NUCLEAR ENERGY IN MARITIME

From **Core Physics** to **Propulsion**

ISSUE 3

Engineering Considerations for Maritime Nuclear Energy

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ON THE HORIZON

Advanced reactors and small modular reactors (SMRs) are moving from early concepts toward detailed design and testing. At the same time, interest in maritime nuclear energy is shifting from broad feasibility discussion toward practical questions that are unique to the industry: how nuclear systems integrate with ship design, how ports and coastal states manage operational interfaces, and how safety and security are demonstrated in an offshore environment. Floating nuclear power plants, offshore energy hubs and nuclear-powered commercial vessels each introduce different design requirements and regulatory pathways that shape engineering decisions from the outset.

This edition, the third in the series, focuses on engineering fundamentals that will help determine whether nuclear concepts can be applied safely and credibly at sea. Rather than reexplaining nuclear technology, it highlights what changes when nuclear systems are used on the water: motion and stability effects, space and weight constraints, crew and maintenance realities, port and coastal state interfaces, and the need to align maritime and nuclear regulatory regimes. These are the considerations designers, regulators, operators and classification societies will need to address as concepts move beyond paper studies and toward demonstration.

MARITIME NUCLEAR APPLICATIONS AND **OPERATING MODELS**

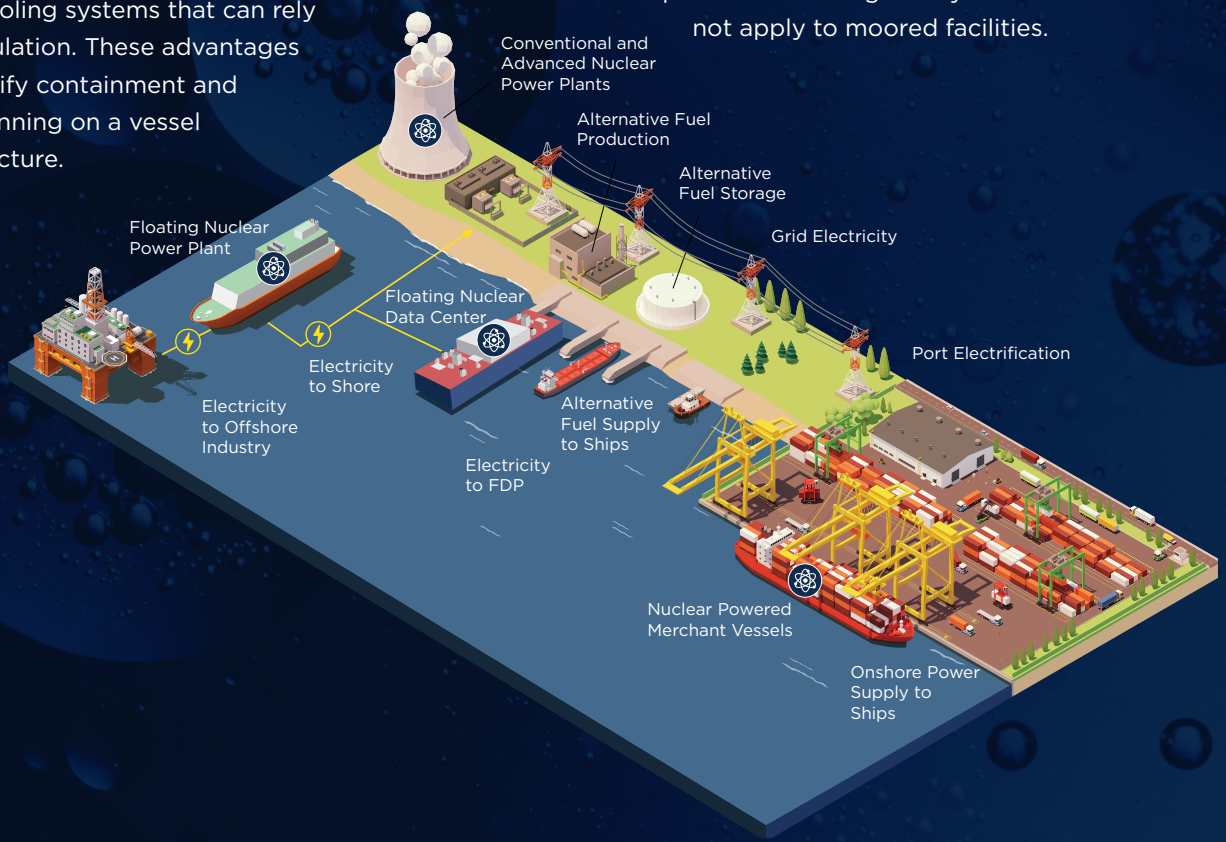
The term advanced reactor encompasses both evolutionary light-water designs and nontraditional concepts that use gas, liquid metal or molten salt coolants**.** Small modular reactors are defined primarily by size, generally 300 megawatts electric (MWe) or less, and modular construction rather than by reactor physics. Typical conventional land-based reactors generate around 1,000 MWe, enough to supply hundreds of thousands of homes.

Many SMR concepts are compact pressurized water reactors (PWRs), which draw on the most established reactor technology in commercial nuclear power. Other concepts include high temperature gas cooled reactors, fast spectrum liquid metal reactors and molten salt reactors.

For maritime applications, compactness, passive safety features and extended refueling intervals are key considerations. Small modular reactors can offer advantages over large reactors through smaller radioactive inventories, more integrated reactor designs and cooling systems that can rely on natural circulation. These advantages may help simplify containment and emergency planning on a vessel or floating structure.

Nuclear applications for ships, ports, remote power hubs, data centers, fuel production, desalination and propulsion each create different design and operational demands that extend beyond reactor selection. Mission profile influences not only power conversion and integration with marine infrastructure, but also hull layout and stability margins, available shielding mass and volume, staffing models, maintenance access and the operational interfaces that ports and coastal states may require for emergency response, security and oversight.

In the near term, many SMR concepts are better suited to floating or moored installations that operate at a fixed location for extended periods, such as floating nuclear power plants (FNPPs) that supply shore power or industrial energy services. These assets simplify certain challenges while still requiring robust design, port interfaces and security planning. Fixed or semi-fixed installations may provide a more practical path to early deployment, as mobility introduces additional operational and regulatory demands that do not apply to moored facilities.



REACTOR DESIGN UNDER MARITIME CONSTRAINTS

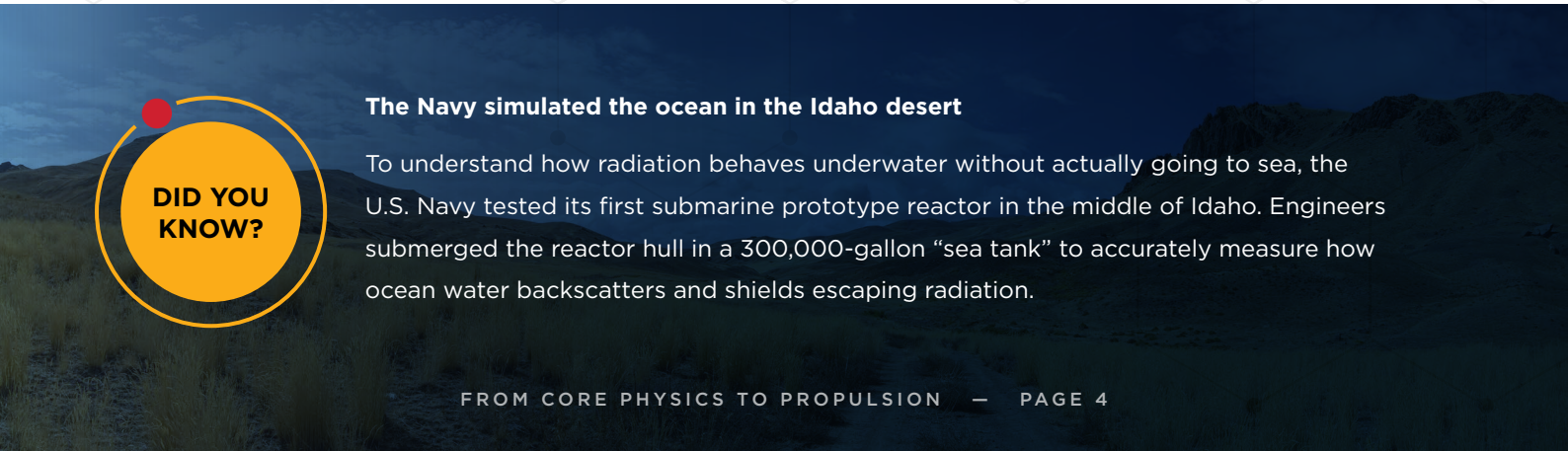
All reactor designs need to address the same fundamental challenges of fuel arrangement, heat removal and reactivity control to produce useful power in a stable and controlled way.

For use on vessels and floating installations, tradeoffs are shaped by constraints that are less dominant on land. These can include limited containment and shielding space, stability impacts from concentrated mass, and operating conditions. Light-water SMRs benefit from extensive operating experience and established safety cases, but their pressure boundaries and auxiliary systems must be adapted to marine and offshore reliability and maintainability expectations. Higher-temperature concepts may offer integration advantages for certain energy services, but those benefits must be evaluated against challenges such as thermal management, material compatibility in harsh environments and operational support models that may differ from land-based assumptions.

Experience to-date suggests that **successful maritime nuclear concepts** benefit from integrating reactor physics and **safety considerations** early in vessel or platform design.

Reactor systems are not modular components that can simply be added late in the design process. Physical, thermal, and safety requirements influence hull layout, shielding, power conversion, and operational procedures.

Ship motion introduces additional complexity. In concepts with liquid surfaces that can move, such as pools, tanks or molten salt systems, vessel motion can shift coolant within the system. That may affect heat removal and local power distribution. The key question is how the design demonstrates acceptable performance across defined operating envelopes and credible sea states because those envelopes become part of the operational case and the approval pathway.



DID YOU KNOW?

The Navy simulated the ocean in the Idaho desert

To understand how radiation behaves underwater without actually going to sea, the U.S. Navy tested its first submarine prototype reactor in the middle of Idaho. Engineers submerged the reactor hull in a 300,000-gallon “sea tank” to accurately measure how ocean water backscatters and shields escaping radiation.

FUEL CHOICES AND **MARITIME OPERATIONAL IMPLICATIONS**

Fuel choice strongly influences operating models because it shapes refueling frequency and logistics, nuclear safeguards requirements and the scope of shore-side support. Longer core life can reduce port-dependent maintenance events, but it can also shift design considerations toward higher enrichment, different fuel forms and associated supply-chain and oversight requirements.

That raises practical questions about where refueling and fuel handling could occur, what port infrastructure and procedures are required for transfer and storage, how spent fuel and operational waste are managed across jurisdictions, and how these choices affect staffing, emergency planning, and public acceptance. Because these factors sit at the boundary between nuclear fuel cycles and operations, fuel decisions are not purely technical. They also shape the operating model and the regulatory and commercial pathway.

Fuel choice strongly influences maritime operations. It affects vessel endurance, refueling strategy, waste profile, safeguards regime and overall economic performance.

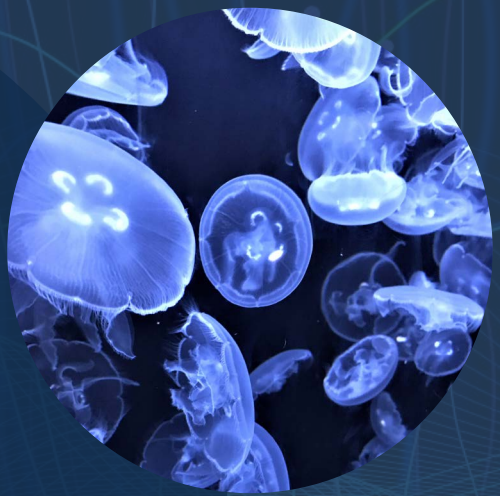
POWER CONVERSION AND HEAT MANAGEMENT IN MARINE ENVIRONMENTS

Reactors produce heat, but ships and offshore assets require that energy in electrical, mechanical and thermal forms, often under operating profiles that differ significantly from those of land-based grids. Power conversion and distribution in those applications must account for space constraints, redundancy expectations, maintenance access, and the integration of propulsion and other major loads with the overall electrical architecture. Most near-term SMR concepts employ steam Rankine cycles with multiple loops to provide radiological separation. In these applications, loop and balance-of-plant decisions are closely tied to equipment layout, system resilience, and the ability to maintain safe states under constrained staffing and variable operating conditions.

DID YOU KNOW?

A swarm of jellyfish can shut down a nuclear reactor

Because some marine reactors and coastal power plants rely on seawater for cooling, massive blooms of jellyfish can occasionally get sucked in and clog the cooling water intake screens. To prevent systems from overheating, operators are forced to safely shut down the reactor until the blockage is cleared.



Largue, P. (August 2025) Jellyfish shut down French nuclear power plant. Power Engineering. https://www.power-eng.com/nuclear/jellyfish-shut-down-french-nuclear-power-plant/

Thermal-hydraulics and power conversion systems **serve as the critical engine and safety boundary** of a nuclear reactor, bridging the gap between raw fission energy and viable maritime applications.

Thermal-hydraulics, or how coolant behaves as it removes heat from the core, is particularly sensitive to marine conditions because passive safety assumptions developed for static plants must be demonstrated under motion, heel and changing operating states. Ship motion can alter flow paths and fluid layering in pools and tanks and may affect the performance of natural-circulation heat removal during normal transient and abnormal conditions. For these applications, demonstrating decay heat removal across realistic motion and operating envelopes is not a secondary detail, it is central to design confidence and to the credibility of the operational and approval case.

These are the reasons that all critical components of traditional nuclear power plant need to be thoroughly tested in marine environment.

RADIATION PROTECTION, STABILITY AND CREW SAFETY AT SEA

Radiation shielding has historically been a key hurdle for nuclear vessels because of the space and weight required, with direct implications for stability, trim and compartment arrangement. Early civilian nuclear ships used extensive all-around shielding to support broader access. Modern concepts, by contrast, increasingly evaluate directional and integrated shielding to manage dose while limiting concentrated mass.

For ships, shielding is both a radiological design challenge and a naval architecture tradeoff that shapes hull layout, protected zones, and the practicality of crew access and maintenance.

Instrumentation and control systems form the other critical component of reactor safety and operational resilience. At sea, these systems must tolerate vibration and electrical transients while meeting nuclear-grade reliability expectations under constrained staffing models. They must also interface coherently with shipboard operational practices, including procedures, training and reporting structures that are typically managed through a vessel's Safety Management System. As a result, nuclear concepts will need to demonstrate technical reliability and how they will integrate with shipboard operations. Key questions include how alarms, protective actions and abnormal event management function in real operating conditions.

WASTE HANDLING, PORT INTERFACES AND **LIFE-CYCLE RESPONSIBILITY**

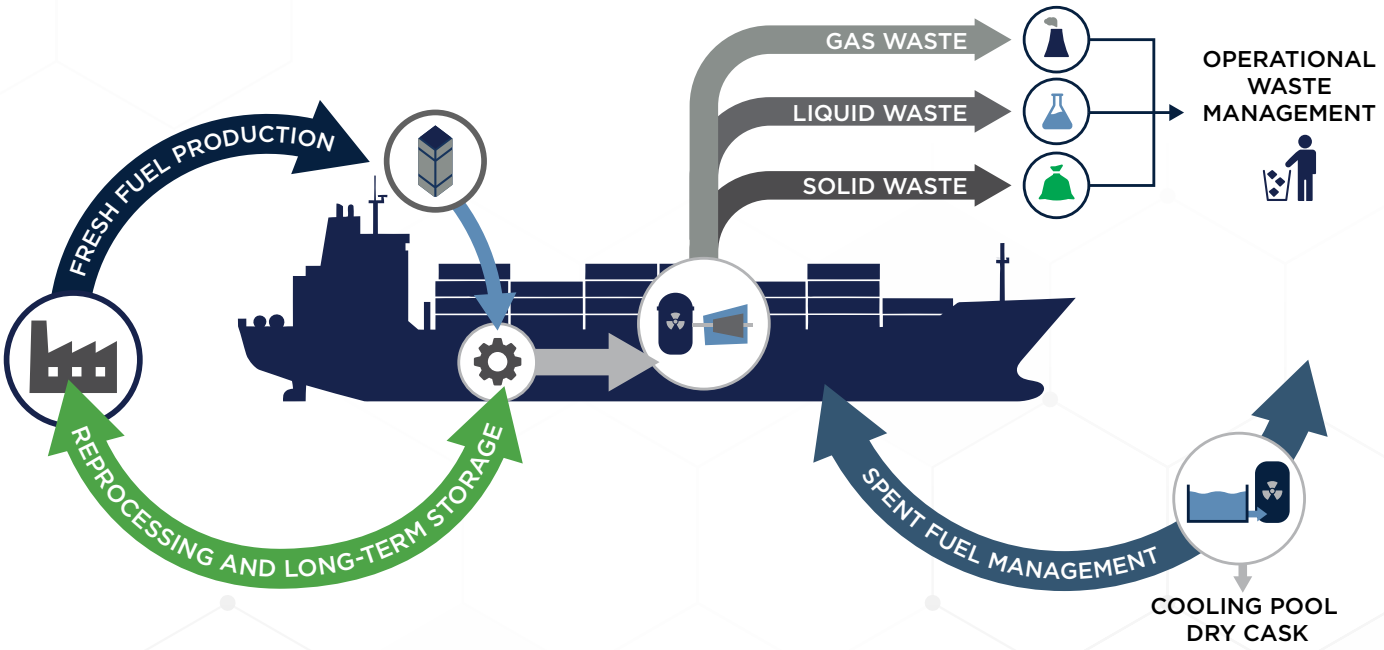


Figure 2: Possible considerations for nuclear waste and lifecycle management at sea

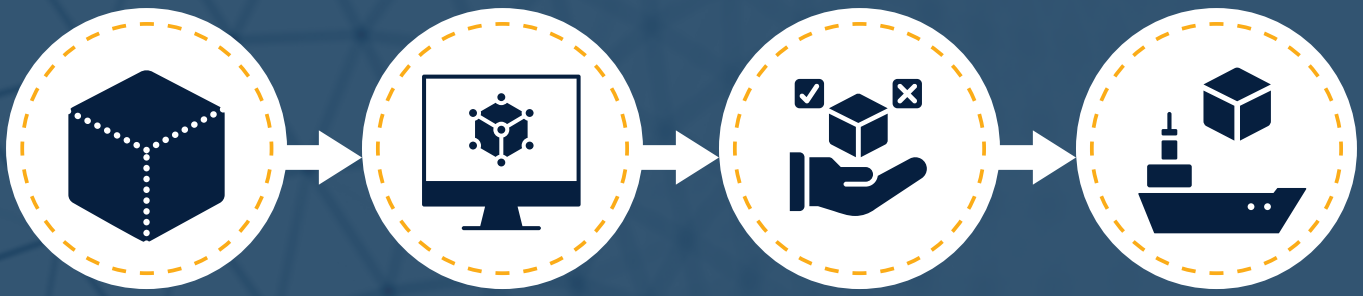
A conventional reactor deployed at sea deployed at sea produces the same broad waste categories as a land-based plant, including gaseous, liquid and solid operational wastes, as well as spent fuel and activated structures at end of life. What changes is how waste is handled, where it can be stored and who is responsible at each step.

Operational waste may need to be retained on board until transfer to shore is possible, which elevates the importance of shipboard storage arrangements, transfer procedures and port readiness. Waste management then becomes a systems issue that includes not only technical treatment methods but also port facility requirements, documentation and handling processes, and the alignment of nuclear controls with maritime oversight.

Life-cycle assessments must cover fuel fabrication, transport, operation, interim storage, take-back or disposal, and decommissioning, with clear responsibility across jurisdictions and stakeholders.

This also means making sure ports can safely handle these materials at every stage by building dedicated berths and storage areas, having strong radiation protection and emergency response plans, training staff in specialized handling and security, upgrading monitoring and containment systems, and working closely with local authorities and communities to manage risk and maintain transparency and trust.

TESTING, DEMONSTRATION AND **MARITIME READINESS**



CONCEPTUAL DESIGN

VIRTUAL TESTING AND SIMULATION

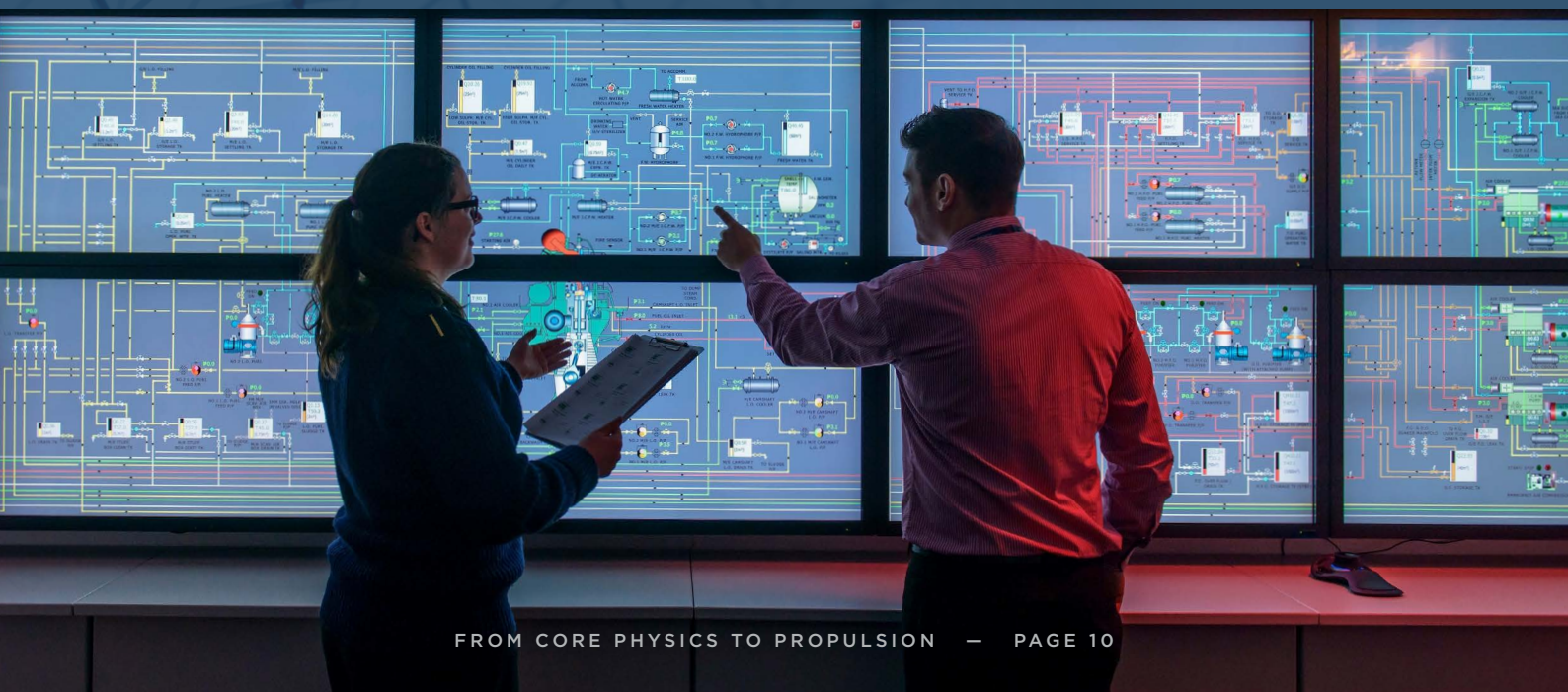
PHYSICAL TESTING AND BENCHMARKING

SHIP INTEGRATION

Before nuclear technologies are deployed at sea, validation must extend beyond reactor performance to the evidence needed for integration and approval. Modeling and simulation can support analysis of compact cores and passive safety features, but readiness for marine and offshore applications will also depend on physical testing, including component and integral testing, ship-motion simulation and representative balance-of-plant evaluation.

Demonstration programs will likely follow a staged approach, beginning with lower-complexity installations, such as fixed or moored assets, before progressing to more demanding mobile applications.

Each stage can help build confidence not only in the technology, but also in port readiness, insurance treatment and the alignment of regulatory pathways.



WHAT MARITIME STAKEHOLDERS **MUST DECIDE**

Nuclear energy presents both opportunities and challenges at sea. Its potential viability will depend on disciplined engineering, credible testing and alignment between nuclear safety principles and operational realities. For marine and offshore stakeholders, the near-term decisions are less about selecting a reactor concept and more about defining practical operating models. What types of assets are feasible first? What port interfaces and emergency capabilities are required? How will responsibilities be allocated across the life cycle? How can approval pathways be coordinated across regimes?

A measured, evidence-based approach grounded in safety performance, life-cycle responsibility and operational practicality will help determine whether nuclear energy becomes a credible tool in the evolving maritime energy landscape.

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FOOD FOR THOUGHT

- How should engineering maturity be measured in parallel with regulatory readiness to progress maritime nuclear beyond feasibility studies?
- What level of testing and demonstration would be sufficient to build confidence among port authorities, insurers, and coastal states?
- How early should classification societies, nuclear regulators, and maritime stakeholders align to avoid fragmented approval pathways?

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