Preliminary Screening of the Risk Spectrum for Commercial Maritime Nuclear Propulsion

Technical Report

Report No.: NSSPI-26-001

Mohamed Elhareef, and Mansung Yim

Center for Nuclear Security Science and Policy Initiatives,
Texas A&M Engineering Experiment Station,
College Station, TX, USA

October 2026

Executive Summary

The renewed interest in nuclear energy for commercial maritime applications has created a need to understand the current state of relevant technologies, their potential integration into maritime systems, and the risks associated with their adoption. This report presents a literature review of the state of nuclear maritime technology, a preliminary screening of the associated risk spectrum, and a conceptual examination of the cross-domain interfaces arising from the integration of nuclear reactor systems into commercial maritime platforms. The objective is to establish an initial understanding of the technological landscape, identify relevant risk considerations, and explore the interactions and dependencies between nuclear engineering, maritime operations, safety, security, environmental, regulatory, and economic domains.

The literature review examined historical experience with naval and civilian nuclear-powered vessels, emerging applications of small modular reactors (SMRs) and advanced reactor technologies, and the technical and institutional considerations associated with maritime integration. Candidate technologies include pressurized-water reactors, molten-salt reactors, high-temperature gas-cooled reactors, lead-cooled fast reactors, and heat-pipe microreactors. Their technological characteristics, development status, and potential maritime applicability are discussed alongside technology, investment, and community readiness considerations. Particular attention is given to reactor safety characteristics, shipboard integration requirements, propulsion architectures, radiation shielding, decay-heat removal, fuel-cycle arrangements, and the existing regulatory environment.

The report characterizes the conventional maritime risk spectrum across six categories: navigational, physical, and operational risks; geopolitical, security, and supply-chain risks; technological and cybersecurity risks; environmental risks; financial and economic risks; and regulatory, legal, and human-factor risks. These baseline hazards provide a reference for examining how nuclear propulsion may influence existing maritime risks. The preliminary screening distinguishes potential changes in initiating-event likelihood or frequency from changes in consequence severity and identifies additional nuclear-specific risks associated with reactor safety, radiological protection, nuclear material safeguards, nuclear security, emergency response, and lifecycle management. While nuclear propulsion may reduce certain fuel-related hazards and operational dependencies, conventional maritime risks remain, and the introduction of nuclear systems creates additional safety, security, and institutional considerations.

The report further develops a cross-domain risk-informed design matrix. The matrix provides a preliminary conceptual representation of how engineering and operational decisions in one domain may influence conditions, constraints, and risks in other domains. It identifies potential dependencies, competing objectives, indirect effects, and mechanisms of risk transfer that may not be apparent when individual technical or institutional domains are considered independently.

The principal outcome of this study is a structured characterization of the nuclear maritime technology risk considerations, together with an initial conceptual understanding of the cross-domain interfaces introduced by nuclear propulsion. The analysis indicates that integrating nuclear technology into commercial maritime systems represents more than a substitution of conventional propulsion machinery. Nuclear proplsion introduces tightly coupled interfaces that exxtends beyoned the scope of individual domains. This report is intended as a preliminary exploratory study. Its findings provide a foundation for subsequent hazard identification, detailed risk analysis, and the development of more systematic cross-domain risk-informed evaluation methodologies for commercial maritime nuclear applications.

Contents

Executive Summary ii

1 Introduction 1

2 Reactor Configurations and Development Status 4
2.1 Nuclear Maritime Deployment Configurations . . . 4
2.2 Desirable Characteristics for Maritime Nuclear Reactors . . . 4
2.3 Reactor Technologies Considered for Maritime Applications . . . 4
2.3.1 Pressurized Water Reactors (PWR SMRs) . . . 5
2.3.2 Molten Salt Reactors (MSRs), Including MCFRs . . . 5
2.3.3 High-Temperature Gas-Cooled Reactors (HTGRs) . . . 5
2.3.4 Heat Pipe Microreactors and Lead-Cooled Fast Reactors (LFRs) . . . 5
2.4 Propulsion System Architectures . . . 6
2.5 Shipboard Nuclear Integration . . . 6
2.5.1 Reactor Location . . . 6
2.5.2 Radiation Shielding Architecture . . . 7
2.5.3 Emergency Core Cooling and Seabed Salvageability . . . 7
2.6 Current Development Status . . . 8
2.6.1 Technology Readiness Levels (TRL) . . . 8
2.6.2 Investment Readiness Levels (IRL) . . . 8
2.6.3 Community Readiness Levels (CRL) . . . 9
2.6.4 Institutional Governance and Regulatory Harmonization Initiatives . . . 10
2.7 Strategic Pathways and Future Outlook . . . 10
2.7.1 Phased Implementation Roadmap (2026–2045) . . . 10
2.7.2 Key Policy and Industry Recommendations . . . 11

3 Conventional Maritime Risk Spectrum 11
3.1 Navigational, Physical, and Operational Risks . . . 11
3.2 Geopolitical, Security, and Supply Chain Risks . . . 12
3.3 Technological, Digital, and Cybersecurity Risks . . . 13
3.4 Environmental, Marine Pollution, and Climate Transition Risks . . . 14
3.5 Financial, Economic, and Market Volatility Risks . . . 15
3.6 Regulatory, Legal, Human, and Management Risks . . . 16

4 Preliminary Characterization of Nuclear Propulsion Risks 17
4.1 Navigational, Physical, and Operational Risks . . . 17
4.2 Geopolitical, Security, and Supply Chain Risks . . . 18
4.3 Technological, Digital, and Cybersecurity Risks . . . 19
4.4 Environmental, Marine Pollution, and Climate Transition Risks . . . 20
4.5 Financial, Economic, and Market Volatility Risks . . . 21
4.6 Regulatory, Legal, Human, and Management Risks . . . 21
4.7 Nuclear-Specific Risks . . . 22
4.8 Cross-Domain Risk-Informed Design Matrix . . . 23

5 Summary 40

References 42

A Multidimensional Readiness Level Frameworks **46**
A.1 Technology Readiness Level (TRL 1–9) 46
A.2 Investment Readiness Level (IRL 1–6) 46
A.3 Community Readiness Level (CRL 1–6) 47

List of Tables

I. Maritime Propulsion Energy Alternatives. 2
II. Maritime Reactor Concepts and Integration Characteristics. 5
III. Marine Radiation Shielding Architecture Comparison. 7
IV. Readiness Assessment of Maritime Nuclear Reactor Classes. 9
V. Conventional Navigational, Physical, and Operational Risks. 11
VI. Conventional Geopolitical, Security, and Supply Chain Risks. 12
VII. Conventional Technological, Digital, and Cybersecurity Risks. 14
VIII. Conventional Environmental and Climate Transition Risks. 15
IX. Conventional Financial, Economic, and Market Risks. 16
X. Conventional Regulatory, Legal, Human, and Management Risks. 17
XI. Nuclear Propulsion Effects on Navigational, Physical, and Operational Risks. 18
XII. Nuclear Propulsion Effects on Geopolitical, Security, and Supply Chain Risks. 19
XIII. Nuclear Propulsion Effects on Technological, Digital, and Cybersecurity Risks. 20
XIV. Nuclear Propulsion Effects on Environmental and Climate Transition Risks. 20
XV. Nuclear Propulsion Effects on Financial, Economic, and Market Risks. 21
XVI. Nuclear Propulsion Effects on Regulatory, Legal, Human, and Management Risks. . . . 22
XVII. Cross-Domain Risk-Informed Design Matrix for Commercial Maritime Nuclear Propulsion. 23
XVIII. Technology Readiness Levels for Maritime Nuclear Applications. 46
XIX. Investment Readiness Levels for Maritime Nuclear Applications. 46
XX. Community Readiness Levels for Maritime Nuclear Applications. 47

1 Introduction

The global maritime industry stands at an unprecedented crossroads. Responsible for transporting approximately 80% of world trade, commercial shipping contributes roughly 2.8% to 3.0% of global greenhouse gas (GHG) emissions, along with 4% to 9% of global sulfur oxides (SOx) and 15% of nitrogen oxides (NOx) [1, 2]. Under the International Maritime Organization (IMO) Strategy on Reduction of GHG Emissions, the sector faces an uncompromising mandate to achieve net-zero GHG emissions by or around 2050. While low-carbon chemical alternatives such as e-ammonia, green methanol, and liquid hydrogen offer partial decarbonization pathways, their widespread adoption is severely constrained by low volumetric energy density, severe toxicological and flammability risks, immense bunker storage space penalties, and high life-cycle supply chain costs [3]. In this context, Small Modular Reactors (SMRs) and advanced reactor concepts, including microreactors and Generation IV technologies, are being considered for maritime propulsion. Nuclear fission provides an exceptionally high energy density, on the order of 106 to 107 MJ/kg compared to 45 MJ/kg for conventional marine diesel, 120 MJ/kg for hydrogen, and 20 MJ/kg for ammonia [1]. Nuclear propulsion eliminates direct operational greenhouse gas emissions from fuel combustion and can enable extended fuel cycles ranging from 3 to 30 years without refueling [1, 4].

Nuclear propulsion at sea is backed by seven decades of operational experience. The historical trajectory spans two distinct domains: highly successful military naval applications and experimental civilian merchant vessels built between 1959 and 1988 [5]. The era of marine nuclear power began on 17 January 1955 with the maiden voyage of the USS Nautilus (SSN-571), powered by a Submarine Thermal Reactor (STR Mark II PWR). The success of the Nautilus established the technical dominance of light water pressurized reactors for marine propulsion [5, 6]. To date, over 500 naval nuclear reactors have been constructed globally. The United States Navy alone has accumulated over 7,500 operational reactor-years across its nuclear-powered submarine and aircraft carrier fleets without a single reactor safety accident or radiological release [5–7]. Similarly, Russia has operated extensive fleets of nuclear submarines and surface icebreakers since 1959.

Following naval successes, four non-naval merchant vessels were constructed as government-backed demonstration projects to evaluate the commercial feasibility of peaceful nuclear shipping:

a. **NS Savannah (United States, 1962–1972)**: Commissioned as part of President Dwight Eisenhower's 'Atoms for Peace' initiative, the NS Savannah was a joint project between the U.S. Atomic Energy Commission (AEC) and Maritime Administration (MARAD). The 22,000-ton vessel was powered by a 74 MWt (later uprated to 80 MWt) PWR delivering 16.4 MW (22,000 shaft hourse power) to the propeller shaft. Over its 10-year operational life, the Savannah traveled over 450,000 nautical miles and visited 45 foreign and 32 U.S. ports [4]. While technically flawless, its hybrid cargo/passenger design resulted in high capital costs ($46.9 million construction cost in 1959), poor cargo handling efficiency, labor union wage disputes, and public concerns over early liquid radioactive waste discharges (115,000 gallons released in its first year), leading to its deactivation in 1971 before the 1973 oil crisis [3, 5].

b. **NS Otto Hahn (West Germany, 1968–1979)**: Built by GKSS and launched in 1964, the NS Otto Hahn was a 15,000-ton ore carrier and research vessel powered by an advanced 38 MWt integral PWR delivering 8.1 MW of propulsion power. The Otto Hahn logged 650,000 nautical miles across 126 voyages and visited 46 international ports without technical failures [4, 5]. However, the vessel faced severe administrative hurdles: negotiating bilateral port entry agreements required years of diplomatic effort for every host country. In 1979, despite technical success, high operating expenses prompted GKSS to remove its reactor and convert the ship to conventional diesel power [5].

c. **NS Mutsu (Japan, 1974, 1991–1992)**: The 8,000-ton general cargo prototype NS Mutsu was launched in 1970 equipped with a 36 MWt PWR. During initial sea trials in September 1974, as the reactor reached 1.4% full power, a design defect in the primary upper shield caused a minor fast-neutron leakage [4, 5]. Although radiation exposure was negligible, the incident ignited intense public backlash from local fishing associations, barring the ship from returning to its home port of Ohminato.

Following extensive shield redesigns and decade-long overhauls, the Mutsu completed successful test voyages in 1991–1992 before being decommissioned and rebuilt as the diesel oceanographic research vessel Mirai in 1995 [5].

d. **NS Sevmorput (USSR/Russia, 1988–Present)**: Delivered in 1988, the 260.3-meter, 61,880-ton LASH container ship and icebreaking freighter NS Sevmorput represents the world's only operational nuclear-powered merchant vessel. Powered by a single 135 MWt KLT-40 PWR generating 29.4 MW shaft power, the vessel can cut through 1.5-meter sea ice [1, 5] Despite early port entry rejections in 1990 (e.g. Vancouver, BC), the Sevmorput has demonstrated continuous commercial viability along Russian Arctic trade routes for over 35 years [4, 5].

The renewed interest in marine nuclear energy is driven by fundamental physical and economic advantages over conventional fossil fuels and emerging chemical zero-carbon alternatives [1, 2]. Nuclear fuel possesses an unprecedented energy density. A single loading of conventional low-enriched uranium (LEU, typically $\leq$5 wt% U-235) or high-assay low-enriched uranium (HALEU, >5 to <20 wt% U-235) fuel allows a commercial merchant vessel to operate continuously for 3 to 10 years (for PWRs) or 10 to 30 years (for MSRs and heat pipe microreactors) without refueling [1, 4]. This eliminates reliance on global bunkering networks, shielding shipowners from regional fuel supply shortages. Additionally, on long-haul transoceanic routes (e.g. Asia to Europe or Americas), conventional container ships must allocate up to 10,000 metric tons of deadweight and volumetric capacity to heavy fuel oil (HFO) or low-sulfur fuel oil (VLSFO). Low-density alternative fuels (such as liquid hydrogen or green ammonia) require 4 to 8 times more storage volume than diesel, causing severe cargo volume penalties [1, 8]. In contrast, SMR power plants eliminate massive fuel storage tanks, enabling shipbuilders to maximize revenue-generating cargo holds (TEU capacity) [9]. Furthermore, nuclear power allows vessels to maintain higher sustained cruising speeds (e.g., 25–30 knots) without incurring exponential fuel cost penalties, optimizing fleet utilization [4].

In addition to the economic benefits, SMR power plants enable complete elimination of operational GHG and pollutant emissions. Unlike fossil fuels, LNG, or biofuels, which emit residual CO2, unburnt methane (methane slip), and nitrogen oxides; nuclear fission produces zero direct operational emissions of CO2, CH4, NOx, SOx, or particulate matter during transit [1]. Life Cycle Assessments (LCA) demonstrate that marine SMRs yield the lowest total greenhouse gas footprint per kilowatt-hour of propulsion power among all maritime energy options, outperforming solar, wind, and hydrogen derived from fossil reforming [2, 4]. Table I. compares the economics and environmental impact of the maritime propulsion energy alternatives.

Table I. Maritime Propulsion Energy Alternatives [1, 4].

Energy Source	**Energy Density (MJ/kg)**	**Refueling / Bunkering Interval**	**Operational Emissions**	**Cargo Volume Impact**	**Economic Volatility Risk**
Marine Diesel / HFO	42 – 45	10 – 30 days	High CO2, SOx, NOx, PM	Baseline tankage required	High (exposed to crude markets)
Liquefied Natural Gas (LNG)	48 – 50	15 – 35 days	CO2 reduced; Methane slip risk	1.6x storage volume vs diesel	Moderate to High
Green Ammonia (NH3)	18 – 22	7 – 20 days	Zero CO2; NOx & toxicity risk	3.2x storage volume vs diesel	High (expensive e-fuel production)
Liquid Hydrogen (LH2)	120 (3.6 MJ/L)	5 – 12 days	Zero CO2; boil-off risk	4.5x storage volume	Very High (infrastructure lacking)
Nuclear Fission (uranium fuel)	3,900,000	3 – 30 years	No direct propulsion-combustion GHG or air-pollutant emissions	Eliminates bunker-fuel tanks	Low exposure to short-term bunker markets

Despite technical promise, commercial marine nuclear propulsion faces formidable economic, regulatory, operational, and societal hurdles that have stymied widespread adoption [1, 2].

The overnight capital cost of a nuclear-powered merchant vessel is estimated to be 2 to 3 times higher than a conventional diesel vessel. A marine-certified SMR power plant (100–150 MWe) represents an initial

investment of $800 million to $1.2 billion per ship, or an incremental power plant cost premium of $30M to $50M over conventional engines [1, 2, 4]. Furthermore, port infrastructure retrofitting for nuclear-ready berths requires up to $500 million per port facility [1]. To de-risk capital requirements, novel financing structures such as 'Reactor-as-a-Service' (RaaS), where reactor vendors retain ownership, licensing, and refueling obligations while leasing thermal/electric power to shipowners, are actively being developed [1, 4].

In addition to financial risks, operating a nuclear reactor aboard a sea-going vessel introduces unique physical hazards absent in terrestrial installations:

a. **Ship Motion & Thermal-Hydraulics**: Wave-induced motions (rolling, pitching, yawing, heaving) exert dynamic centrifugal and angular accelerations on the reactor core. In liquid-cooled reactors, inclination and sloshing cause asymmetric flow distribution, alter natural circulation cooling, and induce reactivity feedback transients [8, 10].

b. **External Marine Accidents**: Vessels face grounding, mid-ship collisions, capsizing, and extreme weather. Reactor compartments must be reinforced with double bulkheads, double bottoms, and impact-absorbing structures. Passive Residual Heat Removal Systems (PRHRS) must operate autonomously without external electrical power even during complete ship inversion or submersion [1, 2].

c. **Fuel Cycle, HALEU, Safeguards, and Nuclear Security**: Advanced marine reactors using High-Assay Low-Enriched Uranium (HALEU, >5 to <20% U-235) face fuel-cycle and supply-chain constraints. International safeguards address nuclear-material accountancy and verification of peaceful use, while nuclear security and physical-protection requirements, including those associated with the Convention on the Physical Protection of Nuclear Material (CPPNM) and its Amendment, address theft, sabotage, and unauthorized removal [4]. These requirements, combined with current HALEU enrichment and fuel-fabrication bottlenecks, pose major near-term constraints.

Finally, the existing international legal framework governing marine nuclear power is severely outdated and fragmented:

a. **IMO SOLAS Chapter VIII & 1981 Code of Safety**: The IMO Code of Safety for Nuclear Merchant Ships (Resolution A.491(XII), 1981) was promulgated over four decades ago, tailored exclusively to legacy land-based PWRs. Its strict emergency planning zone (EPZ) and high-pressure containment requirements are unworkable in densely populated commercial ports and incompatible with advanced Generation IV reactors [1, 2, 5]

b. **Port Access & Bilateral Vacuum**: Under the United Nations Convention on the Law of the Sea (UNCLOS), coastal and port states retain sovereign rights to deny entry to foreign nuclear-powered vessels into their territorial waters or ports [1, 4]. Without a harmonized international certification body, shipowners face the prospect of negotiating separate bilateral treaties with every destination port.

c. **Nuclear Liability & Insurance Vacuum**: Existing nuclear liability conventions (the 1960 Paris Convention and 1963 Vienna Convention) were designed for stationary land-based power plants, failing to address mobile reactors operating across transboundary maritime zones. Commercial Protection & Indemnity (P&I) clubs and marine underwriters currently lack established underwriting frameworks for third-party radiological liabilities [1, 2].

Despite these constraints, renewed industry and research interest continues to position nuclear propulsion as a candidate pathway for deep decarbonization of long-haul commercial shipping.

2 Reactor Configurations and Development Status

A diverse spectrum of SMR and microreactor designs is under development for commercial maritime integration, including PWR, MSR, HTGR, LFR, and heat-pipe concepts [1, 10].

2.1 Nuclear Maritime Deployment Configurations

Maritime nuclear application spans three distinct structural configurations:

a. **Self-Propelled Merchant Vessels**: Direct integration of SMR power plants into high-power, long-haul ocean carriers, including Ultra-Large Container Vessels (15,000–24,000 TEU), Capesize bulk carriers, Aframax/VLCC crude tankers, and 174,000 m^3 LNG carriers [11].

b. **Floating Nuclear Power Plants (FNPPs) & Power Barges**: Non-self-propelled or towed floating platforms moored near ports, industrial hubs, or offshore mining sites. FNPPs export electricity and district heat to shore grids, supply cold ironing power to docked ships, or drive coastal e-fuel synthesis (producing green hydrogen, ammonia, or synthetic methanol) [1, 4, 10]. Examples include Russia's operational Akademik Lomonosov and Seaborg's 200–800 MWe CMSR Power Barge.

c. **Offshore Mobile Power Hubs & Charging Vessels**: Concepts such as the Ulstein Thor, a 149-meter replenishment vessel equipped with a thorium MSR, that serves as an offshore mobile power station, recharging battery-electric expedition cruise ships (e.g., Ulstein SIF) at sea [5, 10].

These diverse applications require different reactor concepts to satisfy their power, endurance, integration, and fuel-cycle requirements.

2.2 Desirable Characteristics for Maritime Nuclear Reactors

While all designs of SMRs and microreactors for maritime applications need to address the same fundamental requirements for fuel arrangement, heat removal, and reactivity control, the most desirable characteristics are providing reliable power in a compact package with manageable total weight while remaining safe under ship motion, marine accidents, and limited access to external support. Other desirable characteristics of maritime nuclear reactors include: power output matched to the mission including flexible power delivery, strong inherent and passive safety features, reliable and independent heat removal, low radiation exposure and strong confinement, long operating intervals between refueling, simple operation and maintainability, security and safeguards by design, credible nuclear fuel cycle, and credible arrangement for liability and insurance.

Also, depending upon the application concepts, the high-priority characteristics of the system could vary. These are enumerated below:

a. **Self-propelled merchant ships**: Low total mass and volume, motion tolerance, flexible power delivery, propulsion continuity, long refueling intervals, and acceptance along intended routes.

b. **Floating nuclear power plants**: Reliable stationary output, mooring and storm resilience, protected shore connections, maintainability, and emergency coordination with the host community.

c. **Offshore mobile power hubs and charging vessels**: Simple operation and maintenance, manageable shielding, infrequent servicing, and adequate output without excessive module duplication.

2.3 Reactor Technologies Considered for Maritime Applications

The leading reactor concepts considered for maritime applications are discussed below.

2.3.1 Pressurized Water Reactors (PWR SMRs)

Integral PWR designs eliminate external primary coolant piping by enclosing steam generators and pressurizers inside the main reactor pressure vessel. Key designs include Russia's RITM-200 (175 MWt / 50 MWe, LEU/HALEU, 6–10 year cycle), South Korea's SMART100 (330 MWt / 110 MWe, certified by ABS for floating platforms) and BANDI-60S (200 MWt / 60 MWe), and NuScale's VOYGR (250 MWt / 77 MWe) [1, 6].

2.3.2 Molten Salt Reactors (MSRs), Including MCFRs

In liquid-fueled MSRs, fissile fuel is dissolved directly into molten fluoride or chloride salts (e.g., LiF-BeF2 or NaCl-UCl3), serving as both fuel and primary coolant at near-atmospheric pressures [10]. Prominent designs include:

a. **Compact Molten Salt Reactor (CMSR)**: Developed by Denmark's Seaborg Technologies in partnership with Samsung Heavy Industries and KHNP. The CMSR features 100 MWe modular units utilizing liquid fluoride salt fuel, sodium hydroxide (NaOH) moderator, and a 12-year fuel cycle. If exposed to air, the liquid salt solidifies into rock, encapsulating fission products [4, 10].

b. **Molten Chloride Fast Reactor (MCFR)**: Advanced by UK-based Core Power in collaboration with TerraPower, Southern Company, and Idaho National Laboratory. Designed for 100–300 MWe outputs utilizing HALEU chloride salt fuel and 10–20 year refueling intervals, targeted for 14,000+ TEU container ships [5, 10].

c. **KUN-24AP Container Ship Concept**: Unveiled in late 2023 by China's Jiangnan Shipyard (CSSC), the KUN-24AP is an ultra-large 24,000 TEU container ship powered by a Thorium Molten Salt Reactor (TMSR), demonstrating state-level commitment to non-LWR commercial shipping [4, 8].

2.3.3 High-Temperature Gas-Cooled Reactors (HTGRs)

Helium-cooled reactors utilizing TRISO (tristructural isotropic) fuel particles encased in silicon carbide layers capable of withstanding temperatures above 2,000 °C without melting [8, 12]. Delivering gas outlet temperatures of 700–950 °C, HTGRs achieve high thermodynamic efficiency (>40%) and are shortlisted by the Norwegian NuProShip consortium for commercial cargo ships.

2.3.4 Heat Pipe Microreactors and Lead-Cooled Fast Reactors (LFRs)

Westinghouse's eVinci microreactor (15 MWt / 5 MWe) utilizes passive alkali-metal heat pipes to transfer thermal energy from a TRISO fuel core without active pumps, offering an 8–10+ year sealed core for auxiliary power [1, 8]. Sweden/Canada's LeadCold SEALER-M (10 MWt / 3 MWe) employs liquid lead cooling for a 10+ year sealed Arctic transport core.

Table II. compares the principal maritime reactor concepts and their target configurations.

Table II. Maritime Reactor Concepts and Integration Characteristics [1, 2, 4–7, 9, 10, 13–15].

Reactor Design	Developer & Nation	Reactor & Coolant Type	Thermal / Electric Output	Fuel, Enrichment & Cycle	Target Maritime Configuration
RITM-200	Rosatom / OKBM (Russia)	Integral PWR (Water)	175 MWt / 50 MWe	HALEU (19.75% U-235); 6-10 yr refueling	Icebreakers, Cargo Ships, FNPPs (Operational)
SMART100 / BANDI-60S	KAERI / KEPCO (S. Korea)	Integral PWR (Water)	200-330 MWt / 60-110 MWe	Conventional LEU (≤5% U-235); 3-5 yr refueling	Floating Power Platforms, Merchant Propulsion

Table II. (continued)

Reactor Design	Developer & Nation	Reactor & Coolant Type	Thermal / Electric Output	Fuel, Enrichment & Cycle	Target Maritime Configuration
CMSR Power Barge	Seaborg / SHI (Denmark/Korea)	Molten Salt (Fluoride)	250 MWt / 100 MWe (module)	Fluoride-salt fuel; LEU/thorium basis; 12-yr cycle	Power Barges (200-800 MWe), Port Power Hubs
MCFR / MCRE	Core Power / TerraPower (UK/USA)	Molten Salt (Chloride Fast)	100 – 300 MWe	HALEU chloride-salt fuel; 10-20 yr cycle	Ultra-Large Container Ships (14,000+ TEU)
KUN-24AP TMSR	Jiangnan Shipyard / CSSC (China)	Thorium Molten Salt	Scalable SMR output	Thorium-based molten-salt fuel; long-duration core	24,000 TEU Ultra-Large Container Ship
eVinci Microreactor	Westinghouse (USA)	Heat Pipe-Cooled	15 MWt / 5 MWe	HALEU TRISO fuel; 8-10+ yr sealed core	Auxiliary Marine Power, Remote Ports
SEALER-M	LeadCold (Sweden/Canada)	Lead-Cooled Fast (LFR)	10 MWt / 3 MWe	LEU, including possible HALEU; 10+ yr sealed core	Arctic Transport Vessels, Small Cargo

2.4 Propulsion System Architectures

Integrating nuclear energy into shipboard drive trains relies on two main architectures: direct mechanical shaft drive and turbo-electric integrated power systems.

a. **Direct Mechanical Shaft Drive**: In traditional mechanical drive configurations, high-pressure steam turbines are coupled directly to propulsion shafts via reduction gears and controllable-pitch propellers. While offering high mechanical efficiency at steady-state cruising, direct mechanical drives force the reactor core to experience thermal and reactivity transients during rapid ship maneuvering or crash-stop procedures [3].

b. **Turbo-Electric & Integrated Power Systems (IPS)**: Modern commercial SMR proposals universally favor turbo-electric drive architectures. The nuclear steam or gas turbine drives high-efficiency turbo-generators, converting thermal energy into electrical power fed to a centralized shipboard microgrid. Electric propulsion motors (such as azimuth thrusters or podded propulsors) drive the ship. Turbo-electric IPS decouples reactor thermal output from propulsor dynamics, enables battery-buffered energy storage for load leveling during high sea states, and allows excess electrical power to be exported to port grids when docked [3, 10].

2.5 Shipboard Nuclear Integration

Integrating a nuclear reactor into a commercial merchant vessel requires a fundamental departure from conventional naval architecture. Beyond selecting reactor physics and propulsion cycles, shipbuilders must engineer the reactor plant into the hull structure while accounting for dynamic motion, extreme weather, wave slamming, collision, grounding, and potential deep-water submersion.

2.5.1 Reactor Location

Across all commercial nuclear ship concepts, the reactor compartment is universally positioned amidships (near the vessel's longitudinal center of flotation, LCF). Placing the reactor amidships isolates the core from extreme wave-induced pitch accelerations and slamming impacts experienced at the bow, as well as heavy propeller vibrations generated at the stern [5, 10]. Furthermore, historical casualty statistics indicate that over 85% of ship-to-ship collisions occur at the bow or stern quarters; midship positioning maximizes the physical buffer distance from potential impact zones [11].

The reactor vessel or primary reactor module and its associated confinement/containment structure are installed low in the hull, directly above the double bottom [5]. Because the reactor plant and radiation

shielding represent a concentrated deadweight of approximately 1,500 to 4,000+ tonnes, locating this mass near the tank top helps maintain a low vertical center of gravity (VCG), transverse stability, and metacentric height (GM) compliance [5, 16].

Shipboard reactors operate under continuous angular motions (pitch, roll, and yaw) and linear translations (heave, surge, and sway). A low, amidships installation reduces inertial loading and helps limit coolant sloshing, asymmetric flow distribution, and reactivity transients in liquid-cooled cores [10].

2.5.2 Radiation Shielding Architecture

Shielding represents the single largest weight and volumetric constraint in marine nuclear power plant design, far exceeding the weight of the reactor core itself [16]:

a. **Primary (Biological) Shielding**: Encloses the reactor pressure vessel directly to absorb prompt fission neutrons and core gamma radiation during operation. It typically consists of a water-filled steel annulus (neutralizing fast neutrons) lined with heavy steel thermal shields and lead jackets [16].

b. **Secondary Shielding**: Encloses the entire primary containment vessel to protect the crew, cargo holds, and adjacent ship machinery from secondary decay gamma radiation emitted by activated primary coolants (e.g., Nitrogen-16 in PWRs). Secondary shielding utilizes a composite sandwich structure consisting of high-density reinforced concrete (0.6 to 1.2 meters thick), lead plates (15 to 20 cm thick), polyethylene or borated paraffin (for thermal neutron capture), and heavy structural steel plating [16, 17].

Table III. compares the shielding materials and mass burden reported for historical nuclear merchant vessels with a representative modern marine SMR concept.

Table III. Marine Radiation Shielding Architecture Comparison.

Vessel / Concept	Reactor Type	Shielding Material Composition	Total Shield Weight	Shield Mass %
NS Savannah	74 MWt PWR	Lead, water annulus, heavy concrete, polyethylene, redwood mats	2,053 tonnes	14.5% Machinery
NS Otto Hahn	38 MWt iPWR	Water containment tank, lead jackets, concrete containment wall	1,850 tonnes	16.0% Machinery
NS Mutsu	36 MWt PWR	Lead plates, borated water, concrete upper/lower biological shield	2,260 tonnes	18.2% Machinery
Gen IV Marine SMR	100 MWt MSR/PWR	Integral borated lead-bismuth, tungsten-composite, heavy steel	~1,100 tonnes	8.5% Machinery

2.5.3 Emergency Core Cooling and Seabed Salvageability

Marine reactors are engineered to maintain core cooling and the integrity of radionuclide-retention barriers during catastrophic ship losses, including deep-water sinking and total inversion [1, 5, 10]:

a. **Hydrostatic Pressure Equalization (Containment Flood Valves)**: If a vessel sinks in deep water, rising external seawater pressure could cause catastrophic implosion of an airtight, hollow containment vessel. To prevent structural collapse, designs such as the NS Otto Hahn featured automatic hydrostatic flood valves. Set to trip at a pre-calibrated external water overpressure (~300 kPa / 3 bar), these valves flood the outer containment space with clean seawater, equalizing internal and external pressures while keeping the primary core boundary intact [5].

b. **Passive Decay Heat Removal Under Extreme Listing / Capsizing**: Emergency Core Cooling Systems (ECCS) and Passive Residual Heat Removal Systems (PRHRS) rely on unpowered natural circulation, gravity-fed water accumulators, or solid-state heat conduits. These systems are designed to operate autonomously without electrical power at any angle of inclination, including permanent 45° vessel list or complete 180° capsizing [1, 10].

c. **Reactor Trip (Scram) and Shutdown Mechanisms**: Control rod drive mechanisms (CRDMs) utilize spring-loaded or gravity-drop latching devices. If the ship loses electrical power or experiences an extreme roll angle exceeding 45°, the latches disengage, immediately inserting all control rods into the core to shut down the chain reaction [5].

d. **MSR Fuel Salt Self-Solidification**: In liquid-fueled Molten Salt Reactors, a breach of the primary system into a cold environment can cause released fuel salt to cool and solidify, limiting the immediate dispersal of nonvolatile radionuclides. In an underwater release, however, subsequent interaction with seawater may result in dissolution, hydrolysis, precipitation, and redistribution of salt constituents and fission products; therefore, long-term radionuclide retention depends strongly on fuel-salt composition and radionuclide chemistry [10].

e. **Seabed Salvageability Requirements**: Under IMO Resolution A.491(XII), the reactor hold must be constructed as a modular, structurally reinforced capsule equipped with external recovery trunnions. In the event of a shipwreck, salvage teams can cut the intact reactor hold free from the hull and raise the intact nuclear module from the seabed [18].

2.6 Current Development Status

To evaluate the commercial maturity of marine nuclear propulsion, recent research applies a three-dimensional framework: Technology Readiness Level (TRL 1-9), Investment Readiness Level (IRL 1-6), and Community Readiness Level (CRL 1-6) [1, 10]. The three readiness scales are defined in Appendix A.

2.6.1 Technology Readiness Levels (TRL)

The technological maturity of maritime nuclear power varies significantly depending on the underlying reactor physics and coolant technology:

a. **PWR-Based Marine SMRs (TRL 7–9)**: Pressurized water reactors represent the most mature technology, benefiting from 70 years of naval operational heritage. Russia's KLT-40S (powering the Akademik Lomonosov floating nuclear power plant) and RITM-200 (powering Arktika-class icebreakers) have achieved TRL 9 (commercial operation) [1, 4]. South Korea's SMART100 / BANDI-60S and China's ACP100S are at TRL 7–8, approaching floating demonstration.

b. **Generation IV Advanced Non-LWR SMRs (TRL 3–6)**: Advanced concepts currently range from TRL 3 to 6 [1, 10]. Many non-LWR concepts incorporate inherent safety characteristics and passive safety features. Several molten-salt and liquid-metal concepts operate at relatively low primary-system pressure, reducing high-pressure LOCA concerns, while gas-cooled concepts may operate at elevated pressure. These designs nevertheless require extensive materials qualification, corrosion-resistant nickel/refractory alloys (e.g. Hastelloy-N), and sea-motion validation before commercial shipboard deployment [10, 12].

2.6.2 Investment Readiness Levels (IRL)

The financial viability and commercial maturity of maritime nuclear options are evaluated using the Investment Readiness Level (IRL 1-6), which reflects capital availability, business-model confidence, and investor risk.

a. **PWR-Based Marine SMRs (IRL 4–5)**: Pressurized water reactors benefit from established supply chains, government-backed utility financing, and dual-use naval heritage, positioning them at higher investment readiness. Public-private partnerships and state funding (e.g., Rosatom, U.S. DOE ARDP) significantly de-risk upfront capital costs, though high vessel integration expenditures ($30–50M per ship) and port nuclear electrification capital ($500M+ per port) still constrain pure private equity investments

b. **Generation IV Advanced Non-LWR SMRs (IRL 1–3)**: Advanced reactor concepts attract lower investment readiness due to unproven commercial payback, lack of validated sea-going demonstrators, and HALEU enrichment supply chain bottlenecks. Emerging "Reactor-as-a-Service" (RaaS) and nuclear-as-a-service leasing models (e.g., Core Power, Seaborg / Samsung Heavy Industries) are gradually elevating financial feasibility toward IRL 3–4 by offloading capital ownership and licensing liabilities from shipowners.

2.6.3 Community Readiness Levels (CRL)

The societal acceptance, regulatory preparedness, and port host-nation approval of marine nuclear propulsion are framed under the Community Readiness Level (CRL 1–6) scale:

a. **PWR-Based Marine SMRs (CRL 1–2 Global / ~4 Russia)**: Globally, commercial light water reactors face low community readiness due to outdated international legal frameworks (e.g., IMO SOLAS Chapter VIII from 1981), public radiation anxiety, and absent civilian port emergency planning zones. Russia represents a regional exception (~CRL 4), supported by state-centralized governance and decades of civilian familiarity with Arctic nuclear icebreakers and floating power plants

b. **Generation IV Advanced Non-LWR SMRs (CRL 1–2)**: Non-LWR advanced concepts remain at minimal community readiness globally, compounded by unfamiliarity among port authorities, unresolved backend waste repository protocols, and unresolved safeguards arrangements and nuclear-security/physical-protection requirements for HALEU, including obligations associated with the CPPNM and its Amendment. Institutional initiatives such as the IAEA ATLAS project and the Nuclear Energy Maritime Organization (NEMO) are actively working to modernize international regulatory codes by 2030 to elevate global CRL.

Table IV. consolidates the technology, investment, and community readiness assessments for the principal marine reactor classes and highlights the main constraints to deployment.

Table IV. Readiness Assessment of Maritime Nuclear Reactor Classes [1, 3, 4, 6, 7, 10–14, 17, 18].

Reactor Technology Class	**Coolant / Fuel**	**TRL (1-9)**	**IRL (1-6)**	**CRL (1-6)**	**Key Bottlenecks & Societal/Regulatory Hurdles**	**Deployment Horizon**
PWR SMRs (KLT-40S, RITM-200, SMART100, ACP100S, VOYGR)	High-Pressure Water LEU $\leq$5%; HALEU 14-19.75%	7 – 9	4 – 6	1 – 2 (Global) ~4 (Russia)	SOLAS Ch. VIII modernization; port access rights; public radiation anxiety; $30-50M ship retrofit CAPEX.	Immediate – 2028 (Operational)
Molten Salt Reactors (CMSR, MCFR, ThorCon)	Liquid Fluoride / Chloride Salt LEU (including HALEU) & thorium-based fuel cycles	3 – 6	2 – 4	1 – 2	Liquid salt corrosion; tritium/off-gas control; lack of commercial precedent; unproven spent fuel take-back.	2028 – 2035 (Pre-commercial)
High-Temp Gas-Cooled (HTGR / VHTR)	Helium Gas HALEU TRISO Particles	4 – 6	2 – 3	1 – 2	TRISO fuel qualification under ship motion; thermal output scaling; gas turbine containment packaging.	2030 – 2035 (Pilot testing)

Table IV. (continued)

Reactor Technology Class	Coolant / Fuel	TRL (1-9)	IRL (1-6)	CRL (1-6)	Key Bottlenecks & Societal/Regulatory Hurdles	Deployment Horizon
Lead-Cooled Fast (LFR / SEALER-M)	Molten Lead / Pb-Bi Eutectic LEU, including HALEU	4 – 5	1 – 2	1 – 2	Lead opacity & freezing risk; high structural weight; material corrosion at high temp; early concept phase.	2032 – 2040 (Concept phase)
Heat Pipe Microreactors (Westinghouse eVinci)	Alkali-Metal Heat Pipes HALEU TRISO	5 – 6	2 – 3	1 – 2	Power density limits (~5 MWe); 6-DOF marine motion validation; limited to auxiliary power or small cargo.	2028 – 2032 (Pilot testing)

2.6.4 Institutional Governance and Regulatory Harmonization Initiatives

To bridge the gap between technology readiness and commercial adoption, major international bodies have established targeted governance initiatives:

a. **IAEA ATLAS Project (2024–2028)**: The International Atomic Energy Agency launched the ATLAS project to establish harmonized global licensing frameworks, radiation safety thresholds, transport logistics, and emergency protocols specifically tailored for floating nuclear power plants and mobile SMR merchant ships [1, 4].

b. **Nuclear Energy Maritime Organization (NEMO, 2024)**: Founded in London in early 2024, NEMO brings together reactor developers, shipbuilders, classification societies (ABS, Lloyd's Register, Bureau Veritas, DNV), and insurers to advise the IMO and national regulators on drafting modern marine nuclear safety standards [4, 12].

2.7 Strategic Pathways and Future Outlook

To transition marine nuclear propulsion from specialized icebreakers and conceptual designs into mainstream commercial shipping, a coordinated roadmap across technology, regulation, and finance is required [1, 4, 19].

2.7.1 Phased Implementation Roadmap (2026–2045)

- **Phase 1**: Regulatory Sandboxes & Offshore Power Barges (2026–2030): Initial commercial deployment will occur via stationary floating nuclear power plants (FNPPs) and power barges (e.g., Seaborg CMSR barge, South Korean FSMR). Deploying stationary offshore platforms simplifies port state approval, establishes operational track records, and generates data to support regulatory modernization under the IAEA ATLAS project [1, 12].

- **Phase 2**: First-of-a-Kind (FOAK) Shipboard Demonstrators (2030–2035): Full-scale merchant vessel demonstration projects, such as SMR-powered container ships (NuProShip, Core Power MCFR, Jiangnan KUN-24AP), will operate on fixed transoceanic point-to-point routes under bilateral regulatory agreements between cooperative flag and port states [1, 4]

- **Phase 3**: Serial Nth-of-a-Kind (NOAK) Commercial Fleet Scaling (2035–2045): Factory-based mass fabrication of standardized SMR modules will significantly reduce overnight CAPEX. With an updated IMO SOLAS framework and established 'Reactor-as-a-Service' leasing markets, nuclear propulsion will achieve widespread commercial penetration across long-haul container, bulk, and tanker fleets [1, 8].

2.7.2 Key Policy and Industry Recommendations

a. **Modernize IMO Safety Codes**: Accelerate the comprehensive revision of SOLAS Chapter VIII and the 1981 Code of Safety for Nuclear Merchant Ships to establish risk-informed, performance-based standards tailored for non-LWR Generation IV reactors.

b. **Establish Mutual Recognition & Liability Frameworks**: Develop international treaties under the IAEA and IMO to establish standardized nuclear liability limits, mutual certification acceptance across flag states, and designated port state emergency protocols.

c. **Secure HALEU & Advanced Fuel Supply Chains**: Expand commercial HALEU enrichment and fuel fabrication capacity in Western jurisdictions (e.g. US DOE $2.7B HALEU enrichment initiative) to de-risk fuel availability for advanced marine cores.

3 Conventional Maritime Risk Spectrum

Global maritime shipping operates in a complex and volatile environment. The following subsections organize the baseline risks facing conventional vessels before the introduction of nuclear propulsion. The risks are grouped into six categories: operational, geopolitical and supply-chain, technological and cyber, environmental, financial, and regulatory/human factors. Each table identifies the underlying mechanism, principal consequences, and representative mitigation measures.

3.1 Navigational, Physical, and Operational Risks

Physical hazards directly threaten vessel integrity, seafarer safety, and cargo operations during transit, maneuvering, and port handling. Table V. summarizes the main baseline hazards, consequences, and mitigation measures for conventional vessels.

Table V. Conventional Navigational, Physical, and Operational Risks.

Risk and Source Reference	Risk Mechanism	Consequences	Mitigation Measures
Vessel Collisions & Allisions [20–23]	Impact or contact between two moving vessels or a vessel and a fixed structure (e.g., bridge, quay), triggered by high speed in restricted waters, navigational error, or heavy traffic density.	Structural hull breach, water ingress, catastrophic loss of life, severe cargo damage, immediate waterway blockage, and localized toxic spills.	Advanced COLREGs compliance training, mandatory speed reductions in congested channels, real-time AIS/VTS vessel monitoring, and AI-driven collision avoidance systems.
Vessel Grounding & Stranding [20, 22, 23]	Ship striking the seabed or channel bank due to adverse wind/currents, restricted visibility, shallow bathymetry, or steering gear malfunction.	Bottom plating rupture, severe structural stress, vessel hull fracture, bunker oil leakage, and prolonged blocking of key shipping lanes.	Continuous bathymetric updates, real-time ECDIS integration, mandatory tug assistance in narrow straits, and automated depth-sounding alarms.
Onboard Fire, Explosions & Hazmat Accidents [21, 22, 24]	Ignition of volatile cargo, misdeclared hazardous goods (IMDG Code violations), short-circuits, or engine room thermal explosions.	Total loss of vessel and cargo, catastrophic crew casualties, atmospheric toxic releases, and long-term marine habitat contamination.	Strict IMDG Code compliance, mandatory physical container inspection before loading, advanced infrared fire detection, and automated CO2/water mist smothering.

Table V. (continued)

Risk and Source Reference	Risk Mechanism	Consequences	Mitigation Measures
Hull Failure, Structural Rupture & Capsizing [20, 23, 25]	Catastrophic failure of ship structure (deck plating, side shell) from severe wave loading, metal fatigue, corrosion, or loss of intact stability.	Total loss of vessel, thousands of containers falling overboard, navigational hazards from floating debris, and rapid sinking.	Hull stress and fatigue monitoring, strict IACS classification society surveys, dynamic ballast water management, and load master software checks.
Uncertified 'Dark Fleet' Operations & Collisions [26]	Substandard, uncertified, or aging tankers operating without top-tier P&I insurance, switching off AIS transponders to evade sanctions.	High-risk collisions at sea, uncompensated environmental oil spills, ghost fleet groundings, and severe compromise of maritime safety standards.	Enhanced satellite tracking, global AIS dark-target detection, flag-state enforcement, and strict port entry documentation verification.
Mechanical Failure, Propulsion & Power Blackouts [20, 27, 28]	Sudden loss of main engine power, steering gear hydraulic failure, or electrical blackout during critical maneuvers or bad weather.	Drifting into hazards, grounding, collision with offshore structures, vessel immobilisation, and high salvage rescue expenses.	Rigorous planned maintenance systems (PMS), redundant power generator installation, fuel quality testing, and emergency steering drills.
Improper Cargo Stacking & Overloading [21, 29]	Incorrect container weight declarations, flawed lashing plans, excessive stack heights, or failure to account for dynamic vessel rolling.	Container stack collapse, cargo loss overboard, hull list, severe structural damage to lashing bridges, and port crane damage.	Mandatory SOLAS Verified Gross Mass (VGM) verification, automated container loading software, and routine physical lashing gear inspections.
Asset Aging, Corrosion & Deferred Maintenance [30, 31]	Structural degradation, hull thinning from seawater corrosion, and engine wear exacerbated by deferred maintenance to cut short-term costs.	Higher rate of mechanical breakdowns, PSC vessel detentions, structural hull fractures, and elevated operational insurance premiums.	Scheduled drydocking cycles, regular ultrasonic hull thickness measurements, predictive maintenance software, and strict classification society audits.

3.2 Geopolitical, Security, and Supply Chain Risks

Geopolitical, security, and supply-chain risks arise from state conflict, non-state armed actors, criminal networks, and network bottlenecks. Table VI. summarizes how these threats disrupt routes, assets, crews, and cargo flows and identifies representative mitigations.

Table VI. Conventional Geopolitical, Security, and Supply Chain Risks.

Risk and Source Reference	Risk Mechanism	Consequences	Mitigation Measures
Piracy & Armed Robbery at Sea [21, 24, 26]	Attacks by armed non-state actors targeting commercial vessels for ransom, cargo theft, or crew hostage-taking in high-risk areas.	Seafarer injury, death, or kidnapping; operational route re-routing; increased security guard costs; and elevated war risk insurance premiums.	Best Management Practices (BMP5) implementation, armed onboard security teams, citadel hardening, and naval convoy escorts.

Table VI. (continued)

Risk and Source Reference	Risk Mechanism	Consequences	Mitigation Measures
State-Sponsored Missile, Drone & Kinetic Attacks [26, 32, 33]	Targeted kinetic attacks on commercial vessels using anti-ship missiles, uncrewed aerial vehicles (UAVs), and explosive boats in conflict zones.	Vessel structural damage, onboard fires, seafarer fatalities, forced rerouting around Africa (Cape of Good Hope), and massive fuel cost spikes.	Navigating alternative trade routes, active naval task force protection, real-time threat intelligence feeds, and war-risk operational planning.
Naval Mines & Waterborne Explosive Devices [26, 32]	Floating or anchored sea mines and remote-controlled explosive craft deployed in wartime shipping corridors.	Hull detonation, immediate vessel sinking, major crew loss, complete closure of regional trade corridors, and prohibitive insurance rates.	Mine-countermeasure (MCM) naval clearance, route de-mining verification, high-resolution forward-looking sonar, and visual lookout watches.
Geopolitical Blockades, Chokepoints & Systemic Network Cascades [22, 26, 34–36]	Physical or military closure of critical maritime chokepoints (Suez Canal, Bab al-Mandab, Strait of Hormuz, Panama Canal) triggering network-wide cascading disruptions.	Severe bottlenecking of global trade, massive port congestion, exponential freight rate inflation, supply chain shortages, and systemic economic shocks.	Diversification of trade corridors, land-bridge intermodal routing, AI-driven geopolitical disruption forecasting, and systemic network load redistribution modeling.
Port Congestion, Bottlenecks & Network Load Redistribution [21, 24, 32, 37]	Delays in cargo handling caused by longshore labor strikes, unexpected arrival surges, cyber outages, or reduced berth capacity.	Schedule unreliability, vessel demurrage costs, inventory backlogs, container equipment misallocation, and vessel blank sailings.	Intermodal route flexibility, off-peak terminal operations, dynamic port call optimization, and Coupled Map Lattice (CML) network capacity planning.
Sovereign Asset Seizure & Vessel Detention [22, 26]	State authorities seizing merchant ships or cargo due to international geopolitical sanctions, state disputes, or regulatory enforcement.	Months of vessel immobilizations, total cargo loss, legal arbitration costs, and severe counterparty exposure.	Comprehensive sanctions compliance screening, international legal protection clauses, flag-state diplomatic intervention, and route avoidance.
Cargo Theft, Pilferage & Terminal Breaches [21, 24]	Unauthorized removal of high-value goods from containers during port transit, terminal storage, or inland transport.	Multi-billion dollar annual financial losses, inventory shortfalls, rising insurance claims, and brand reputation damage.	Tamper-evident smart seals, GPS container tracking, terminal perimeter biometrics, and continuous CCTV security monitoring.
Smuggling (Narcotics, Arms) & Human Trafficking [21, 33]	Criminal exploitation of commercial shipping networks to transport illicit contraband, narcotics, weapons, or illegal migrants.	Severe criminal penalties, vessel arrest and confiscation by port authorities, operational delays, and reputation destruction.	Advanced container X-ray scanning, sniffer dog inspections, strict crew access controls, and compliance with ISPS Code security levels.

3.3 Technological, Digital, and Cybersecurity Risks

Technological and cybersecurity risks arise from vessel automation, digital navigation, ship-to-shore connectivity, and operational technology (OT) networks. Table VII. summarizes the principal cyber and digital failure modes, their consequences, and mitigation measures.

Table VII. Conventional Technological, Digital, and Cybersecurity Risks.

Risk and Source Reference	Risk Mechanism	Consequences	Mitigation Measures
Ransomware, Malware & OT/IT Cyberattacks [28]	Cybercriminals or state actors infiltrating shipboard IT (networks, email) or Operational Technology (engine management, cargo systems).	Total shutdown of commercial booking and terminal management systems, loss of vessel control, costly operational downtime, and data breaches.	Network segmentation between IT and OT, mandatory multi-factor authentication, endpoint protection, offline backups, and IMO cyber risk management compliance.
GPS, GNSS & AIS Spoofing or Jamming [28]	Intentional interference with satellite positioning signals, broadcasting false vessel positions or disrupting navigation receivers.	Navigational disorientation, false collision alarms, grounding in narrow channels, involuntary entry into hostile territorial waters, and loss of AIS tracking.	Traditional visual and radar navigation cross-checking, inertial navigation systems (INS), anti-jamming antenna installation, and crew electronic warfare training.
Unauthorized Access & ECDIS Tampering [28]	Hackers gaining access to Electronic Chart Display and Information Systems via infected USB drives or unencrypted satellite connections.	Direct grounding on undetected shoals, route alteration into hazardous waters, loss of navigational trust, and potential vessel collision.	Encrypted chart updates via secure maritime firewalls, physical locking of USB ports on bridge hardware, and strict bridge access protocols.
Remote Manipulation of Cargo, Ballast & Engine OT [28]	Cyber infiltration of automated cargo management systems, ballast pumps, or main engine governor control units.	Dangerous vessel listing or structural overloading, accidental discharge of untreated ballast water, main engine shutdown, or physical equipment damage.	Hardware-level manual overrides, air-gapped ballast control systems, strict network firewalling, and continuous anomaly monitoring.
Software Glitches & Unpatched Legacy Hardware [21, 28]	System crashes and vulnerabilities resulting from outdated onboard operating systems, unpatched software, or incompatible digital interfaces.	Delayed cargo operations, loss of voyage monitoring, temporary loss of propulsion control, and heightened cyber vulnerability.	Centralized patch management, routine software audits, phase-out of legacy hardware, and fail-safe manual operational protocols.
Human Error via Phishing & Onboard Infected Devices [28]	Shipboard crew inserting infected personal devices into shipboard networks or clicking malicious spear-phishing emails.	Rapid malware propagation across vessel networks, compromised vessel operations, credential theft, and unauthorized network access.	Mandatory cybersecurity awareness training for all seafarers, strict personal device use policies, and isolated crew Wi-Fi networks.
Smart-Ship IoT Failure & Battery Thermal Runaway [31]	Malfunctioning or corrupted Internet-of-Things sensor networks, or thermal runaway in large lithium-ion marine propulsion battery banks.	High-intensity chemical/battery fires that cannot be extinguished with water, toxic gas generation, complete loss of power, and vessel abandonment.	Specialized battery compartment gas suppression systems, continuous thermal imaging monitoring, robust IoT firmware validation, and physical fire barriers.

3.4 Environmental, Marine Pollution, and Climate Transition Risks

Environmental and climate-transition risks include pollution events, physical climate hazards, ecosystem impacts, and the operational consequences of decarbonization. Table VIII. summarizes these baseline environmental risks and representative controls.

Table VIII. Conventional Environmental and Climate Transition Risks.

Risk and Source Reference	**Risk Mechanism**	**Consequences**	**Mitigation Measures**
Severe Weather, Cyclones & Arctic Permafrost Thawing [21, 22, 24, 31, 38]	Increasing frequency and intensity of extreme sea storms, tropical cyclones, freak waves, as well as thawing subsea Arctic permafrost releasing explosive methane gas hydrates along Northern shipping routes.	Structural vessel damage, cargo lost overboard, hull structural stress, unpredictable loss of vessel buoyancy, subsea crater navigational hazards, and crew casualties.	Advanced weather routing software, real-time wave monitoring, slow steaming during storm alerts, Arctic geophysical/methane monitoring networks, and ice-class vessel hull reinforcements.
Marine Oil Spills & Chemical Toxic Contamination [22, 30, 39]	Accidental release of heavy fuel oil (HFO), crude oil, or toxic chemicals resulting from collisions, groundings, or tank ruptures.	Severe biocenosis and coastal ecosystem destruction, massive ecological cleanup costs, multi-million dollar fines, and severe brand damage.	Double-hull tanker designs, oil spill response kits on board, emergency towing arrangements, strict MARPOL compliance, and P&I insurance coverage.
Decarbonization Transition & Alternative Fuel Risks [26, 31]	Operational, safety, and regulatory uncertainties stemming from adoption of zero-carbon alternative fuels (ammonia toxicity, hydrogen flammability, methanol low-flashpoint).	Fuel handling safety incidents, engine retrofitting costs, supply unavailability at ports, asset stranding, and regulatory non-compliance penalties under FuelEU Maritime/IMO CII.	Comprehensive bunkering safety protocols, specialized crew cryogenic training, double-walled fuel piping, advanced gas detection systems, and green corridor partnerships.
Ballast Water Invasive Species & Biofouling Transfer [31]	Transport of non-indigenous marine organisms, pathogens, and biofouling in ship ballast tanks or on hull surfaces across global marine ecosystems.	Ecological disruption, loss of local marine biodiversity, severe regulatory fines under the IMO Ballast Water Management Convention, and port entry bans.	IMO-approved Type-Approved Ballast Water Management Systems (BWMS), UV/chemical treatment, routine hull cleaning, and silicone antifouling coatings.
Whale Strikes & Toxic Antifouling Paint Leaching [31]	Ship collisions with marine mammals (large whales) and leaching of toxic heavy metals/biocides from hull antifouling paints into sensitive marine habitats.	Biodiversity loss, regulatory speed restriction zones, civil litigation by environmental groups, and bans on copper-based antifouling paints.	Slow steaming in designated whale protection zones, real-time acoustic whale monitoring systems, and eco-friendly biocide-free foul release coatings.

3.5 Financial, Economic, and Market Volatility Risks

Financial and market risks include freight-rate volatility, fuel-price shocks, currency exposure, counterparty default, and the capital burden of fleet renewal. Table IX. summarizes the principal mechanisms, commercial consequences, and financial mitigations.

Table IX. Conventional Financial, Economic, and Market Risks.

Risk and Source Reference	Risk Mechanism	Consequences	Mitigation Measures
Freight Rate Volatility, Market Collapses & Trade Shocks [21, 22, 24, 30, 40]	Unpredictable fluctuations in container, dry bulk, and tanker freight rates caused by tonnage oversupply, macro-economic trade contraction, or unexpected geopolitical supply shocks.	Severe operational cash flow collapse, insolvency of shipping lines, vessel lay-ups, cancelled ship orders, and macroeconomic industrial shocks.	Forward Freight Agreements (FFAs), long-term fixed charter parties, fleet deployment flexibility, operational cost rationalization, and macroeconomic risk index tracking.
Fuel & Bunker Price Volatility [21, 24, 30]	Sudden spikes in global crude oil and marine bunker fuel prices (VLSFO, MGO, LNG) driven by geopolitical conflicts or OPEC supply cuts.	Massive increase in voyage operating costs, margin erosion, unrecoverable bunker adjustment factor (BAF) surcharges, and vessel lay-ups.	Bunker fuel hedging (swaps and options), fuel-efficient vessel retrofits (wind-assisted propulsion, air lubrication), slow steaming, and strategic fuel purchasing.
Currency Fluctuations & Capital Controls [21, 24, 30]	Foreign exchange volatility between revenue currencies (USD) and operational expenditure currencies (EUR, JPY, local port currencies) or sovereign capital movement restrictions.	Unfavorable exchange rate losses, liquidity locks in foreign bank accounts, payment default on charter hires, and elevated transaction costs.	Currency derivative hedging (forwards/options), multi-currency treasury management, and invoicing standardization in stable international currencies.
Counterparty Credit Default & Bankruptcy [21, 24, 30, 41]	Failure of charterers, cargo owners, freight forwarders, or shipyard contractors to fulfill financial commitments due to insolvency.	Bad debt write-offs, stranded cargo, delayed shipbuilding deliveries, costly legal arrest of ships, and operational cash chain disruption.	Rigorous counterparty credit scoring, credit insurance policies, demanding advance freight payments, and standard BIMCO cancellation clauses.
High CapEx, Insurance Inflation & Stranded Assets [30, 31, 41]	Massive funding requirements for decarbonization technologies, skyrocketing hull & machinery (H&M) / war-risk insurance premiums, and premature obsolescence of fossil-fueled vessels.	Severe balance sheet strain, reduced return on capital, write-down of uncompliant fossil vessels, and restricted access to commercial bank debt.	Green financing frameworks (Poseidon Principles), ESG-linked capital loans, joint venture fleet investments, and proactive fleet renewal strategies.

3.6 Regulatory, Legal, Human, and Management Risks

Regulatory, legal, human, and management risks arise from compliance obligations, charterparty disputes, commercial pressure, seafarer human factors, and flag-state oversight. Table X. summarizes these baseline governance and workforce risks.

Table X. Conventional Regulatory, Legal, Human, and Management Risks.

Risk and Source Reference	Risk Mechanism	Consequences	Mitigation Measures
Regulatory Non-Compliance & PSC Detentions [27, 30, 31]	Failure to satisfy evolving IMO safety/environmental mandates (SOLAS, MARPOL, EEXI/CII, EU ETS) or flag-state maritime regulations.	Port State Control (PSC) vessel detention, substantial monetary fines, off-hire commercial losses, public blacklisting, and operational suspension.	Continuous onboard Safety Management System (SMS) audits, proactive compliance monitoring, third-party vetting inspections, and crew regulatory training.
Contractual Disputes & Demurrage Claims [31, 41]	Legal conflicts between shipowners, charterers, and cargo owners regarding vessel speed warranties, off-hire claims, weather delays, or demurrage penalties.	High legal arbitration expenses, withheld charter hire payments, operational asset immobilisation during legal disputes, and commercial relationship breakdown.	Standardized BIMCO charterparty clauses, clear force majeure and war risk definitions, clear performance monitoring data, and maritime arbitration agreements.
Seafarer Fatigue, Commercial Pressure & Human Error [20, 21, 30, 41]	Crew fatigue, acute seafarer shortages, excessive administrative workloads, and commercial pressure from ship managers to meet unrealistic port deadlines.	Human error causing up to 80% of maritime accidents, catastrophic navigational mistakes, personal injuries, seafarer burnout, and high crew turnover.	Strict Maritime Labour Convention (MLC 2006) rest hour enforcement, commercial pressure safeguards, mental health support, and bridge resource management (BRM) training.
Forced Labor & Flag State Oversight Deficits [26, 31]	Inadequate oversight by flag of convenience (FOC) registries, leading to seafarer labor exploitation, abandonment, or failure to enforce safety standards.	Regulatory sanctions, import bans under human rights legislation, crew abandonment crisis, civil lawsuits, and reputational damage to cargo owners.	Transparent ESG reporting, vetting flag state performance on Paris/Tokyo MOU white lists, strict adherence to MLC seafarer welfare standards, and independent supply chain audits.

4 Preliminary Characterization of Nuclear Propulsion Risks

Nuclear propulsion does not replace the conventional maritime risk spectrum. Instead, it can change the likelihood or frequency of existing hazards, change the severity of their consequences, and introduce nuclear-specific hazards that are not present in conventional propulsion. In this section, risk is treated qualitatively as the combination of initiating-event likelihood and consequence severity. The assessment uses the reactor, ship-integration, safety, and governance characteristics established in the preceding sections.

The six tables below retain the baseline categories from Section 3 and distinguish between changes in initiating-event likelihood or frequency and changes in consequence or severity. Section 4.7 synthesizes the cross-cutting effects, while Section 4.8 identifies additional nuclear-specific risks.

4.1 Navigational, Physical, and Operational Risks

Table XI. evaluates how nuclear propulsion changes the physical and operational hazards and failure modes identified in Section 3.1. Most initiating events remain maritime in origin, but consequences can increase when a casualty challenges reactor shutdown, cooling, shielding, radionuclide-retention barriers, or structural support.

Table XI. Nuclear Propulsion Effects on Navigational, Physical, and Operational Risks.

Baseline Hazard / Initiating Event	**Change in Likelihood / Frequency**	**Change in Consequence / Severity**
Vessel Collisions & Allisions	No material change in accidental collision likelihood is attributable to the propulsion source.	Potentially higher. A severe impact can trigger reactor trip and restart restrictions; damage to shielding, radionuclide-retention barriers, or the reactor support structure can introduce radiological and structural concerns. If the vessel sinks, shutdown, decay-heat removal, integrity of radionuclide-retention barriers, reactivity control, maintained subcriticality, and eventual salvage must also be maintained.
Vessel Grounding & Stranding	No inherent reduction in grounding likelihood. Greater endurance and route flexibility may reduce fuel-related diversions, but navigation, bathymetry, weather, and steering failures remain.	Potentially higher if grounding loads damage the reactor compartment or bottom support structure. Otherwise, the primary grounding consequences remain those of a conventional vessel.
Onboard Fire, Explosions & Hazmat Accidents	Potential reduction in machinery-space fire and fuel-explosion hazards because large bunker-fuel inventories and combustion engines are removed or reduced. Cargo and auxiliary-system fire hazards remain.	Baseline fire consequences remain, but severity increases if a fire challenges reactor cooling, electrical supply, shielding, radionuclide-retention barriers, or access to safety systems.
Hull Failure, Structural Rupture & Capsizing	No inherent increase is assumed if reactor-plant and shielding loads are incorporated into class-approved hull-strength and stability design; inadequate integration could increase structural-failure susceptibility.	Potentially higher because severe deformation, capsizing, or sinking must also preserve reactor shutdown, decay-heat removal, radionuclide-retention and shielding functions.
Uncertified 'Dark Fleet' Operations & Collisions	=Nuclear propulsion adds licensing, safeguards, security, and port-entry requirements that make uncertified operation more difficult to sustain. But the risk of collisions with the dark fleet remains.	Potentially higher if weak oversight also compromises nuclear safety, security, maintenance, or emergency response during a collision or other casualty. Collision consequences are similar to the above-mentioned consequences.
Mechanical Failure, Propulsion & Power Blackouts	Mixed effect. Long reactor endurance reduces fuel-supply-related interruptions, but turbines or generators, electric motors, switchboards, steering, and auxiliary systems retain conventional failure modes; reactor support systems add additional equipment whose reliability must be managed.	Potentially higher for an extended loss of electrical power or propulsion load because safe reactor shutdown and decay-heat removal must be maintained while propulsion and essential services are restored.
Improper Cargo Stacking & Overloading	No material change. Nuclear propulsion does not alter the basic cargo-loading, weight-declaration, and lashing failure mechanisms.	No material change to the primary cargo consequences; however, a severe list or capsize can create additional reactor safety demands.
Asset Aging, Corrosion & Deferred Maintenance	Potential increase in degradation-related failure likelihood unless nuclear-specific aging-management programs address reactor materials, coolant boundaries, shielding, and safety systems in addition to conventional hull and machinery aging.	Potentially higher if degradation affects nuclear safety functions. Otherwise, conventional vessel consequences remain.

4.2 Geopolitical, Security, and Supply Chain Risks

Table XII. evaluates security, geopolitical, and supply-chain risks. Nuclear propulsion does not remove route-based threats, but the vessel's strategic value, nuclear material, and additional port-access constraints

can alter both targeting incentives and recovery options.

Table XII. Nuclear Propulsion Effects on Geopolitical, Security, and Supply Chain Risks.

Baseline Hazard / Initiating Event	**Change in Likelihood / Frequency**	**Change in Consequence / Severity**
Piracy & Armed Robbery at Sea	Potential increase in attractiveness as a high-value, high-consequence target, although enhanced nuclear security requirements can offset some exposure.	Potentially higher. A piracy event can involve crew hostage-taking, attempts to access protected nuclear areas, sabotage, theft or diversion, and loss of material control or nuclear-security control.
State-Sponsored Missile, Drone & Kinetic Attacks	The baseline exposure remains route- and conflict-driven. Nuclear status could deter some attacks but can also increase strategic value; the net direction is uncertain.	Potentially higher if a strike damages the reactor compartment or safety systems. Conventional structural damage, fire, and casualty consequences remain.
Naval Mines & Waterborne Explosive Devices	No material change in exposure to mines or waterborne explosives along a given route.	Potentially higher if blast effects challenge reactor support structures, cooling, radionuclide-retention barriers, or the vessel's ability to maintain safe shutdown.
Geopolitical Blockades, Chokepoints & Systemic Network Cascades	No direct change in the likelihood of a chokepoint closure. Nuclear-specific port-state restrictions can further constrain rerouting options.	Baseline network disruption remains; limited access to nuclear-capable ports or approved routes can lengthen recovery and diversion time.
Port Congestion, Bottlenecks & Network Load Redistribution	No direct change in port-congestion frequency, but nuclear berth, inspection, and emergency-planning requirements can increase effective exposure to delay by reducing the pool of eligible ports or berths.	Potentially higher delay and diversion costs when only designated or approved nuclear-capable facilities are available.
Sovereign Asset Seizure & Vessel Detention	Potential increase because nuclear licensing, sanctions, safeguards, security, and port-state requirements create additional grounds for detention of a high-value asset.	Potentially higher because detention also affects reactor custody, security, safeguards, specialist staffing, and fuel-cycle or service arrangements.
Cargo Theft, Pilferage & Terminal Breaches	No material change in cargo-theft incentives. Enhanced access control around a nuclear vessel may improve perimeter security but does not remove the baseline cargo risk.	Primary cargo consequences are unchanged; a breach that reaches protected nuclear areas can additionally trigger a nuclear security response.
Smuggling (Narcotics, Arms) & Human Trafficking	No material change in the underlying criminal incentive. Stricter access control may reduce opportunities but does not eliminate the baseline risk.	Baseline legal and commercial consequences remain; a serious security breach can also affect nuclear access authorization and port acceptance.

4.3 Technological, Digital, and Cybersecurity Risks

Table XIII. evaluates digital and cyber risks. The propulsion architecture can increase the consequence of cyber-physical failures, while nuclear-grade quality assurance, segregation, and configuration control can reduce some vulnerabilities in safety-related systems.

Table XIII. Nuclear Propulsion Effects on Technological, Digital, and Cybersecurity Risks.

Baseline Hazard / Initiating Event	**Change in Likelihood / Frequency**	**Change in Consequence / Severity**
Ransomware, Malware & OT/IT Cyberattacks	Potential increase in targeting because of the vessel's value and safety significance. Nuclear safety systems should use stronger quality assurance, segregation, and configuration control, but the overall digital environment remains a target.	Potentially higher if compromise disrupts propulsion, electrical distribution, reactor monitoring interfaces, maintenance data, or configuration control. Safety-related systems must remain fail-safe and segregated from non-safety networks.
GPS, GNSS & AIS Spoofing or Jamming	Potential increase in deliberate targeting; the underlying navigation systems remain vulnerable to spoofing and jamming.	Potentially higher if manipulation causes grounding, collision, entry into hostile waters, or facilitates seizure or sabotage of a nuclear-powered vessel.
Unauthorized Access & ECDIS Tampering	Potential increase in targeting, while the technical vulnerability remains similar to that of other digitally integrated vessels.	Potentially higher if route manipulation produces a casualty, forces entry into restricted waters, or creates an opportunity for seizure or sabotage.
Remote Manipulation of Cargo, Ballast & Engine OT	No inherent change in the technical likelihood of OT compromise, but integrated electric-propulsion, ballast, and power-management systems can create additional safety-significant attack pathways.	Potentially higher if the resulting vessel motion, loss of load, or casualty challenges reactor operating limits or support systems.
Software Glitches & Unpatched Legacy Hardware	Mixed effect. Nuclear-grade quality assurance and configuration management can reduce defects in reactor systems, while non-nuclear shipboard legacy systems retain baseline vulnerabilities.	Potentially higher when faults affect reactor instrumentation and control, electrical distribution, or safety-support systems; otherwise, baseline consequences remain.
Human Error via Phishing & Onboard Infected Devices	Potential increase in targeting because a nuclear vessel is a high-value cyber target. Strict access control and network segmentation become more important.	A successful intrusion can enable the broader cyber-physical consequences described above, including loss of propulsion, data integrity, or access to protected systems.
Smart-Ship IoT Failure & Battery Thermal Runaway	IoT failure risk is largely unchanged. Dependence on large propulsion batteries may decrease, although batteries can still be used for emergency power or load leveling.	Battery-fire and IoT consequences remain. Fire or electrical disturbance can additionally challenge reactor support systems if segregation and redundancy are inadequate.

4.4 Environmental, Marine Pollution, and Climate Transition Risks

Table XIV. evaluates environmental and climate-transition risks. Nuclear propulsion can reduce bunker-fuel and alternative-fuel hazards, but severe structural casualties introduce a distinct radiological release pathway that conventional vessels do not have.

Table XIV. Nuclear Propulsion Effects on Environmental and Climate Transition Risks.

Baseline Hazard / Initiating Event	**Change in Likelihood / Frequency**	**Change in Consequence / Severity**
Severe Weather, Cyclones & Arctic Permafrost Thawing	No material change in severe-weather frequency or exposure is attributable to the propulsion source.	Potentially higher if severe weather, structural damage, capsizing, or sinking challenges reactor shutdown, cooling, shielding, or radionuclide-retention barriers.

Table XIV. (continued)

Baseline Hazard / Initiating Event	Change in Likelihood / Frequency	Change in Consequence / Severity
Marine Oil Spills & Chemical Toxic Contamination	Reduced likelihood of propulsion-fuel spills because nuclear propulsion removes or greatly reduces bunker-fuel storage. Cargo-related chemical spill hazards remain.	Propulsion-fuel spill consequences are reduced. A distinct low-probability radiological contamination pathway is introduced if nuclear safety barriers are severely damaged.
Decarbonization Transition & Alternative Fuel Risks	Substantially reduced exposure to ammonia, hydrogen, methanol, and similar bunkering hazards and to their fuel-supply transition uncertainty.	Alternative-fuel handling consequences are largely removed, but nuclear-specific licensing, fuel-cycle, waste, and public-acceptance risks replace part of the transition burden.
Ballast Water Invasive Species & Biofouling Transfer	No material change.	No material change in the ecological or regulatory consequences.
Whale Strikes & Toxic Antifouling Paint Leaching	No material change attributable to the propulsion source.	No material change in the primary environmental or legal consequences.

4.5 Financial, Economic, and Market Volatility Risks

Table XV. evaluates the principal financial and market risks. Nuclear propulsion reduces exposure to short-term bunker-price volatility but increases capital intensity and creates additional dependencies on specialized vendors, licensing, insurance, and port access.

Table XV. Nuclear Propulsion Effects on Financial, Economic, and Market Risks.

Baseline Hazard / Initiating Event	Change in Likelihood / Frequency	Change in Consequence / Severity
Freight Rate Volatility, Market Collapses & Trade Shocks	No material change in market volatility or freight-rate formation.	Potentially higher financial exposure during downturns because the vessel carries a larger fixed capital base and may have specialized service obligations.
Fuel & Bunker Price Volatility	No change in bunker-market volatility itself; nuclear propulsion greatly reduces the vessel's exposure to that hazard because propulsion energy is not purchased as frequent bunker fuel.	Lower exposure to bunker-price spikes and regional fuel shortages; nuclear fuel, service, and refueling costs remain under longer-term arrangements.
Currency Fluctuations & Capital Controls	No inherent change in exchange-rate or capital-control risk.	The mechanism is unchanged, although large reactor, shipyard, and service contracts can increase the absolute value of cross-border financial exposure.
Counterparty Credit Default & Bankruptcy	No inherent change in a counterparty's default probability, but reliance on specialized reactor vendors, service providers, and shipyards increases dependency concentration.	Potentially higher. A vendor or counterparty failure can delay delivery, interrupt licensing, maintenance, or refueling support, and strand a high-capital asset.
High CapEx, Insurance Inflation & Stranded Assets	Higher. Nuclear vessels require greater initial capital, while liability, insurance, port access, and specialized infrastructure remain less mature.	Greater balance-sheet exposure, financing cost, insurance uncertainty, and stranded-asset risk if licensing, port access, or reactor-service arrangements are not sustained.

4.6 Regulatory, Legal, Human, and Management Risks

Table XVI. evaluates regulatory, legal, human, and management risks. Nuclear vessels remain subject to conventional maritime requirements while adding reactor licensing, safeguards, security, radiation protection, specialist staffing, and port-state obligations.

Table XVI. Nuclear Propulsion Effects on Regulatory, Legal, Human, and Management Risks.

Baseline Hazard / Initiating Event	**Change in Likelihood / Frequency**	**Change in Consequence / Severity**
Regulatory Non-Compliance & PSC Detentions	Higher likelihood of non-compliance or detention because nuclear vessels add reactor licensing, safeguards, nuclear security, radiation protection, classification, and port-state requirements to conventional maritime rules.	Potentially higher. Detention or loss of port access can stop vessel operations and disrupt reactor custody, specialist staffing, service agreements, and revenue.
Contractual Disputes & Demurrage Claims	Potential increase because contracts must address nuclear-specific port access, reactor availability, liability, security, emergency response, and service responsibilities.	Potentially higher when a restricted port call or reactor-related outage extends off-hire or demurrage and triggers specialized liability disputes.
Seafarer Fatigue, Commercial Pressure & Human Error	Potential increase in human-error exposure because nuclear operations add specialized staffing, training, procedures, and safety-culture requirements while conventional fatigue and commercial pressure remain.	Potentially higher if human error affects reactor operation, radiation protection, security, or casualty response; conventional navigational consequences remain.
Forced Labor & Flag State Oversight Deficits	No inherent change in labor-exploitation risk, but nuclear operations require stronger flag-state competence and reduce tolerance for weak regulatory oversight.	Potentially higher if deficient oversight also compromises nuclear safety, security, safeguards, maintenance, or crew qualification.

4.7 Nuclear-Specific Risks

In addition to modifying conventional maritime risks, nuclear propulsion introduces hazards and obligations that do not have direct analogues on conventionally powered merchant vessels. The most important preliminary categories are:

a. **Reactor safety and radiological release.** Internal reactor events, loss of cooling, reactivity transients, damage to confinement or containment barriers, or severe external casualties can create a radiological release pathway. The shipboard design therefore depends on reliable reactor trip (scram) or equivalent shutdown action, passive decay-heat removal, robust shielding and radionuclide-retention barriers, hydrostatic pressure management after sinking, and a recoverable reactor compartment.

b. **Nuclear material safeguards and nonproliferation.** Marine reactors using conventional LEU or HALEU require nuclear-material accountancy, safeguards verification, and controlled fuel-cycle logistics. Physical protection and prevention of malicious acts are nuclear-security functions and are addressed separately below. Long refueling intervals reduce routine fuel handling but increase the importance of continuity of safeguards and secure material custody throughout the vessel life cycle and during refueling, maintenance, and decommissioning.

c. **Nuclear security, sabotage, and insider threats.** A commercial nuclear vessel can attract adversaries seeking sabotage, coercion, sensitive technology, or nuclear material. Security must therefore address unauthorized access, malicious insiders, cyber-physical attacks, piracy, and coordinated external threats while maintaining safe operation and emergency response.

d. **Port access, liability, and transboundary emergency governance.** Nuclear propulsion introduces dependence on flag-state licensing, port-state acceptance, bilateral or multilateral access arrangements, nuclear liability allocation, insurance capacity, and emergency-planning interfaces. Gaps or inconsistencies in these frameworks can prevent otherwise technically capable vessels from operating commercially.

e. **Fuel-cycle, decommissioning, waste, and salvage obligations.** Nuclear vessels require secure arrangements for fuel supply and take-back, radioactive waste management, decommissioning, and

recovery of a damaged or sunken reactor module. These obligations extend beyond normal ship disposal and can persist after the vessel is no longer commercially operable.

4.8 Cross-Domain Risk-Informed Design Matrix

Table XVII. consolidates the preceding maritime and nuclear risk characterization into a single risk-informed design and operational decision matrix. Each row identifies a design or operating choice, states the principal objective within the domain to which that choice most directly belongs, and then identifies potential conflicts, indirect effects, and risk transfers into other domains. The matrix is intended to support concept selection, HAZID and systems-theoretic reviews, licensing pre-application, and lifecycle trade studies; it is not a quantitative ranking of risk.

Table XVII. Cross-Domain Risk-Informed Design Matrix for Commercial Maritime Nuclear Propulsion.

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
A. Reactor Technology, Core, and Fuel Design		
Reactor technology and coolant family (PWR, MSR, HTGR, LFR, heat-pipe, etc.)	Reactor technology / nuclear safety: select a reactor concept whose pressure, temperature, coolant behavior, reactivity characteristics, decay-heat behavior, materials performance, and maturity are compatible with sustained marine service.	Operations/ship integration: pressure, temperature, coolant inventory, shielding, mass, volume, motion sensitivity, and maintenance differ sharply by concept. Security/safeguards: fuel form and enrichment alter material attractiveness and verification methods. Environment: coolant chemistry can create different release, corrosion, activation, tritium, or off-gas issues. Regulatory/financial: less mature non-LWR concepts may reduce some accident mechanisms but increase qualification, licensing, insurance, and supply-chain uncertainty.
Reactor thermal power and propulsion-power sizing	Reactor safety and operations: provide sufficient propulsion and ship-service power while retaining thermal margin for transients, degraded conditions, and expected operating profiles.	Marine safety: oversizing can add shielding, mass, structural loads, and concentrated hazard inventory; undersizing can reduce maneuvering margin or force frequent high-power operation. Economics: excess capacity increases CAPEX and lost cargo volume. Security: a larger plant may increase strategic value. Regulatory/emergency planning: higher inventory and source term may affect accident analysis, liability, and port acceptance.
Core power density and compactness	Reactor design: obtain a sufficiently compact plant for shipboard integration without compromising heat removal, fuel performance, shutdown margin, or thermal limits.	Ship/economics: higher power density reduces machinery volume and cargo penalty but can increase thermal gradients and decay-heat density. Safety: a compact core may have less geometric heat-removal margin. Security/safeguards: compact high-value fuel inventories can be more attractive targets. Maintenance: tighter packaging can reduce inspectability and repair access.

Table XVII. (continued)

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
Fuel enrichment (conventional LEU versus HALEU)	Fuel/core design: achieve required core lifetime, compactness, reactivity control, and power density using an enrichment compatible with the selected reactor and fuel cycle.	Safeguards/security: higher enrichment can increase safeguards significance, physical-protection expectations, and consequences of loss of custody. Supply chain: HALEU availability and fabrication capacity can become critical dependencies. Economics: higher enrichment may enable smaller/longer-life cores but increase fuel and qualification cost. Regulation/port acceptance: host states may impose additional requirements based on material category and national policy.
Fuel form (solid oxide/metal/TRISO versus liquid fuel salt or other advanced form)	Fuel performance and safety: select a fuel form that maintains integrity, predictable reactivity behavior, acceptable fission-product retention, and qualified performance under marine motion and temperature conditions.	Safeguards: liquid versus discrete solid fuel changes material accountancy and verification approaches. Environment: release chemistry and seawater interaction differ materially. Maintenance/decommissioning: drainable or circulating fuel can complicate system boundaries and waste classification, while solid fuel may simplify accountancy but require handling of discrete assemblies. Regulatory: unfamiliar fuel forms can increase licensing uncertainty.
Fuel inventory, core life, and refueling interval	Fuel-cycle / operations: maximize endurance and reduce routine refueling frequency while maintaining adequate reactivity control, fuel qualification, and predictable end-of-cycle performance.	Safety/security: a long-life core reduces handling events but keeps a significant nuclear inventory aboard through more years of piracy, casualty, seizure, and aging exposure. Safeguards: continuity of knowledge must be sustained over longer periods. Economics: long cycles reduce downtime but create stranded-fuel value if the vessel retires early. Supply chain: fewer refuelings reduce logistics frequency but make each outage and provider dependency more consequential.
Sealed core versus serviceable/openable core	Reactor safety / fuel cycle: minimize fuel handling, contamination, maintenance errors, and unauthorized access while preserving the ability to inspect, repair, or refuel when required.	Security: sealing reduces routine access but makes the complete module a concentrated target. Safeguards: tamper-indicating seals can support continuity, but reduced direct access can complicate verification. Maintenance: inaccessible components can allow degradation to remain latent. Economics: module replacement may shorten outages but requires heavy-lift infrastructure and secure transport. Decommissioning: a sealed module can transfer lifecycle obligations complicating the end-of-life processes.
Primary-system pressure and temperature regime	Nuclear safety / thermodynamics: achieve required efficiency and heat transfer while maintaining structural, material, and coolant margins across normal, transient, and casualty conditions.	Ship integration: high pressure drives vessel thickness, containment loads, piping qualification, and rupture consequences; high temperature drives insulation, fire separation, and material aging. Economics: lower-pressure concepts may reduce some containment costs but can require exotic materials. Maintenance/environment: corrosion, freezing, leakage chemistry, and inspection methods vary with regime.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Coolant chemistry, purification, activation-product control, and corrosion management	Reactor materials / radiation protection: maintain coolant properties that limit corrosion, deposition, activation products, and component degradation throughout long marine operating periods.	Operations: chemistry-control equipment adds maintenance and consumables. Radiation protection: activated coolant can drive secondary shielding and worker dose. Environment: leakage or discharge can create chemical and radiological pathways. Supply chain: specialized resins, gases, salts, or chemistry reagents may be difficult to source globally. Cyber/automation: chemistry monitoring may depend on connected sensors and automated dosing.
Refueling architecture (in-vessel refueling versus complete/partial module exchange)	Fuel-cycle operations: perform fuel replacement with minimum outage duration, worker dose, contamination, handling risk, and probability of fuel damage.	Security/safeguards: module exchange reduces onboard fuel handling but creates transportable fueled modules and custody-transfer events; in-vessel refueling requires protected facilities and more direct material handling. Economics/ports: module exchange requires cranes, transport casks, storage, and specialized berths. Regulatory/liability: responsibility can shift between shipowner, reactor vendor, fuel supplier, and port state during transfer.
B. Nuclear Safety, Radiological Barriers, and Severe-Casualty Response		
Reactor shutdown / scram architecture and trip setpoints	Nuclear safety: achieve rapid, reliable, fail-safe shutdown for reactor faults, loss of power, extreme ship motion, collision, grounding, fire, flooding, or other conditions that challenge safe operation.	Marine operations: conservative trip setpoints can remove propulsion during severe weather, restricted-water maneuvering, or collision avoidance. Human factors: frequent nuisance trips can create pressure to bypass protection. Cyber: automatic trip logic becomes safety-significant software. Economics: restart restrictions can create off-hire and demurrage.
Passive residual / decay-heat removal capability	Nuclear safety: maintain decay-heat removal without external power or operator action through extended blackout, list, capsize, flooding, or abandonment.	Ship integration: passive loops, accumulators, heat exchangers, and heat paths consume space and can be sensitive to orientation or flooding. Environment: using seawater as a heat sink introduces corrosion and potential contamination interfaces. Maintenance: passive systems still require surveillance and proof of availability. Economics: added redundancy and qualification increase mass and cost.
Ultimate heat sink selection and heat-rejection interfaces	Nuclear safety: provide a dependable long-duration heat sink for normal shutdown and severe casualty states, including loss of shore support.	Environment: direct seawater interfaces can cause thermal discharge, biofouling, corrosion, intake blockage, and potential contamination pathways. Marine casualty response: isolating a damaged seawater boundary can simultaneously remove the heat sink. Port operations: heat rejection at berth may affect local discharge limits. Security: exposed seawater systems may be accessible to sabotage.

Table XVII. (continued)

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
Safety-system redundancy, diversity, independence, and common-cause protection	Nuclear safety: prevent single failures and credible common-cause events from defeating shutdown, cooling, electrical supply, confinement, instrumentation, or monitoring.	Ship/economics: additional trains increase weight, penetrations, maintenance, spares, and CAPEX. Cyber: replicated digital equipment can reproduce common software vulnerabilities unless genuinely diverse. Human factors: complex system alignments can increase operator error. Security: more distributed equipment expands the protected footprint.
Containment / confinement philosophy and pressure boundary	Nuclear safety: retain radioactive material during internal reactor events and external marine casualties while accommodating pressure, temperature, impact, flooding, and submersion loads.	Ship structure: strong containment creates concentrated mass and stiffness and may transfer collision loads into adjacent hull structure. Heat removal: highly isolated boundaries can impede passive heat rejection. Salvage: a robust capsule improves post-sinking integrity but can remain an intact high-value object. Economics/port access: size and source-term performance influence cargo penalty, liability, and emergency-planning requirements.
Radiation shielding architecture and dose targets	Radiation protection: keep crew, passengers if any, cargo, port workers, and the public within occupational and public dose criteria during normal operation and credible transients.	Naval architecture: shielding can dominate reactor-plant weight and volume, affecting stability, hull loads, draft, cargo capacity, and structural design. Maintenance: very heavy shielding can restrict access and component replacement. Salvage: it increases recovery mass. Economics: conservative dose targets may materially increase CAPEX and lost revenue space; reduced shielding requires stronger operational zoning and access control.
Radionuclide-retention strategy and design source term	Nuclear safety / emergency planning: minimize the amount, mobility, and release fraction of radioactive material under credible accidents and severe external events.	Fuel/reactor choice: retention performance depends on fuel form, coolant chemistry, temperature, and confinement. Port/regulatory: a lower justified source term can reduce emergency-planning burden and improve acceptance. Security: radionuclide inventory can be the target of sabotage attacks. Economics: additional barriers and filtration add cost and maintenance.
Hydrostatic pressure equalization for deep-water sinking	Severe-casualty safety: prevent containment or reactor-compartment implosion as external seawater pressure increases after sinking.	Environmental/radiological: admitting seawater can sacrifice a dry barrier, accelerate corrosion, and complicate contamination control. Salvage: flooded spaces increase recovery mass and decontamination complexity. Security/safeguards: post-casualty access conditions and material verification become harder. Reliability: automatic valves must work after shock, deformation, fouling, and loss of power without creating premature flooding during survivable casualties.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Emergency depressurization, venting, filtration, or pressure-relief strategy	Nuclear safety: prevent uncontrolled pressure-boundary failure while limiting radioactive release during beyond-design-basis conditions.	Environment/public acceptance: controlled release may lower structural risk but create a deliberate release pathway with legal and political consequences. Port access: venting assumptions directly affect emergency planning. Security: vent paths may create sabotage opportunities. Maintenance: filters and isolation valves add surveillance burdens.
Safety instrumentation, reactor protection, and post-accident monitoring	Nuclear safety: provide reliable measurements and protection functions for reactivity, temperature, pressure, level, radiation, electrical state, and post-accident conditions under motion, shock, flooding, and loss of normal power.	Cyber: digital instrumentation expands software and supply-chain assurance needs. Human factors: excessive alarms can degrade decision quality during combined ship/reactor emergencies. Maintenance: sensor drift and harsh marine environments can challenge long intervals. Security: detailed telemetry may expose sensitive plant status. Economics: diverse qualified instrumentation increases lifecycle support cost.
Fire, flooding, watertight subdivision, and safety-function separation around the reactor plant	Nuclear safety / marine safety: prevent a conventional shipboard fire, cargo fire, pipe rupture, or flooding event from disabling multiple nuclear safety functions or spreading contamination.	Operations: barriers, watertight doors, cable separation, and restricted penetrations can impede routine movement, firefighting, and maintenance. Ship design: subdivision consumes volume and affects damage stability. Cyber/electrical: physical separation must align with network and power independence. Security: emergency openings and access routes can weaken protected-area boundaries.
Long-term safe submerged state and recovery criteria	Severe-casualty / lifecycle safety: ensure a sunken reactor remains subcritical, cooled, mechanically stable, and sufficiently contained for the period required to assess, secure, and recover it - including cases where recovery is delayed or impossible.	Security/safeguards: long-term seabed residence creates custody, surveillance, unauthorized salvage, and technology-access concerns. Environment: immediate recovery may disturb an otherwise intact package and increase release risk. Legal: coastal-state rights and liability may conflict with owner preferences. Economics: designing for indefinite in-situ safety can add cost but prevents salvageability from becoming an assumed safety function.
C. Ship Integration, Propulsion, and Maritime Operations		
Reactor longitudinal and vertical location in the hull	Naval architecture / nuclear safety: place the reactor to limit pitch/slamming, vibration, collision exposure, grounding loads, flooding susceptibility, and adverse effects on vessel stability.	Cargo/economics: central protected locations displace valuable cargo volume. Grounding versus collision: low placement improves center of gravity but moves the reactor toward bottom damage. Security/access: location affects protected-area design and emergency response. Salvage: deep internal placement can complicate recovery.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Reactor-module structural support, isolation, and load path to the hull	Structural safety: keep the reactor, shielding, and safety systems supported through wave bending, vibration, collision, grounding, capsize, and progressive hull deformation.	Ship structure: excessive local stiffness can transfer loads to weaker surrounding structure; excessive isolation can permit damaging relative motion at piping, cabling, and ventilation interfaces. Maintenance: complex mounts require inspection. Salvage: independent modules can survive hull loss but may become easier to separate and recover by unauthorized parties. Cost/weight increase with crashworthy supports.
Collision, allision, grounding, blast, and penetration protection	Marine/nuclear safety: prevent external impact energy from directly challenging the reactor boundary, support structure, cooling, shielding, or safety systems.	Economics/naval architecture: double bulkheads, voids, armor, and energy absorbers add weight and reduce cargo. Stability: protective structure changes mass distribution. Security: hardening against credible piracy or terrorism may be feasible, whereas state-level weapons can exceed commercial design basis, making route avoidance more effective. Regulation: defining the design-basis threat and accident spectrum affects certification and insurance.
Hull strength, stability, ballast, and concentrated nuclear-plant mass allocation	Naval architecture: satisfy intact and damage stability, longitudinal strength, fatigue, draft, and maneuvering requirements with the reactor and shielding treated as major concentrated loads.	Nuclear safety: ballast failures or cargo misloading can create list angles and accelerations that challenge coolant behavior or passive systems. Cyber: automated ballast control becomes indirectly safety-significant. Economics: structural reinforcement and lost deadweight reduce payload. Security: deliberate ballast manipulation could be a sabotage pathway. Maintenance: aging and corrosion around heavy supports require enhanced inspection.
Propulsion architecture (direct mechanical shaft versus turbo-electric / integrated power system)	Propulsion / reactor operations: provide efficient propulsion while controlling how rapid maneuvering, crash-stop, and propulsion-load changes are transmitted to the reactor.	Nuclear safety: direct drive can impose stronger reactor thermal transients; electric drive can decouple them but increases dependence on generators, switchboards, converters, and controls. Cyber: integrated electric propulsion expands attack surface. Marine safety: common electrical faults can affect propulsion and reactor support simultaneously. Economics: architecture changes efficiency, redundancy, maintenance skill, and equipment cost.
Shipboard electrical architecture, bus segmentation, load shedding, and safety-power interfaces	Electrical / nuclear safety: ensure propulsion, steering, reactor support, emergency loads, and critical ship services receive power with appropriate independence and prioritized shedding during faults.	Marine safety: aggressive shedding can preserve reactor cooling while losing maneuverability, navigation, pumps, or hotel loads. Cyber: power-management systems can become common-mode attack paths. Economics: split buses and redundant converters increase cost and space. Human factors: restoration sequences after blackout can be complex. Security: electrical distribution must survive deliberate damage as well as random faults.
Emergency propulsion, black-start capability, and independent auxiliary-energy reserve	Marine safety: retain sufficient maneuvering or recovery capability after reactor trip, turbine/generator failure, or total electrical blackout.	Nuclear/fire safety: retaining diesel, gas turbine, batteries, or other backup propulsion reintroduces fuel, fire, explosion, ventilation, and maintenance hazards that nuclear propulsion otherwise reduces. Economics: rarely used backup systems consume space and capital. Environmental: auxiliary fuel storage restores some spill/emission pathways. The design trade is between independence and the hazards of the backup technology itself.

Table XVII. (continued)

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
Battery energy storage and load-leveling capacity	Power-system operations: buffer rapid propulsion loads, support black start, bridge generator transients, and maintain critical loads during short interruptions.	Fire safety: larger batteries introduce thermal-runaway, toxic-gas, and firefighting challenges. Nuclear safety: battery fires or DC faults can threaten nearby safety equipment if separation is inadequate. Economics/weight: energy storage adds mass and periodic replacement cost. Cyber: battery-management systems create digital dependencies. Excessive reliance on batteries can create a new common-cause vulnerability.
Marine-motion, inclination, vibration, shock, and 6-DOF qualification envelope	Reactor/ship integration: demonstrate that core physics, coolant flow, heat transport, control mechanisms, structures, and instrumentation remain within limits under credible roll, pitch, yaw, heave, surge, sway, slamming, and vibration.	Economics/technology readiness: broad qualification envelopes require expensive testing and can delay deployment. Operations: a narrower qualified envelope may require weather avoidance or speed restrictions, reducing route flexibility. Regulation: assumptions must align with class and nuclear licensing. Security/emergency response: deliberate maneuvers or casualty-induced attitudes should not create exploitable unsafe states.
Maintainability, inspection access, lifting paths, and component replacement strategy	Operations / aging management: allow scheduled inspection, nondestructive examination, repair, replacement, contamination control, and worker access throughout vessel life.	Security: access hatches, removable shielding, lifting points, and service passages can become intrusion or theft pathways. Radiation protection: improved access can increase worker exposure unless shielding and remote tooling are planned. Ship design: generous maintenance space reduces cargo capacity. Regulatory/economics: poor maintainability can convert minor failures into long outages and increase dependence on specialized ports.
Operating envelope: speed, route, weather, ice, shallow water, and restricted-water policy	Marine operations: exploit nuclear endurance and power while keeping collision, grounding, structural, and severe-weather exposure within the demonstrated design envelope.	Economics: high sustained speed improves fleet utilization but increases collision energy, stopping distance, structural loads, and ecological impacts. Port/regulatory: route choice is constrained by nuclear-capable ports and coastal-state acceptance. Security: avoiding conflict zones may conflict with commercial schedules. Safety: route restrictions can reduce hazard frequency but create network concentration and chokepoint dependence.
Seabed salvageability, modular recoverability, and external recovery interfaces	Lifecycle / severe-casualty safety: enable authorities and qualified salvors to locate, isolate, free, lift, transport, and ultimately decommission an intact reactor compartment after vessel loss.	Security/safeguards: features that simplify legitimate recovery - modular separation, lifting trunnions, accessible cut lines, standardized interfaces, known location data - can also simplify unauthorized recovery, theft, diversion, or access to sensitive technology. Safety/environment: premature salvage can damage an otherwise stable package. Economics/legal: recovery capability adds structure and cost and requires clear custody, coastal-state authority, funding, and authentication of legitimate recovery operations.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
D. Nuclear Security, Safeguards, and Nonproliferation		
Protected-area boundaries, physical barriers, and security zoning	Nuclear security: delay and detect unauthorized access to nuclear material, sensitive systems, and vital equipment while preserving defense in depth against intrusion and sabotage.	Emergency response: strong barriers can delay firefighting, flooding control, medical access, and evacuation. Operations: protected zones complicate maintenance and cargo workflows. Human factors: excessive access friction can encourage procedural workarounds. Port acceptance: security arrangements must interface with foreign terminal and law-enforcement systems without revealing sensitive details.
Personnel access authorization, credentialing, and visitor/contractor control	Security / safeguards: ensure only appropriately screened and authorized individuals can enter protected spaces or perform material-significant work.	Human resources: stringent vetting can constrain multinational crewing and specialist availability. Emergency response: temporary responders may lack preauthorization. Operations: contractor access controls can lengthen maintenance outages. Legal/privacy: personnel-reliability programs must comply with multiple jurisdictions. Insider risk is reduced only if authorization is paired with behavioral and procedural controls.
Insider-threat controls, two-person rules, separation of duties, and privileged-access governance	Nuclear security: prevent a single trusted individual from obtaining enough access or authority to divert material, defeat protection, or deliberately cause unsafe conditions.	Safety/human factors: mandatory concurrence can delay time-critical casualty response. Staffing/economics: two-person coverage increases minimum crew and watch requirements. Cyber: privileged digital access must follow the same separation logic. Operations: excessive procedural barriers can create fatigue and normalization of workaround behavior. Design should distinguish actions requiring independent verification from emergency actions requiring immediate execution.
Anti-piracy, armed protection, citadel, and forced-boarding response	Maritime/nuclear security: deter or delay hostile boarding, protect crew, prevent access to nuclear areas, and preserve reactor safety during piracy or armed attack.	Port/regulatory: armed guards and weapons complicate port entry and jurisdictional rules. Safety: firefights, explosives, or lockdown can impede reactor operations and emergency response. Human factors: security forces must understand nuclear safety boundaries. Geopolitics: visible hardening can deter opportunistic actors but also signal strategic value. Economics: high-end protection raises recurring operating and insurance costs.
Nuclear-material accountancy, seals, tamper indication, and safeguards continuity	Safeguards/nonproliferation: maintain knowledge of nuclear-material quantity, location, integrity, and authorized use throughout operation, maintenance, refueling, casualty, and decommissioning.	Operations: inspection points and seals can constrain maintenance. Security: safeguards access and records may reveal sensitive plant information. Cyber: digital accountancy and remote seals create spoofing and data-integrity concerns. Casualty response: continuity may be lost after sinking, fire, seizure, or communications failure. Design should enable re-establishment of material status without unnecessary dismantling or exposure of proprietary technology.
Remote safeguards monitoring, vessel tracking, and loss-of-custody detection	Safeguards/security: provide continuity of knowledge and timely indication of route deviation, tampering, prolonged communication loss, or unauthorized movement of the reactor/fuel.	Security: precise location and status data can aid targeting or unauthorized salvage if compromised. Cyber/privacy: authenticated, resilient communications and data governance become critical. Operations: false alarms or satellite outages can trigger unnecessary security responses. Sovereignty: some states may restrict transmission of detailed nuclear or vessel data while in their waters.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Theft resistance of fuel, reactor modules, and salvage/recovery interfaces	Nuclear security: make unauthorized removal of fuel or a complete reactor module sufficiently difficult, detectable, and time-consuming to permit intervention.	Safety/salvage: permanent anti-removal features can obstruct legitimate emergency recovery and decommissioning. Economics: hardened interfaces add mass and specialized equipment. Safeguards: whole-module theft can defeat assumptions based on inaccessible internal fuel. Design should treat the complete fueled module as a security object, not only individual fuel elements.
Protection of export-controlled, proprietary, and security-sensitive technology	Technology security: prevent unauthorized acquisition of sensitive reactor design information, components, software, materials, or security arrangements during operation, maintenance, casualty, and disposal.	Regulatory/transparency: port states, class societies, emergency responders, insurers, and safeguards authorities still require enough information to evaluate safety. Maintenance: restricting drawings and tools can increase vendor dependence. Salvage: wreckage may expose technology outside normal access controls. Cyber: technical data repositories and remote support become high-value targets.
Nuclear-material custody, reactor ownership, and jurisdictional handoff	Safeguards/security governance: maintain unambiguous legal and physical custody of nuclear material and the reactor across flag states, port states, charter arrangements, vendor ownership, refueling, and casualty response.	Financial/legal: shipowner, reactor owner, fuel owner, and operator may be different entities with different insolvency or sanctions exposure. Sovereign detention can separate the physical asset from the licensed operator. Emergency response: unclear authority can delay decisions. Insurance/liability: custody and liability may not follow the same contractual boundary.
Security through abandonment, sinking, detention, decommissioning, and other off-normal lifecycle states	Nuclear security: ensure physical protection does not disappear when normal crewing, propulsion, port support, communications, or commercial ownership is disrupted.	Safety: security measures during casualty must not block cooling, rescue, or environmental protection. Economics: long-duration guard, monitoring, and recovery obligations can persist after revenue ceases. Legal: coastal states or courts may control a detained or wrecked vessel. Safeguards: continuity must be restored after chaotic events. Decommissioning sites need security until material and sensitive equipment are dispositioned.
E. Digital Systems, Cybersecurity, and Automation		
Degree of automation and minimum-manning philosophy	Operations / human factors: use automation to improve consistency, reduce routine workload, manage complex power systems, and potentially reduce specialist crew requirements.	Cyber: greater automation increases dependence on software, sensors, networks, and update supply chains. Safety: rare combined maritime/nuclear emergencies may exceed automated logic. Human factors: reduced routine involvement can degrade operator skill and situation awareness. Economics: manning savings must be balanced against higher verification, redundancy, and shore-support costs. Regulation may limit autonomous nuclear functions.
Network architecture, safety-system segregation, data diodes, and air gaps	Cyber/nuclear safety: prevent compromise of business, crew, cargo, navigation, or propulsion networks from propagating into safety-significant reactor systems.	Maintenance/operations: strict isolation complicates diagnostics, data transfer, patching, and vendor support and can encourage temporary bridges or removable-media use. Emergency response: responders may need information across zones. Economics: duplicate infrastructure increases cost. Security: physical ports used to cross air gaps can become insider pathways. Architecture must preserve necessary information flow without command pathways.

Table XVII. (continued)

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
Remote vendor access, remote diagnostics, and shore-based reactor support	Maintenance / operations: provide scarce expert support, condition monitoring, troubleshooting, and fleet learning without carrying every specialist aboard.	Cyber/security: remote connectivity creates a high-consequence access path and a supply-chain trust dependency. Geopolitics: sanctions, conflict, telecom outages, or vendor insolvency can remove support. Regulation: some states may prohibit remote control or foreign data access. Human factors: onboard crews may defer excessively to remote experts during time-critical events.
Integration of propulsion, electrical power, ballast, steering-support, and reactor-support controls	Operations: coordinate plant output, load management, maneuvering, and vessel services efficiently across an integrated power system.	Cyber/safety: integration creates pathways for a fault or compromise in non-nuclear systems to produce reactor-significant load transients, list, blackout, or loss of cooling support. Marine safety: common controllers can disable multiple functions. Economics: integration reduces duplicated equipment but increases verification scope. Security: deliberate manipulation of ballast or power can become an indirect sabotage route.
Manual overrides, local control stations, and degraded-mode operation	Safety/resilience: retain the ability to operate or safely shut down essential functions when automation, networks, sensors, or remote support are unavailable or untrusted.	Security/insider risk: local override authority can bypass cyber protections or automated interlocks. Human factors: rarely used controls require training and clear indications. Radiation/fire: local stations may become inaccessible during the casualty they are intended to address. Design should specify which functions require local independence and which must remain protected from unilateral manual action.
Software lifecycle, patching, configuration management, and vulnerability response	Cyber / nuclear quality assurance: maintain a known, verified, supportable software baseline while correcting defects and emerging vulnerabilities throughout a long vessel life.	Safety/regulation: rapid patching can invalidate verification and licensed configurations; slow patching leaves known cyber vulnerabilities exposed. Economics: long-term software support can lock the operator to vendors. Operations: fleet-wide patches can create common-mode failures. Supply chain: discontinued operating systems or hardware can force major upgrades mid-life.
Commercial off-the-shelf versus nuclear-grade digital equipment	Engineering/economics: balance qualified reliability, traceability, cybersecurity assurance, availability of spares, obsolescence risk, and cost.	Supply chain: COTS products can have opaque firmware and short lifecycles; bespoke nuclear-grade systems may have few suppliers and high replacement cost. Cyber: mass-market vulnerabilities can affect many ships simultaneously. Regulation: qualification burden differs by safety classification. Maintenance: proprietary equipment can increase vendor dependence and stranded-asset risk.
Sensor density, IoT, condition monitoring, predictive maintenance, and digital twins	Reliability / maintenance: detect degradation early, support condition-based maintenance, improve availability, and reduce intrusive inspections.	Cyber: every sensor, gateway, and analytics connection adds attack surface and data-integrity requirements. Human factors: false positives can create alarm burden. Security/export control: high-fidelity plant data can expose design details. Economics: monitoring may reduce outages but requires calibration and lifecycle support. Regulation: credit for predictive methods requires validation and configuration control.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Navigation cyber resilience: GNSS/AIS/ECDIS dependence, inertial/radar cross-checks, and spoofing response	Marine safety/security: maintain trustworthy position, route, and collision-avoidance information despite jamming, spoofing, corrupted charts, or communications loss.	Nuclear security: navigation manipulation can intentionally drive a nuclear vessel toward grounding, hostile waters, detention, or a prepared attack location. Operations: strict cross-check requirements increase bridge workload. Economics: redundant navigation systems and electronic-warfare resilience add cost. Port/regulatory: spoofing incidents can trigger conservative exclusion or escort requirements.
Cyber incident safe-state, isolation, recovery, and reactor/ship restart logic	Cyber/nuclear safety: contain suspected compromise and place affected systems in a controlled condition without trusting potentially corrupted commands or data.	Marine safety: automatically shutting down the reactor or power system can create an immediate navigation hazard. Security: retaining propulsion may preserve an adversary's control path. Human factors: operators need criteria for deciding when instrumentation is trustworthy. Economics/regulation: forensic isolation can extend outages. The safe state must be defined for the integrated ship, not a single subsystem.
F. Environmental Protection, Radiation Protection, and Waste Management		
Routine radioactive effluent and discharge philosophy	Radiation/environmental protection: minimize and control routine liquid and gaseous releases and demonstrate doses and environmental concentrations within applicable limits.	Operations: zero-discharge policies require larger onboard storage and treatment systems. Waste: retaining all effluent transfers risk to later port handling. Port access/public acceptance: even compliant releases may be politically unacceptable. Economics: treatment and storage consume space. Security: stored radioactive liquids become additional inventories requiring control during casualty and decommissioning.
Onboard radioactive-waste storage capacity and offloading frequency	Waste management: safely accumulate filters, resins, contaminated materials, liquid wastes, and other operational waste until transfer to an authorized facility.	Safety/environment: larger retained inventories increase casualty source term; frequent offloading increases handling and transport events. Port access: only some ports may accept radioactive waste. Security/safeguards: waste characterization must show whether material has safeguards or security significance. Economics: storage competes with cargo space and creates long-term service dependence.
Tritium, off-gas, noble-gas, and volatile-fission-product control for advanced reactors	Reactor/environmental safety: prevent uncontrolled migration or release of mobile radionuclides and maintain acceptable worker dose and system chemistry.	Ship integration: capture, cleanup, storage, and monitoring systems add volume and penetrations. Waste: captured species create disposal obligations. Port regulation: unfamiliar effluent streams may complicate permitting and emergency planning. Maintenance: systems can require specialized media and leak-tight equipment. Security: gas-processing systems may expose sensitive fuel-cycle information.
Seawater cooling, intake/outfall design, biofouling control, and thermal discharge	Thermal/environmental management: reject heat reliably while controlling intake blockage, marine growth, corrosion, and local thermal impacts.	Nuclear safety: seawater systems may be safety-significant ultimate heat sinks and therefore require higher assurance than conventional cooling. Environment: antifouling treatments and heated discharge affect ecosystems. Security: exposed intakes/outfalls are accessible external interfaces. Port operations: warm, shallow, icy, or debris-laden waters may constrain reactor operation. Maintenance requires cleaning without compromising safety availability.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Materials selection for corrosion resistance, activation, irradiation, and marine exposure	Materials / aging management: maintain pressure-boundary, structural, shielding, and heat-transfer integrity over long service in radiation, temperature, saltwater, and cyclic mechanical loading.	Economics/supply chain: exotic alloys can be expensive, export controlled, difficult to fabricate, and available from few suppliers. Decommissioning: activation can complicate recycling and waste classification. Inspection: some coolants or geometries reduce inspectability. Shipyard capability: nuclear-grade welding and repair may not be available at ordinary ports.
Radiological monitoring, environmental sampling, and emergency characterization capability	Radiation protection / emergency response: rapidly determine dose rates, contamination, releases, and environmental conditions during normal operation and after a casualty.	Cyber/security: networked monitors require integrity and can reveal sensitive operational data. Human factors: crews and port responders need training to interpret measurements. Port/regulatory: standardized data can support acceptance, but disagreement over methods can delay decisions. Economics: calibrated instruments, laboratories, consumables, and specialist staffing add lifecycle cost.
Design for decontamination, cleanup, and contaminated-water control	Lifecycle / radiological protection: limit contamination traps and enable surfaces, systems, and spaces to be isolated, flushed, sampled, decontaminated, and dismantled after leaks or accidents.	Security: removable panels, drains, access routes, and decontamination connections can create unauthorized access paths. Ship structure: smooth accessible layouts may compete with compactness and crash protection. Waste: decontamination generates secondary liquid/solid wastes. Economics: features may appear nonproductive during normal service but greatly reduce casualty and decommissioning cost.
Environmental operating restrictions and sensitive-area route policy	Environmental/marine risk: reduce ecological consequences through routing, speed management, ice/whale protections, discharge restrictions, and avoidance of highly sensitive coastal areas.	Economics: restrictions can reduce the speed/utilization advantage of nuclear propulsion. Security/geopolitics: alternate routes may pass through less secure waters or fewer approved ports. Emergency planning: remote routes reduce population exposure but can delay rescue, towing, salvage, and radiological response. Route policy should optimize combined ecological, safety, security, and supportability risk.
G. Regulatory, Legal, Port Access, Liability, and Emergency Governance		
Licensing basis, design certification strategy, and prescriptive versus performance-based compliance	Regulatory/nuclear safety: establish a defensible safety basis that integrates nuclear regulation, classification rules, SOLAS requirements, and marine external hazards.	Technology/economics: highly prescriptive requirements can lock advanced designs into legacy assumptions; performance-based approaches allow innovation but require stronger analysis, data, and regulator capability. Port access: one flag-state approval may not guarantee foreign acceptance. Schedule risk: unresolved standards can strand a technically complete vessel. Security information must be protected within an otherwise transparent licensing process.
Port-access strategy: globally flexible vessel versus fixed/bilateral nuclear corridors	Commercial/regulatory: secure reliable access to loading, unloading, repair, refuge, and service ports sufficient for the intended business model.	Economics: fixed corridors can enable early deployment but create route and sovereign concentration risk; global compatibility increases design and licensing cost. Emergency response: fewer approved ports lengthen diversions. Geopolitics: policy changes can strand assets. Security: repeated predictable routes can aid adversarial planning. Infrastructure investment can become stranded if traffic or policy changes.

Table XVII. (continued)

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
Emergency-planning basis, source-term assumptions, and emergency-planning-zone expectations	Emergency governance / public protection: define credible accident consequences, protective actions, communications, monitoring, and response interfaces for ports and coastal communities.	Ship/reactor design: tighter source-term performance may reduce planning burden but add containment/shielding cost. Commercial feasibility: very large emergency zones can make dense-port operation impractical. Public acceptance: technically small risk may still be socially unacceptable. Security: emergency plans can reveal sensitive access routes and vulnerabilities. Liability/insurance assumptions depend on the same consequence analysis.
Place-of-refuge / distress-port strategy for a disabled or damaged nuclear vessel	Marine emergency management: ensure a vessel in distress has a preplanned safe destination or alternative where it can be stabilized, cooled, towed, inspected, and supported.	Sovereignty/public risk: the locally safest action for the ship may be politically unacceptable to the coastal state. Environment: keeping a damaged vessel offshore may increase sinking risk. Security: refuge locations require protection. Legal/liability: denial of entry can shift consequences and responsibility. Design independence from shore support reduces this conflict but increases onboard complexity and cost.
Transboundary emergency command, decision authority, and information-sharing interfaces	Emergency governance: define who can order reactor actions, vessel maneuvers, evacuation, towing, port entry, exclusion zones, monitoring, and salvage when several jurisdictions are involved.	Human factors: competing orders from master, reactor operator, flag state, port state, coast guard, and nuclear regulator can delay action. Security: information sharing must not expose sensitive data. Liability: authority and financial responsibility may diverge. Cyber/communications outages can sever coordination. Procedures must remain workable when normal diplomatic channels are slow.
Nuclear liability allocation, compensation limits, and financial security	Legal/financial: ensure third parties can be compensated and define responsibility among shipowner, reactor owner, operator, fuel supplier, vendor, charterer, flag state, and insurers.	Economics: broad or unlimited liability can make financing/insurance unavailable; narrow liability may undermine public acceptance. RaaS models can split reactor and maritime ownership in ways not matched by existing conventions. Port access may depend on proof of coverage. Salvage and long-term environmental monitoring can create obligations long after conventional marine policies terminate.
Insurance structure: hull and machinery, P&I, war risk, nuclear liability, business interruption, and salvage	Financial resilience: provide insurable mechanisms for property loss, third-party claims, radiological liability, war events, prolonged outage, cleanup, and recovery.	Design: insurers may require additional hardening, monitoring, training, route restrictions, or deductibles that alter operations. Security/geopolitics: war-risk exclusions can remove coverage exactly where strategic targeting increases. Economics: uncertain premiums increase financing cost. Data: underwriting may require access to sensitive safety/security information. Lack of coverage can become a de facto design constraint.
Interface among flag state, port state, nuclear regulator, maritime authority, and classification society	Governance/assurance: allocate oversight responsibilities and avoid gaps between reactor safety, ship safety, security, safeguards, environmental protection, and class certification.	Schedule/economics: overlapping or contradictory requirements can drive redesign and inspection burden. Emergency authority: regulators may prioritize different risks. Security: different agencies require different access to information. International operations: a competent flag-state regime may still be rejected by a port state. Design documentation should map requirements to a single configuration baseline.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Transparency, public disclosure, security classification, and protected information	Regulatory/public acceptance: provide enough evidence for independent safety review, emergency planning, insurer confidence, and public legitimacy while protecting sensitive technology and security information.	Security/export control: excessive disclosure can aid sabotage, proliferation, or technology acquisition; excessive secrecy can undermine trust and foreign regulatory approval. Cyber: repositories containing licensing and security data become high-value targets. Operations: crews and responders need usable information even when detailed design data are restricted.
Foreign inspection, port-state control, safeguards access, and verification arrangements	Regulatory/safeguards: enable authorized authorities to verify vessel condition, compliance, nuclear-material status, radiation conditions, and required certificates before or during port calls.	Security/proprietary information: inspection access can expose protected areas or technology. Operations: repeated inspections create schedule uncertainty and radiation/work controls. Sovereignty: inspectors may apply inconsistent standards. Cyber: electronic records shared abroad require integrity and access control. Standardized inspection interfaces can reduce burden but may create predictable security patterns.
Detention, sovereign seizure, sanctions, and loss-of-port-access contingency	Legal/operations: preserve safe reactor custody, qualified staffing, maintenance, security, cooling, and eventual disposition if the vessel is immobilized by authorities or geopolitical events.	Security/safeguards: normal operator access may be restricted while nuclear obligations continue. Economics: high-capital assets can be stranded for months or permanently. Supply chain: sanctioned vendors may be unable to provide parts or software. Liability: the detaining state may not accept reactor responsibilities. Design should support prolonged safe shutdown without proprietary external services.
Mutual recognition, bilateral agreements, and international standardization strategy	Regulatory/commercial: reduce the need to relicense the same ship separately for every port and create predictable operating rules across jurisdictions.	Design: harmonization can drive standardization and lower cost, but the most restrictive participating state may effectively set global requirements. Sovereignty: states may reserve independent denial rights. Security: common procedures can create common vulnerabilities. Economics: early bilateral arrangements speed demonstration but risk creating incompatible regional fleets if global standards later diverge.
Charterparty, reactor-service, refueling, outage, force-majeure, and off-hire contractual allocation	Commercial/legal: define responsibility and payment consequences for reactor trips, inspections, denied port entry, security alerts, refueling outages, vendor service, emergency diversions, and regulatory changes.	Safety culture: poorly structured incentives can pressure crews to defer shutdown or maintenance. Finance: long outages can trigger cascading defaults among shipowner, charterer, and reactor vendor. Liability: contractual allocation cannot always override statutory nuclear responsibilities. Security: service rights may grant external parties significant access to the vessel. Contracts should reinforce rather than undermine conservative safety decisions.
H. Human Factors, Crew, Organization, and Management		
Command authority between vessel master, chief engineer, reactor operator, security lead, and shoreside organization	Human/organizational safety: establish unambiguous authority for navigation, reactor safety, security, evacuation, and emergency actions under normal and casualty conditions.	Integrated risk: the reactor-safe action may conflict with the navigation-safe action, such as scram versus maintaining propulsion. Security lockdown can conflict with firefighting access. Remote experts can conflict with onboard command. Legal regimes may assign authority differently. Procedures need explicit conflict-resolution rules rather than assuming all safety objectives align.

Table XVII. (continued)

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
Crew complement and minimum nuclear-specialist staffing	Operations/safety: maintain enough qualified personnel for continuous watchkeeping, maintenance, radiation protection, security, emergency response, and degraded operations.	Economics: larger specialist crews reduce the operating-cost advantage of automation. Human resources: global availability of licensed nuclear mariners may constrain fleet scale. Security: more authorized personnel enlarge the insider population. Fatigue: too-small crews become fragile during sickness, detention, long emergencies, or simultaneous ship/reactor casualties. Accommodation and lifesaving capacity must also scale.
Specialization versus cross-training of marine and nuclear personnel	Human reliability: ensure deep technical competence while providing sufficient redundancy if specialists are unavailable and improving coordination between bridge, engineering, reactor, and damage-control teams.	Security: broader qualification can mean broader access privileges. Training cost rises with cross-disciplinary competence. Human factors: excessive role breadth can dilute expertise, while narrow specialization creates single-person dependencies. Emergency response benefits from shared mental models. Regulation may require licenses that are not mutually recognized across countries.
Watchkeeping model, work/rest limits, and fatigue management	Human factors: maintain alert decision-making and compliance with maritime and nuclear staffing requirements during continuous operation, port calls, maintenance, and emergencies.	Economics/staffing: conservative rest rules increase crew size. Security: emergencies may require sustained watches beyond normal limits. Commercial pressure from port schedules can conflict with nuclear conservatism. Automation can reduce workload but may create vigilance problems. Detention or extended casualty response can exhaust the qualified crew unless relief arrangements are preplanned.
Training, licensing, simulators, drills, and combined casualty exercises	Human performance: prepare crews for reactor transients, collision, grounding, flooding, fire, blackout, cyber events, security incidents, radiological emergencies, abandonment, and combinations of these events.	Economics: high-fidelity simulators and recurrent training are costly and remove personnel from service. Security: realistic security scenarios and plant models contain sensitive information. Regulation: multinational crews may face incompatible credentialing. Operations: excessive training requirements worsen staffing shortages, but insufficient integrated drills leave gaps between marine and nuclear response cultures.
Safety culture, reporting culture, commercial pressure, and stop-work authority	Management / nuclear safety: ensure operational and financial incentives do not suppress reporting, defer maintenance, normalize deviations, or discourage conservative shutdown decisions.	Commercial: strong stop-work authority can create schedule and demurrage costs, making contract design important. Security: reporting systems must distinguish safety transparency from disclosure of sensitive vulnerabilities. Human resources: punitive security or performance regimes can discourage reporting. Regulatory oversight must account for both maritime commercial pressure and nuclear safety culture.
Maintenance organization, nuclear-quality assurance, configuration control, and aging management	Reliability/safety: ensure work is correctly planned, performed, documented, inspected, and reflected in the licensed configuration across hull, machinery, reactor, electrical, digital, and security systems.	Economics: nuclear-grade QA can make routine marine repairs slower and more expensive. Port operations: ordinary shipyards may not be qualified. Cyber: configuration management includes software and firmware. Supply chain: approved parts may have long lead times. Human factors: excessive paperwork can burden crews and encourage informal workarounds. Deferred maintenance can compromise multiple risk domains simultaneously.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Personnel reliability, background screening, behavioral observation, and fitness for duty	Security/human reliability: reduce insider threat and ensure personnel performing safety- or security-significant work are trustworthy and fit for duty.	Labor/privacy: multinational privacy, employment, and human-rights rules can conflict with intrusive screening. Staffing: strict criteria reduce the available workforce. Safety culture: personnel may conceal problems if reporting threatens clearance. Emergency staffing: replacement workers may not complete vetting rapidly. Programs must balance security assurance with reporting, welfare, and practical crewing resilience.
Integrated damage-control, firefighting, radiological response, rescue, and medical capability	Emergency response: control conventional marine casualties while protecting reactor safety functions, limiting dose/contamination, rescuing personnel, and preserving evacuation options.	Security: emergency access can weaken protected boundaries. Staffing: simultaneous fire, flooding, radiation, and security events can exceed crew capacity. Ship design: equipment and protected staging areas consume space. Port dependence: specialized external responders may not be available in remote waters. Training burden is high because nuclear response cannot replace conventional seamanship and damage control.
Shore-based technical support, fleet operations center, and emergency-support organization	Organizational resilience: provide specialist analysis, engineering, regulatory liaison, security coordination, logistics, and emergency support beyond the onboard crew.	Cyber/communications: shore dependence creates connectivity and data-security requirements. Geopolitics: cross-border support may be unavailable during sanctions or conflict. Human factors: unclear division between onboard authority and remote advice can delay decisions. Economics: centralized support improves fleet economies of scale but becomes a common-mode organizational dependency. Continuity plans are needed for loss of the support center.
I. Economics, Supply Chain, Infrastructure, and Lifecycle Strategy		
Safety margin, structural hardening, redundancy, and shielding versus CAPEX, payload, and vessel performance	Financial/design optimization: achieve an economically viable vessel while providing sufficient margin against nuclear and maritime hazards and meeting regulatory expectations.	Safety/public acceptance: cost optimization that erodes visible margin can reduce trust and increase consequence risk; over-conservatism can make deployment uneconomic and strand decarbonization benefits. Naval architecture: added mass reduces cargo and efficiency. Insurance/port access may reward additional margin. Decisions should use risk-informed marginal benefit rather than treating either maximum conservatism or minimum cost as inherently optimal.
Standardization, modularity, and fleet commonality	Economics / manufacturing: reduce design, licensing, training, spares, construction, and maintenance cost through repeatable reactor modules and standardized ship interfaces.	Security/cyber: a vulnerability discovered on one ship can apply to the entire fleet. Safety: common design defects become fleet-wide common-cause risks. Salvage/theft: standardized removal interfaces can aid unauthorized handling. Regulation: standardization supports mutual recognition but can reduce route-specific optimization. Supply chain: large fleets can become dependent on a narrow set of standardized components.

Table XVII. (continued)

Design / Operation Feature or Choice	**Primary-Domain Design Objective(s)**	**Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers**
Single-vendor dependence versus qualified multi-sourcing	Supply chain / quality: obtain reliable nuclear-grade components and services with controlled configuration, traceability, and technical authority.	Economics/geopolitics: a sole vendor creates bankruptcy, sanctions, export-control, strike, and capacity risk; multiple vendors reduce concentration but expand qualification burden and configuration variants. Safety: unauthorized substitutions can undermine the safety basis. Cyber: each supplier adds software and data supply-chain exposure. Long service life requires support beyond normal commercial product cycles.
Reactor-as-a-Service, leasing, vendor ownership, and long-term service model	Finance/operations: reduce shipowner upfront capital and transfer specialized licensing, fuel, maintenance, and refueling responsibilities to a competent reactor provider.	Legal/custody: reactor owner and shipowner may be in different jurisdictions and face different sanctions, insolvency, or seizure risks. Safety: vendor withdrawal cannot be allowed to remove essential capability. Security/safeguards: ownership and material custody may diverge. Contracts can create long-term monopoly dependence. Lenders and insurers need step-in rights that do not create unqualified operational authority.
Nuclear-fuel supply chain, enrichment/fabrication capacity, and strategic inventory	Fuel-cycle/economic resilience: assure qualified fuel availability over decades of vessel operation and refueling schedules.	Geopolitics: enrichment and fabrication are concentrated strategic industries subject to export controls and sanctions. Security/safeguards: stockpiling fuel increases protected inventories and transport obligations. Economics: long-lead fuel can require prepayment and working capital. Reactor choice can lock the vessel to a specific supplier or enrichment level. Fuel scarcity can strand otherwise functional ships.
Spares strategy, component obsolescence, export controls, and long-term technical data rights	Lifecycle reliability: ensure safety-significant mechanical, electrical, digital, shielding, and security components remain repairable or replaceable throughout the ship/reactor service life.	Economics: large strategic spares inventories tie up capital; lean inventories increase outage risk. Cyber: obsolete digital hardware can become unpatchable. Export control: parts and drawings may not be transferable to foreign ports. Vendor lock-in increases counterparty risk. Configuration control limits substitution. Decommissioning and salvage also require technical data decades after initial delivery.
Nuclear-capable port, shipyard, refueling, waste, and emergency-response infrastructure concentration	Infrastructure/economics: concentrate specialized facilities to achieve competence, security, regulatory oversight, and economies of scale.	Network resilience: a small number of facilities become chokepoints vulnerable to congestion, attack, natural disaster, political closure, or loss of license. Port access: ships may require long diversions for service. Security: concentrated nuclear activity creates high-value targets. Distributed infrastructure improves resilience but multiplies capital cost, training, emergency-planning, and regulatory burden.
Decommissioning funding, financial assurance, and responsibility after commercial service	Lifecycle/legal: ensure funds and responsible entities remain available for defueling, decontamination, dismantling, waste disposition, surveillance, and site/ship cleanup even if the operator fails financially.	Finance: prefunding increases early-life capital cost; underfunding transfers risk to governments or future owners. Ownership models can fragment responsibility among ship, reactor, and fuel entities. Security/safeguards obligations continue until material is removed. Technology changes and uncertain waste pathways make cost estimates volatile. Funds must remain protected through bankruptcy and asset transfer.

Table XVII. (continued)

Design / Operation Feature or Choice	Primary-Domain Design Objective(s)	Potential Cross-Domain Conflicts, Indirect Impacts, and Risk Transfers
Reactor reuse, transfer between hulls, and mismatch between reactor life and ship commercial life	Economics/lifecycle: extend the useful life of expensive reactor modules and avoid discarding remaining fuel or plant life when the host hull becomes obsolete.	Safety: irradiation aging, fatigue history, and configuration changes must be carried into the new installation. Security/safeguards: module transport and custody transfer create high-consequence handling events. Regulation: relicensing in a new hull or jurisdiction may be substantial. Economics: designing for reuse aids residual value but can make modules easier to remove and can constrain future ship architecture.
Spent-fuel take-back, radioactive-waste disposition, and backend repository dependency	Fuel-cycle/lifecycle: provide a credible path for spent fuel and operational/decommissioning wastes from removal through transport, storage, treatment, and final disposition.	Geopolitics/legal: take-back agreements may fail decades later or be affected by state policy. Security/safeguards: spent-fuel transport and storage require continued protection and accountancy. Economics: uncertain backend costs affect financing. Port access: ports may accept an operating reactor but reject spent-fuel transfer. Reactor concepts without established waste pathways face additional community-readiness and licensing risk.
Wreck recovery, salvage financing, and allocation of recovery responsibility	Lifecycle / environmental protection: ensure technical capability, funding, equipment, authority, and responsible parties exist to secure and recover a damaged or sunken reactor when recovery is warranted.	Security: public salvage preparations can disclose location and recovery methods. Safety/environment: immediate recovery may be riskier than monitored in-situ stabilization. Legal: coastal state, flag state, insurer, shipowner, reactor owner, and fuel owner may disagree over authority or cost. Finance: salvage after total vessel loss can exceed ordinary wreck-removal coverage and persist long after the revenue asset is gone.
FOAK deployment pace, technology/readiness threshold, and transition to fleet-scale NOAK deployment	Investment/technology governance: obtain operational evidence soon enough to build commercial confidence while avoiding premature fleet-scale replication of unproven technology or governance arrangements.	Safety/security: early demonstrators provide essential marine data but may expose immature designs to real hazards. Finance: slow deployment increases development cost; rapid replication magnifies common defects and stranded-asset risk. Regulation/community readiness may lag technical readiness. Supply chains and crew pipelines must scale with fleet growth. Stage gates should integrate TRL, IRL, and CRL rather than optimize any one readiness dimension.

5 Summary

This report conducted a literature review of the current state of nuclear maritime technology, a preliminary screening of the associated risk spectrum, and a conceptual examination of cross-domain interfaces arising from the integration of nuclear reactor systems into commercial maritime platforms. The purpose of this work is to establish a preliminary, literature-informed understanding of the nuclear maritime risk landscape and its cross-domain interfaces as a foundation for subsequent systematic hazard identification and risk-informed analysis.

The literature review indicates that nuclear propulsion benefits from naval operating experience and demonstrated civilian maritime applications. However, the maturity of candidate reactor technologies varies considerably, and their applicability to commercial maritime operations depends on more than reactor performance alone. Advanced reactor concepts offer different combinations of operational characteristics and potential safety advantages, but introduce additional uncertainties related to technology qualification, marine environmental conditions, fuel-cycle infrastructure, and regulatory readiness. The integration of

nuclear systems into maritime platforms also requires consideration of ship motion, structural protection, collision and grounding, flooding, capsizing, loss of power, decay-heat removal, and potential long-term submersion.

The preliminary risk screening suggests that nuclear propulsion affects the consequences of conventional maritime hazards more consistently than their initiating-event likelihood. Conventional risks associated with navigation, extreme weather, cargo operations, geopolitical threats, cybersecurity, and human factors largely remain. Potential risk reductions arise from reduced dependence on frequent bunkering, lower conventional propulsion-fuel inventories, and reduced exposure to bunker-fuel supply disruptions, price volatility, and fuel-related emissions. Conversely, nuclear propulsion introduces additional safety, security, regulatory, and lifecycle considerations, including reactor shutdown and cooling, radionuclide retention, nuclear material safeguards, physical protection, specialized maintenance, port access, liability, emergency preparedness, and radioactive waste management.

A cross-domain matrix was developed to systematically idenify the cross-doain interfaces. It highlights the interconnected nature of nuclear maritime systems. These interfaces suggest that individual design and operational considerations cannot be fully understood in isolation and that a systems-level perspective is necessary to identify potential conflicts, dependencies, and unintended consequences.

Overall, the findings provide an initial conceptual characterization of the relationships between nuclear maritime technologies, conventional and nuclear-specific risks, and the cross-domain interfaces governing their integration. The assessment remains qualitative and exploratory. The resulting framework provides a basis for future scenario-based hazard identification, detailed evaluation of cross-domain dependencies, coupled ship-reactor safety assessments, and systematic risk-informed trade studies for selected reactor technologies and vessel configurations.

References

[1] Seon-Gon Kim, Jophous Mugabi, and Jae-Ho Jeong. "Feasibility and Readiness of Next-Generation Small Modular Reactors for Marine Decarbonization: A Technical, Economic, and Societal Review". In: *Progress in Nuclear Energy* 198 (2026), p. 106459. DOI: 10.1016/j.pnucene.2026.106459. URL: https://doi.org/10.1016/j.pnucene.2026.106459.

[2] Phan Anh Duong et al. "Nuclear propulsion for merchant ships: a path to sustainable maritime energy". In: *International Journal of Sustainable Energy* 44.1 (2025), p. 2579469. DOI: 10.1080/14786451.2025.2579469. URL: https://doi.org/10.1080/14786451.2025.2579469.

[3] Nima Fathi and Milton Korn. "Merchant Nuclear-Powered Vessels: A New Frontier in Maritime Propulsion". In: *Nuclear Fission Energy – Deployment, Applications, and Beyond*. Ed. by Pavel Tsvetkov and Piyush Sabharwall. IntechOpen, 2026. DOI: 10.5772/intechopen.1009829. URL: https://doi.org/10.5772/intechopen.1009829.

[4] Ioannis Chalaris et al. *Navigating the Future: A Review of Nuclear Power in Decarbonizing Commercial Shipping*. Tech. rep. Research Note No. 5. Athens, Greece: Institute of Energy for South-East Europe (IENE), 2025. URL: https://www.iene.eu/publications/research-notes/iene-research-note-no-5-navigating-the-future-a-review-of-nuclear-power-in-decarbonizing-commercial-shipping-p8168.html.

[5] Lukas Wulff. "Feasibility of the Implementation of Nuclear Reactors as Main Energy Source in Passenger Vessels". MA thesis. Espoo, Finland: Aalto University, 2023. URL: https://aaltodoc.aalto.fi/bitstream/123456789/123226/1/master_Wulff_Lukas_2023.pdf.

[6] Erna L. Grelle and Christopher P. Kolodziej. "Generic Nuclear NOAK Configurable Design Assessment for U.S. Floating Applications". In: *Offshore Technology Conference*. OTC-37069-MS. Offshore Technology Conference. Houston, Texas, May 2026. DOI: 10.4043/37069-MS. URL: https://doi.org/10.4043/37069-MS.

[7] John Olbrys. "Nuclear powered maritime industry: The economic and infrastructural preconditions to acceptance". MA thesis. Erasmus University Rotterdam, 2024. URL: https://thesis.eur.nl/pub/70588.

[8] Prachi Patel. "Merchant Shipping's Nuclear Option: Nuclear-powered cargo ships failed decades ago, but small modular reactors could make all the difference". In: *IEEE Spectrum* 61.2 (2024), pp. 36–41. DOI: 10.1109/MSPEC.2024.10418947. URL: https://doi.org/10.1109/MSPEC.2024.10418947.

[9] E. Dedes et al. "Possible power train concepts for nuclear powered merchant ships". In: *International Conference on Technologies, Operations, Logistics and Modelling for Low Carbon Shipping (LCS 2011)*. Glasgow, UK, June 2011, pp. 261–274. URL: https://eprints.soton.ac.uk/198501/.

[10] Seongchul Park et al. "Fundamental Understanding of Marine Applications of Molten Salt Reactors: Progress, Case Studies, and Safety". In: *Journal of Marine Science and Engineering* 12.10 (2024), p. 1835. DOI: 10.3390/jmse12101835. URL: https://doi.org/10.3390/jmse12101835.

[11] Sanjay Mukhi, Abdalla Abou-Jaoude, and Levi M. Larsen. *Configurations of Commercial Advanced Nuclear-Maritime Applications*. Tech. rep. INL/RPT-23-74632. Idaho National Laboratory, July 2025. URL: https://nric.inl.gov/content/uploads/34/2025/09/RPT-23-74632-Rev-0-Configurations-of-Commercial-Advanced-Nuclear-Maritime-Applications.pdf.

[12] J. E. Stephens. "Manufacturing of Nuclear Reactors for Civil Maritime Applications". In: *Offshore Technology Conference*. D041S046R003. Offshore Technology Conference. Apr. 2025. URL: https://2025.otcnet.org/technical-program/nuclear-in-offshore.

[13] J. A. Whitley, R. A. Calkins, and D. E. Carpenter-Graffy. *Small Nuclear Reactors for Maritime Ports (No.* Tech. rep. PNNL-39328. Richland, WA: Pacific Northwest National Laboratory, 2026. URL: https://www.pnnl.gov/publications/small-nuclear-reactors-maritime-ports.

[14] Marc Fialkoff et al. “Surveying civilian nuclear-powered vessels deployment from an economic, technological, and nonproliferation perspective”. In: *Proceedings of the INMM 63rd Annual Meeting*. Institute of Nuclear Materials Management. July 2022. URL: https://resources.inmm.org/annual-meeting-proceedings/surveying-civilian-nuclear-powered-vessels-deployment-economic.

[15] M. Bayraktar and M. Pamik. “Nuclear power utilization as a future alternative energy on icebreakers”. In: *Nuclear Engineering and Technology* 55.2 (2023), pp. 580–586. DOI: 10.1016/j.net.2022.10.033. URL: https://doi.org/10.1016/j.net.2022.10.033.

[16] Luciano Ondir Freire and Delvonei Alves de Andrade. “Historic survey on nuclear merchant ships”. In: *Nuclear Engineering and Design* 293 (2015), pp. 176–186. DOI: 10.1016/j.nucengdes.2015.07.031. URL: https://doi.org/10.1016/j.nucengdes.2015.07.031.

[17] Koen C. F. Houtkoop. “Nuclear reactors for marine propulsion and power generation systems”. MA thesis. Rotterdam, Netherlands: C-Job Naval Architects, 2022. URL: https://safety4sea.com/wp-content/uploads/2022/08/C-Job-Nuclear-reactors-for-marine-propulsion-and-power-generation-systems-2022_08.pdf.

[18] Anthony R. Valiaveedu, Nat Edmonds, and Drew Honson. “Navigating the regulatory seas for commercial maritime nuclear propulsion”. In: *MIT Science Policy Review* 6 (2025), pp. 91–99. DOI: 10.38105/spr.i6t8fxvvwo. URL: https://doi.org/10.38105/spr.i6t8fxvvwo.

[19] J. E. Segovia et al. “A Detailed Overview for Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies”. In: *Offshore Technology Conference*. D041S046R007. Offshore Technology Conference. May 2026. URL: https://2026.otcnet.org/2026-technical-program/smart-project-execution-digital-tools-and-breakthroughs-under-extreme-conditions.

[20] Liye Zhang et al. “Ship accident consequences and contributing factors analyses using ship accident investigation reports”. In: *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability* 233.1 (2019), pp. 35–47. DOI: 10.1177/1748006X18768917. URL: https://doi.org/10.1177/1748006X18768917.

[21] C. Wan et al. “Analysis of risk factors influencing the safety of maritime container supply chains”. In: *International Journal of Shipping and Transport Logistics* 11.6 (2019), pp. 476–507. DOI: 10.1504/IJSTL.2019.103872. URL: https://doi.org/10.1504/IJSTL.2019.103872.

[22] Shuiyang Chen et al. “Dynamic effects of maritime risk on macroeconomic and global maritime economic activity”. In: *Transport Policy* 167 (2025), pp. 246–263. DOI: 10.1016/j.tranpol.2025.03.035. URL: https://doi.org/10.1016/j.tranpol.2025.03.035.

[23] Aggelos N. Pilatis et al. “A statistical analysis of ship accidents (1990–2020) focusing on collision, grounding, hull failure, and resulting hull damage”. In: *Journal of Marine Science and Engineering* 12.1 (2024), p. 122. DOI: 10.3390/jmse12010122. URL: https://doi.org/10.3390/jmse12010122.

[24] Chia-Hsun Chang, Jingjing Xu, and Dong-Ping Song. “Risk analysis for container shipping: from a logistics perspective”. In: *The International Journal of Logistics Management* 26.1 (2015), pp. 147–171. DOI: 10.1108/IJLM-07-2012-0068. URL: https://doi.org/10.1108/IJLM-07-2012-0068.

[25] E. Eliopoulou, A. Papanikolaou, and M. Voulgarellis. “Statistical analysis of ship accidents and review of safety level”. In: *Safety Science* 85 (2016), pp. 282–292. DOI: 10.1016/j.ssci.2016.02.001. URL: https://doi.org/10.1016/j.ssci.2016.02.001.

[26] Sergiy Kivalov. “Current Threats to Sustainable Shipping-from War Risks to Climate Changes”. In: *Lex Portus* 10.2 (2024), pp. 15–24. DOI: 10.62821/lp10202. URL: https://doi.org/10.62821/lp10202.

[27] Sergiy Kotenko et al. “Determination of the expected value of losses caused by the cargo transportation insurance risks by water transport”. In: *Inventions* 7.3 (2022), p. 81. DOI: 10.3390/inventions7030081. URL: https://doi.org/10.3390/inventions7030081.

[28] Oleksiy Melnyk et al. “Review of ship information security risks and safety of maritime transportation issues”. In: *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation* 16.4 (2022), pp. 717–722. DOI: 10.12716/1001.16.04.13. URL: https://doi.org/10.12716/1001.16.04.13.

[29] Oleksiy Melnyk, Svitlana Onyshchenko, and Kostyantin Koryakin. “Nature and origin of major security concerns and potential threats to the shipping industry”. In: *Scientific Journal of Silesian University of Technology. Series Transport* 113 (2021), pp. 145–153. DOI: 10.20858/sjsutst.2021.113.11. URL: https://doi.org/10.20858/sjsutst.2021.113.11.

[30] Frederik Holm and Vitalijs Kalinovs. “Risk and Risk Management in the Shipping Industry: An Exploratory Study of the Danish Shipping Industry and the Perception of Risk”. MA thesis. Copenhagen Business School, 2017. URL: https://research.cbs.dk/en/studentProjects/35d25382-451e-4c4b-9a6d-fc317255d2e4/.

[31] Hannah Mosmans et al. “Climate risks in shipping”. In: *Journal of Shipping and Trade* 11.1 (2026), p. 17. DOI: 10.1186/s41072-026-00233-7. URL: https://doi.org/10.1186/s41072-026-00233-7.

[32] Oleksii Drozhzhyn. “International liner shipping: current challenges and threats”. In: *Scientific Journal of Silesian University of Technology. Series Transport* 125 (2024), pp. 51–68. DOI: 10.20858/sjsutst.2024.125.4. URL: https://doi.org/10.20858/sjsutst.2024.125.4.

[33] Demetrios N. Tsailas. “Risks And Threats In The 21st Century Maritime Security”. In: *Security Science Journal* 6.1 (2025), pp. 106–144. DOI: 10.37458/ssj.6.1.7. URL: https://doi.org/10.37458/ssj.6.1.7.

[34] Claudia-Iohana Voicu. “Maritime Supply Chain Disruptions: An Ai-Conceptual Framework for Geopolitical Risk Forecasting”. In: *International Conference Knowledge-Based Organization* 31.2 (2025), pp. 110–116. DOI: 10.2478/kbo-2025-0056. URL: https://doi.org/10.2478/kbo-2025-0056.

[35] Yui-yip Lau et al. “Maritime transport resilience: A systematic literature review on the current state of the art, research agenda and future research directions”. In: *Ocean & Coastal Management* 251 (2024), p. 107086. DOI: 10.1016/j.ocecoaman.2024.107086. URL: https://doi.org/10.1016/j.ocecoaman.2024.107086.

[36] Bingmei Gu and Jiaguo Liu. “A systematic review of resilience in the maritime transport”. In: *International Journal of Logistics Research and Applications* 28.3 (2025), pp. 257–278. DOI: 10.1080/13675567.2023.2165051. URL: https://doi.org/10.1080/13675567.2023.2165051.

[37] Keyu Xu, Jiaguo Liu, and Zhenfu Li. “Vulnerability assessments of global liner shipping network based on extended coupled map lattices”. In: *Reliability Engineering & System Safety* 264 (2025), p. 111306. DOI: 10.1016/j.ress.2025.111306. URL: https://doi.org/10.1016/j.ress.2025.111306.

[38] A. N. Vinogradov and V. A. Tsukerman. “Specific Character of Natural Hazards on High-latitude Sea Transport Passages Europe-Asia-Pacific Region: Challenges for Technosphere Safety”. In: *IOP Conference Series: Earth and Environmental Science*. Vol. 272. 2. IOP Publishing, June 2019, p. 022143. DOI: 10.1088/1755-1315/272/2/022143. URL: https://doi.org/10.1088/1755-1315/272/2/022143.

[39] Necmettin Akten. “Shipping accidents: a serious threat for marineenvironment”. In: *Journal of Black Sea / Mediterranean Environment* 12.3 (2006), pp. 269–304. URL: https://dergipark.org.tr/en/pub/jbme/article/121936.

[40] Yan Liu et al. “Bibliometric analysis and literature review on maritime transport resilience and its associated impacts on trade”. In: *Maritime Policy & Management* 52.3 (2025), pp. 440–477. DOI: 10.1080/03088839.2024.2367971. URL: https://doi.org/10.1080/03088839.2024.2367971.

[41] Muhammad Mazharul Islam. *Effect on Safety of Navigation Due to Commercial Pressure in Merchant Ships*. Bachelor's thesis, Novia University of Applied Sciences. 2025. URL: https://www.theseus.fi/bitstream/handle/10024/901817/Islam_Muhammad.pdf?isAllowed=y&sequence=2.

[42] W. J. Carmack et al. "Technology readiness levels for advanced nuclear fuels and materials development". In: *Nuclear Engineering and Design* 313 (2017), pp. 177–184. DOI: 10.1016/j.nucengdes.2016.11.024. URL: https://doi.org/10.1016/j.nucengdes.2016.11.024.

[43] Australian Renewable Energy Agency. *Commercial readiness index for renewable energy sectors*. Tech. rep. Australian Renewable Energy Agency (ARENA), 2014. URL: https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf.

A Multidimensional Readiness Level Frameworks

A.1 Technology Readiness Level (TRL 1–9)

Originally developed by NASA and widely adopted across defense, aerospace, and energy sectors, the TRL framework provides a standardized metric for assessing technical maturity from basic physical principles (TRL 1) to proven commercial operation in a real environment (TRL 9) [42]. Table XVIII. maps each level to a maritime nuclear benchmark.

Table XVIII. Technology Readiness Levels for Maritime Nuclear Applications.

TRL Level	Standard NASA / DOE Definition	Maritime Nuclear Benchmark / Criteria
TRL 1	Basic principles observed and reported	Fundamental nuclear fission physics and marine thermal fluid equations.
TRL 2	Technology concept formulated	Conceptual design of SMR marine application and thermodynamic power cycles.
TRL 3	Analytical/experimental critical proof of concept	Laboratory-scale testing of liquid salts, TRISO fuel particles, or coolant chemistry.
TRL 4	Component validation in laboratory environment	Bench-scale testing of heat exchangers, shielding materials, or digital twin algorithms.
TRL 5	System/component validation in relevant environment	Testing SMR sub-components under simulated sea motions (6-DOF pitch, roll, vibration).
TRL 6	System model/prototype in relevant environment	Full-scale prototype testing on terrestrial testbeds or stationary floating barges.
TRL 7	System prototype demonstration in operational environment	Full-scale pilot reactor deployed on operational marine vessels or icebreakers.
TRL 8	Actual system completed and qualified	SMR vessel design fully certified by classification societies and marine authorities.
TRL 9	Actual system proven in commercial operation	Sustained commercial operation of nuclear vessels in global shipping or grid supply.

A.2 Investment Readiness Level (IRL 1–6)

Adapted from clean-energy investment metrics (such as ARENA and LRQA), the IRL scale measures financial maturity, market confidence, capital availability, and business-model feasibility [43]. It evaluates whether private equity, institutional lenders, or state funds are prepared to finance development, construction, and fleet deployment. Table XIX. provides the maritime commercial interpretation for each level.

Table XIX. Investment Readiness Levels for Maritime Nuclear Applications.

IRL Level	Standard Financial Definition	Maritime Commercial Interpretation
IRL 1	Concept stage / No clear business case	Early research phase; unquantified capital costs and high financial risk.
IRL 2	Preliminary feasibility / Emerging market interest	Initial techno-economic modeling; high CapEx uncertainty and unclear ROI.
IRL 3	Emerging business case / Early pilot investment	Vendor business models established; pilot projects receive initial venture funding.
IRL 4	Growing market confidence / Early adoption	Commercial order books open; preliminary charter agreements and de-risked CapEx.
IRL 5	Mature investment case / Strong financial backing	Large-scale utility/shipowner backing; standardized modular serial manufacturing.

Table XIX. (continued)

IRL Level	Standard Financial Definition	Maritime Commercial Interpretation
IRL 6	Fully established / Widespread adoption	Standard commercial debt financing; competitive levelized cost of fuel (LCOF).

A.3 Community Readiness Level (CRL 1–6)

The CRL framework measures sociopolitical alignment, public acceptance, legal and regulatory clarity, stakeholder trust, and host-port community approval required for commercial nuclear vessel operations [10]. Table XX. defines the corresponding maritime regulatory and public benchmarks.

Table XX. Community Readiness Levels for Maritime Nuclear Applications.

CRL Level	Standard Sociopolitical Definition	Maritime Regulatory & Public Benchmark
CRL 1	Limited awareness / Ambiguity	Minimal knowledge; public anxiety regarding radiation and nuclear proliferation.
CRL 2	Early discussions / Informal dialogue	Initial industry/regulatory conversations; no formal legal or port entry frameworks.
CRL 3	Initial engagement / Preliminary sandboxes	Stakeholders explore adoption; draft bilateral port access agreements drafted.
CRL 4	Active support / Policy guidelines	National regulators and class societies actively establish formal safety standards.
CRL 5	Broad acceptance / Widespread approval	General public and international port state authorities approve nuclear ship port calls.
CRL 6	Full integration / Standardized baseline	Modernized IMO/SOLAS legal codes in force; seamless international port access.