the IMO and IAEA will ensure smooth operations and improve regulatory compliance across international waters.
3. Facilitate Collaboration Between National and International Regulators: National regulatory bodies should coordinate with the IAEA, IMO, and other international organizations to adopt best practices for maritime SMR licensing, operation, and decommissioning.
4. Develop Global Safety Standards for Maritime Accidents: Given the unique risks of accidents at sea, a harmonized approach to emergency preparedness and radiation management is essential. Establishing regional agreements will improve cross-border coordination in case of incidents.
5. Promote Transparent Modular Licensing Processes: National and international regulators should streamline the licensing process for modular SMRs, ensuring that components certified in one jurisdiction are recognized globally, and reducing approval timelines and costs.
6. Align Public Communication Strategies to Improve Acceptance: Harmonized public outreach initiatives that explain the safety, environmental, and economic benefits of maritime SMRs will help build public trust and support for nuclear-powered vessels.

5. Conclusions

The adoption of Small Modular Reactors (SMRs) in maritime propulsion presents a transformative opportunity for the shipping industry, offering key benefits such as reduced emissions, enhanced fuel efficiency, and greater operational autonomy. These advantages align with global efforts to achieve decarbonization and improve energy efficiency in the maritime sector. However, the integration of SMR technology is complex due to the intersection of nuclear and maritime regulatory frameworks, requiring extensive international cooperation and the development of harmonized standards. This convergence highlights the need for a robust and cohesive global regulatory framework that addresses the unique challenges posed by SMR-powered vessels.

A critical priority is the harmonization of national and international standards. The International Maritime Organization (IMO), International Atomic Energy Agency (IAEA), and national regulators must work together to create consistent licensing frameworks for SMR-powered vessels. Collaboration among stakeholders, including the Nuclear Energy Agency (NEA) through its Multinational Design Evaluation Programme (MDEP), will be essential in developing uniform safety protocols. These efforts should focus on standardizing reactor components and operational procedures, ensuring that SMRs certified in one jurisdiction are recognized across borders, thus streamlining licensing processes and reducing deployment costs.

Despite existing efforts by the IAEA and NEA to promote regulatory harmonization, the current frameworks lack specificity regarding maritime applications. Maritime SMRs introduce distinct challenges, such as marine environmental risks, navigation laws, international port regulations, and accident management at sea. Therefore, future regulatory initiatives—such as the IAEA's Nuclear Harmonization and Standardization Initiative (NHSI)—must include tailored strategies that reflect the unique risks of SMR-powered vessels. Additionally, enhanced emergency response protocols, risk assessments, and waste management solutions specific to maritime reactors are crucial to ensuring the safe integration of SMRs.

The Russian NP-079-18 regulatory framework for nuclear ships offers valuable insights for managing reactor-equipped vessels. For example, its emphasis on real-time monitoring, standardized emergency protocols, and regular updates to safety action plans could serve as a model for Korea and other countries developing SMR-powered vessels. Integrating these practices into the IMO's SOLAS Chapter VIII framework and aligning them with IAEA standards will provide a comprehensive safety framework for the maritime sector.

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