Introductory Review of the Maritime Nuclear Regulatory Landscape

January 2024

Sanjay Haresh Mukhi
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Introductory Review of the Maritime Nuclear Regulatory Landscape

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Introductory Review of the Maritime Nuclear Regulatory Landscape

EXAMINATION OF THE MARITIME NUCLEAR REGULATORY GAPS
September 2023
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Executive Summary

The successful deployment of nuclear technology for maritime applications has the potential to assist in the pursuit of net-zero carbon emissions. In addition, the maritime sector presents unique opportunities. For example, by leveraging the maritime sector’s experience with modular shipyard manufacturing, the nuclear industry can achieve significant cost and schedule reductions, increased productivity, and improved quality control. However, the new technologies being developed need to overcome many of the major hurdles that have historically hindered the progress of the nuclear sector.

The successful implementation of nuclear technology for maritime applications will depend on tailoring a comprehensive and robust regulatory framework. This framework must effectively address safety, environmental and security considerations, while simultaneously fostering innovation, paving the way for the successful deployment of nuclear technologies supporting the maritime industry, and ensuring they can play their significant role in reaching decarbonization targets. The evaluation of licensing, siting, construction, and operational factors will be crucial for the successful deployment and operation of marine based nuclear facilities. While there are existing regulations and guidelines for both commercial nuclear power plants and for the maritime sector, advanced nuclear reactors and specifically advanced nuclear reactors deployed in maritime applications will require unique approaches to various challenges. These include siting, compliance with transportation requirements, and decommissioning, all of which will require coordination between nuclear and maritime regulators.

A concise summary of the key gaps resulting from the introductory review of the regulatory and licensing landscape for floating nuclear power plants (FNPPs) conducted by the Maritime Nuclear Applications Group (MNAG) are listed below. The findings of the MNAG review emphasize the necessity for evolving regulations that are robust and adaptable to the unique challenges posed by maritime nuclear applications.

- Lack of clarity on how to complete consistent licensing at an international scale and in a cost-effective manner
- Lack of an internationally recognized classification authority and procedure for nuclear-powered ships
- Lack of integration of maritime security with nuclear security
- International Nuclear Transportation Framework is not integrated with Nuclear Maritime Applications
- Emergency planning zone (EPZ) size requirements do not always scale based on specific design characteristics and site-specific considerations
- Lack of an End-of-Life Framework for FNPP
- Restrictions on Port Access for FNPP
- High licensing cost and duration
- Uncertainty around jurisdiction and difficulty in harmonizing potentially overlapping and contradictory regulatory requirements

A number of reactor designs that could be suitable for marine environments are being developed in the USA, and therefore it is possible that first-of-a-kind (FOAK) licensing cases may be submitted to U.S. regulatory agencies. However, international collaboration between key stakeholders such as country regulators will be crucial to harmonize standards. This partnership has already begun to gain momentum and is vital for promoting knowledge sharing and driving regulatory change. By bringing essential stakeholders together to lay the foundation for an effective and supportive regulatory environment, the full potential of marine nuclear technology can be realized. By implementing the recommendations of this report and showcasing strong leadership, the challenges associated with marine nuclear technology can be effectively addressed, leading to its successful deployment and operation while ensuring safety and sustainability.
1. Introduction

1.1. The Maritime Nuclear Application Group

The Maritime Nuclear Application Group (MNAG) is a working group convened by the National Reactor Innovation Center (NRIC) at Idaho National Laboratory (INL), the American Bureau of Shipping (ABS), and Morgan, Lewis, and Bockius LLP. MNAG is a research hub and resource center that brings together experts from the maritime and nuclear energy sectors to facilitate the demonstration of advanced nuclear technologies for a range of marine applications. MNAG fulfills this mission through strategic studies of potential maritime applications, by identifying domestic and international legal and regulatory hurdles, cataloging and sharing of relevant information resources, and collaborating and coordinating with global stakeholders of all types. MNAG aims to support near-term field demonstrations of advanced reactor technologies in marine settings by partnering with the U.S. Department of Energy’s NRIC.

MNAG’s membership includes representatives of organizations and firms from:

- Nuclear industry: structure and system designers, vendors, national laboratories, policy non-profits, academia
- Maritime: vessel owner/operator, classification, maritime law, insurance, flag states
- U.S. Government: independent regulatory organizations and executive branch department
- Environmental: industry groups

1.2. Scope of this Report

This report offers an introductory review of the regulatory landscape pertaining to advanced nuclear developments within the maritime industries, both historical and current, identifying the key parties that will be involved in future regulation. Current applicable rules have been described, and the regulatory requirements for both nuclear and maritime industries have been examined. In this way, the report aims to begin establishing a regulatory connection (parity) between the two sectors by identifying high-level regulatory gaps that must be bridged in any future regulatory framework. This includes establishing uniform definitions for the technology and application cases, which are essential for categorization and standardization.

As with any new technology, regulators need to ensure that appropriate regulations are in place to address safety, security, and environmental concerns. The successful deployment of marine nuclear technology for maritime applications requires a fit-for-purpose regulatory framework that can be responsive, as technologies emerge, to different types of reactors and marine deployment technologies including shoreside stationary systems, offshore stationary, floating offshore installations, or mobile power systems and commercial nuclear propulsion.

Nuclear Regulators are already interpreting and revising regulatory requirements for next generation nuclear projects. However, one of the challenges in doing this is developing requirements and licensing structures that ensure safety and security measures remain highly reliable without unreasonably hindering advanced nuclear deployments. The current efforts are, for the most part focusing on land-based facilities and have not yet begun in earnest for marine
based nuclear technologies and projects. International collaboration and funding will play a role in realizing the potential of nuclear technologies used in a marine deployment environment. Given the global nature of maritime activities, it is vital for nations to work in conjunction to harmonize or leverage common regulatory requirements and industry standards to the extent practicable. This collaboration can, as a start, facilitate knowledge sharing, exchange of best practices, and the development of internationally recognized guidelines. Adequate funding (both government and commercial) will be crucial to reaching this goal, both for R&D efforts, but also to drive regulatory developments.

Nations developing civilian and commercial floating nuclear power will likely follow a unilateral path initially towards licensing and permitting rather than wait for full international consensus on all rules and regulations. However, the need for internationally accepted safety and security standards that are applicable to FNPPs will be essential in achieving greater harmonization of rules that would allow FNPPs to transit the territorial waters of other nations and for nuclear ships to call in ports overseas. It is therefore important to create a foundation for a regulatory framework that includes floating nuclear power starts at the International Atomic Energy Agency (IAEA) and the International Maritime Organization (IMO).

### 1.3. New IAEA Terminologies and Definitions

The following recommended definitions were developed in April 2023 by an IAEA Transportation Safety Standard Committee (TRANSSC) Technical Expert Group (TEG) to assist the agency in upcoming work in adapting current nuclear safety and security standards to transportable, mobile, and floating nuclear power plants (FNPPs).

- **Transportable Nuclear Module (TNM)** is a nuclear module designed to be transported and that is not permanently mounted on or integrated into a conveyance (defined by IAEA as a vehicle, vessel, hold, compartment, or aircraft). This definition applies to transportable nuclear modules, even if some components are temporarily detached for transport.

- **Mobile Nuclear Power Plant (MNPP)** is a nuclear power plant permanently mounted on or integrated into a conveyance, other than a marine vessel, to produce energy. This definition also applies where the nuclear power plant only provides energy to the conveyance.

- **Floating Nuclear Power Plant (FNPP)** is a nuclear power plant permanently mounted on or integrated into a marine vessel to produce energy. This definition also applies where the nuclear power plant only provides energy to the conveyance.

The terms MNPP and FNPP include both conveyances propelled by nuclear power, and those that are not. The definition is independent of whether the MNPP/FNPP is self-propelled or not. The propulsion properties may be added later to the definition for the maritime regulations as set out in the International Maritime Organizations convention for Safety of Life at Sea (SOLAS), Chapter VIII, Resolution A.491 (XII) – Safety Code for Nuclear Ships (1981) [6].

With IAEA definitions now being proposed to include an FNPP as both a non-propelled and self-propelled floating nuclear asset, the relevance of the IMO Safety Code for Nuclear Ships would be significantly enhanced.

It should be noted that the definitions describe the object(s) only and not the associated safety features as these are planned outputs of upcoming work at the IAEA.

Those safety features will be subject to the safety requirements and will include:

- Operations of TNM/FNPP/MNPP
- Fueled or not fueled
- Components that are necessary for their proper functioning at the site of operation

Furthermore, it should be noted that the following IAEA definitions continue to apply:
• Nuclear Power Plant (NPP) is an installation designed to produce energy from a controlled nuclear reaction.

• Nuclear Module (NM) is a component of a nuclear reactor that contains nuclear material or radioactive waste.

• Nuclear material as is defined in the IAEA Nuclear safety and security glossary (2022). Nuclear material or radioactive waste that is packaged in accordance with Special Safety Requirements No. 6 (SSR-6) is out of the scope of this study. Nuclear batteries, such as a radioisotope thermoelectric generator (RTG), are also out of the scope of this report.
2. Regulatory Overview

This report delves into the realm of nuclear energy, with a focus on safety, regulation, and the evolution of relevant protocols in the United States and internationally. We will navigate the nuances of Nuclear Reactor Safety, trace the development of nuclear regulations in the United States, and investigate the current structure of costs and timelines within the regulatory process. Additionally, we will define the overarching regulatory framework, compare nuclear energy regulations worldwide, and explore the specifics of licensing nuclear power maritime systems. The discussion will also provide an overview of the classification process, the IMO Safety Code for Nuclear Ships, and an examination of the security implications associated with FNPPs.

2.1. Nuclear Reactor Safety

The safety of a nuclear reactor system is dependent on a set of safety functions that must be effectively carried out to regulate the reactor during normal operation and ensure its safety during non-normal events, whether they occur within the plant or because of external hazards. By performing these safety functions effectively, the discharge of radioactive materials into the environment is either prevented or limited to acceptable levels [1].

Key Safety Functions:

- Controlling reactor reactivity during startup, operation, and shutdown.
- Managing heat removal to a designated heat sink.
- Regulating the volume, temperature, and discharge rate of coolant inventory.
- Managing chemically reactive or radioactive substances.

To ensure the safe operation of nuclear reactors, each must be designed with the appropriate safety features and systems capable of effectively performing their safety functions. This includes the design, operation, and maintenance of supporting systems, such as electric power, refrigeration, and pressurized air, which are required for the safety functions to be carried out. When applicable, reactor designs should also incorporate physical separation, independence, diversity, and redundancy in safety systems to reduce the risk of common-cause or single-point failures that could impede the performance of a safety function. In addition, designs must incorporate defense-in-depth and engineering margins to account for potential safety function challenges that may arise from an incomplete understanding of reactor system behavior. These design principles aim to guarantee the successful completion of all safety functions and the system’s overall safety.

Nuclear reactor safety regulation and licensing are the responsibility of the government, which reviews and independently assesses (and in, certain cases, may independently verify) how a given nuclear reactor system design has been demonstrated to perform the necessary safety functions with reasonable assurance to protect public health, safety, and the environment [1].

Approximately 80 percent of all commercial nuclear reactors in operation are light-water reactors (LWRs) that use low enriched uranium fuel (3.5 to 5%) and are cooled with water [2]. Some water-cooled designs are capable of using natural uranium at 0.7% enrichment. Critical safety functions in water-cooled reactors are accomplished by a combination of active and passive fallback systems, including reactor shutdown, cooling, and electrical systems, as well as operator actions. These systems minimize the likelihood of safety function failures and mitigate the potential impact they may have.

Safety always comes first. New nuclear is increasingly leveraging inherent and passive safety features to reduce the degree of human
intervention needed when an event occurs in the reactor. However well-trained staff will remain a mainstay of safe operations.

2.2. Development of Nuclear Regulation in the United States

Following the establishment of the Atomic Energy Commission (AEC) in 1946 and the enactment of the Atomic Energy Act in 1954, nuclear regulation in the United States has experienced significant transformations. These changes have been shaped by advancements in NPP design and operational knowledge, as well as the evolving public sentiment. Initially, the AEC assumed the role of developing, promoting, and regulating the emerging nuclear power industry under its jurisdiction. During the 1950s and early 1960s, the federal government’s support for nuclear energy spurred the construction of various commercial and demonstration reactor technologies, including heavy water reactors and high-temperature gas reactors. Since reactor technologies were still in flux, the AEC had to individually oversee each reactor, relying on limited experimental data, engineering expertise, and professional guidance to establish the technical foundation for licensing and operation.

The AEC employed a number of strategies to ensure reactor safety in the early nuclear reactor designs:

- A framework for acceptable risk derived from scientific information on radiation dose to humans.
- Using designs with a smaller radionuclide source term from catastrophes by operating at low reactor power.
- The use of multiple overlapping layers of prevention and mitigations (defense-in-depth) combined with multiple highly reliable physical barriers between the radioactive materials and the environment. A robust containment structure and other supporting systems were used as a final barrier to restrict accidental radiological releases in the event that other engineered barriers failed during an accident.
- Utilization of significant conservatisms such as robust engineering design margins to accommodate for uncertainties in the performance of the design.
- Remote siting in sparsely populated areas to reduce potential for public exposure in the event of an accident.

While case-by-case evaluations facilitated the construction and licensing of innovative reactor designs, the AEC, the Joint Committee on Atomic Energy, and the nuclear power industry sought to standardize NPP design criteria. These criteria aimed to reduce regulatory ambiguity and expedite licensing reviews by harmonizing safety analysis with AEC staff’s expectations. In 1971, the AEC’s technical staff formulated general design criteria outlining the essential design characteristics and technical data required for NPP license applications. Over time, these requirements shifted from being technology-neutral to technology-specific for the LWR technology, which was chosen for initial commercialization. This shift towards technology-specific reactor requirements was meant to optimize plant designs and improve consistency in regulatory decision making.

The Energy Reorganization Act of 1974 separated the AEC’s nuclear development and regulation responsibilities. Nuclear development was assigned to the newly formed Energy Research and Development Administration, which later merged with the Federal Energy Administration to form the Department of Energy, while nuclear regulation was assigned to the newly formed and independent U.S. Nuclear Regulatory Commission (NRC). The current principles of nuclear regulation and safety have evolved due to improved technical understanding, the lessons learned from significant industry incidents that highlighted the strengths and weaknesses of existing plant designs, and public concerns about the safety of NPPs [1].

Even though reactors of various advanced designs were constructed and safely operated in the early 1960s, the pursuit of regulatory decision making optimization which enables more streamlined and predictable licensing processes led to the establishment of licensing guidelines...
and procedures centered on the prevailing LWR technologies in the United States. In the decades following, refinements were made to safety practices based on experience and lessons learned and applied to nuclear reactors in a controlled manner. This was further influenced by the expansion of reactor capacities, and the evolution of siting policies which have impacted the regulatory requirements for nuclear power facilities.

The NRC staff is recommending the addition of 10 Code of Federal Regulations (CFR) Part 53, “Risk-Informed, Technology-Inclusive Regulatory Framework for Commercial Nuclear Plants,” (Part 53). The draft proposed rule offers a voluntary, performance-based alternative regulatory framework for licensing future commercial nuclear plants. In the context of this proposed rulemaking, future commercial nuclear plants, including non-LWRs and LWRs, would have the option to be licensed under Part 53. Pending Commission approval, the NRC staff would provide the final rule package, including key guidance, to the Commission by December 2024, and would expect to issue the Final Rule by July 2025. The NRC has also been involved with numerous efforts with the IAEA and other Member States regarding regulatory approaches for advanced reactors.

2.3. Current Cost and Timeline for Regulatory Process Effort

Public debate has surrounded the economic viability and comparison of advanced NPPs to alternative energy sources. This is predominantly due to the expense and length of the licensing process [3]. Previous attempts to grant licenses for reactors in the United States were met with unanticipated delays, resulting in higher regulatory costs. Comprehensive design certification assessments have been known to cost up to $100 million on their own, while site-specific combined operating licenses have cost between $25 and $50 million, excluding additional costs incurred in response to NRC staff inquiries [4].

Over and above the time needed to obtain a design certification (4-5 years) for a specific reactor design, the licensing process for a new build project typically takes at least five years, prompting the investigation of new methods and technologies that can shorten the required review cycles. In many cases, this is due to a lack of operating experience or a sufficient body of compelling and relevant supporting information to inform the development of requirements and guidance.

2.4. Distinguishing Between Regulatory Frameworks

In general, regulatory frameworks used to evaluate the safety of nuclear power plants and grant licenses for new plants can be categorized by three main characteristics: technology, risk, and the degree to which requirements are prescriptive or performance-based [1].

Technology:
One aspect of these frameworks is whether they are applicable to all types of nuclear reactor technologies or whether they are specific to a subset. Technology-specific regulatory requirements have been tailored to a specific reactor technology, establishing performance standards against which applications will be evaluated. This ensures uniform application of regulations and reduces decision making burden by regulators. However, a technology-specific framework limits a country from efficiently adopting new technologies.

Risk:
The framework’s consideration of the hazards associated with events that could impact on nuclear safety is another aspect. When establishing requirements commensurate with risk, there is an element of assessment of probability and associated potential consequences from key events. Risk factors are considered by regulatory frameworks to ensure adequate protection of public health and safety and can be articulated as qualitative safety goals and objectives or quantified such as dose limits to vulnerable members of the public.
Performance-Based or Prescriptive Requirements:

Performance-based requirements establish an outcome that must be achieved but allow for a number of different ways to achieve the outcome as long as the performance of the proposed method can be supported with sufficient evidence commensurate with safety importance. An example of this is a reactor shutdown. A regulator may specify that a reactor must have the ability to achieve a controlled shutdown within a specified time after an event occurs. This gives designers the ability to use different approaches to do this: such as via the inherent response of the reactor plus a highly reliable system to hold the reactor in the shutdown state indefinitely. This may mean using shutoff rods to place the reactor into a shutdown state once the inherent response has reached a low-level, but other options are possible.

Prescriptive requirements establish an outcome to be achieved but also prescribe what is an acceptable method to achieve that outcome as well as characteristics of the method that must be met. For example, a regulator may specify that one of the means to shut down the reactor must be via the use of shutoff rods within a specified time limit. This gives the designer fewer options for selecting an approach unless they make a specific case to the regulator for an exception to the requirement.

It is recognized that in the United States, technical regulatory requirements for water-cooled reactors tend to be more prescriptive, however the U.S. regulatory framework does retain elements of performance-based requirements. The U.S. NRC has recognized the need to offer more performance-based, risk informed requirements for new reactor technologies, such as advanced reactors, and has been making progress in this area over the past few years. However, these rules remain to be tested in practice by applicants for licenses.

All regulatory frameworks aim to ensure public health and safety. However, the choice of a specific framework has a significant impact on how technologies are regulated, and safety concerns are addressed. It is crucial to consider the implications of each framework in terms of wording, structure, readability, and eloquence while maintaining the original meaning. While technology-specific frameworks provide clarity and consistency, they may impede innovation and technology choice, whereas technology-neutral frameworks may be more receptive to novel reactor concepts but harder to interpret.

When considering regulatory requirements for marine based nuclear facilities all of the above factors need to be considered such that the requirements are readily understood but also provide the necessary assurance to the public and key stakeholders.

2.5. Regulation of Nuclear Energy in the World

Over the course of several decades, nuclear regulation in most nations has undergone substantial change in order to expedite the licensing procedure for a single reactor technology. This has typically resulted in regulatory systems that are tailored to the supervision of large, light-water-cooled nuclear reactors. Canada and the United Kingdom deviate from this standard, as their indigenous reactor technologies utilize heavy water and carbon dioxide cooling, respectively. As a result, over time, these nations’ regulatory frameworks became optimized to address the design and operation of their respective dominant reactor technologies. However, both Canada and the U.K. have made significant gains in also making their frameworks usable for new reactor technologies by reinforcing performance-based requirements.

Significant nuclear accidents, such as Three Mile Island, Chernobyl, and Fukushima have significantly impacted safety objectives underpinning regulations around the world. These accidents reinforced that nuclear safety is a global issue; radiation, being invisible, and often poorly understood by laypersons, instills a specific apprehensiveness in the public that influences their support for projects if they feel they cannot
trust the operator of the facility. Evidence from these past accidents has shown that the effects of a nuclear power plant accident can have a chilling effect on the entire industry unless it remains vigilant with community engagement and maintains a very strong safety culture. The IAEA established the Convention on Nuclear Safety (CNS) in 1994 to address these issues. The CNS endeavors to achieve and maintain a high-level of nuclear safety worldwide through the development of national measures and international cooperation, including safety-related technical collaboration. Additionally, it seeks to ensure effective defenses against radiological hazards in nuclear installations, protecting individuals, society, and the environment from the detrimental effects of ionizing radiation. In addition, the CNS aims to compel member states to maintain a strong focus on preventing radiological events and mitigating their consequences over time and area. By adhering to the IAEA’s fundamental safety principles for nuclear power facilities, nations have established diverse national regulatory structures while maintaining international accountability for nuclear regulation and safety [5].

While the ultimate safety objectives remain unchanged, the implementation of nuclear regulation varies from nation to nation due to differences in associated legal frameworks. These differences manifest themselves both philosophically and practically. Diverse approaches to implementing nuclear safety produce philosophical distinctions, such as technology-specific versus technology-neutral, the process by which risk is explicitly factored into decision making, and the degree of prescriptive versus performance-based requirements. On the other hand, Member States have practical variations in their regulatory implementations, for example there are varying frequencies of license renewal for nuclear reactors. For instance, license durations in Canada are set by the Commission based on the historic performance of the licensees, but for NPPs license durations are becoming standardized at every 10 years to coincide with a ten-year periodic safety review frequency. France has a ten-year renewal as well for similar reasons. The United States has a twenty-year renewal period for operating licenses. The deployment of any technology in a Member State will need to take the practical differences of the Member State’s framework into account.

Member States are responsible for nuclear safety and for regulating their respective activities. This is a Fundamental Safety Principle of the IAEA. However, obstacles to the global deployment of new nuclear power facilities could be reduced or even removed by Member States agreeing on and employing international best practices and enabling greater alignment and cooperation among national regulators. Multiple nations have always participated in the design, construction, and deployment of nuclear reactors, comprising a truly international enterprise. Despite this, these endeavors have been marked by a profusion of design concepts. Vendors can be enabled to sell a standardized design that can be used globally. Streamlining the process would reduce costs, shorten development timelines, and alleviate certain licensing burdens. Nonetheless, achieving a standardized international deployment paradigm necessitates greater understanding, agreement and eventually alignment between diverse nuclear regulators in order to prevent the need for unnecessary duplicative review efforts. This can be achieved through greater leveraging of IAEA safety standards and guides and then supplementing with more detailed agreement between regulators on specific regulatory requirements and guidance.

United Kingdom – Nuclear Regulation

In the United Kingdom, the Office of Nuclear Regulation (ONR) is responsible for issuing licenses and regulating commercial power facilities. Established as an independent government agency in 2014, the ONR oversees the use and transportation of civilian nuclear materials. By consolidating several government agencies that previously managed nuclear installations, security, and safeguards, the ONR aims to effectively license new nuclear power plants and supervise the expanding nuclear industry, and they do so in cooperation with other government agencies.
The ONR adopts a primarily objective-based regulatory approach along with prescriptive industry standards adopted by the authorized party to assure the safety of nuclear facilities in the United Kingdom. It sets high-level regulatory expectations while allowing flexibility for applicants to demonstrate compliance. This approach encourages innovation in nuclear facility safety, promotes the adoption of new technologies, and holds licensees accountable.

The ONR’s regulatory strategy is site and duty-holder-specific, involving the approval of specific sites for proposed activities and granting permissions to duty holders as authorized parties for different activities such as facility construction, commissioning, and operation. During the initial site evaluation, the applicant’s safety case for the proposed facility and site is assessed and subsequent authorizations will examine updates to the safety case based on new information from design and safety assessment. Throughout the construction and commissioning process, regulatory documentation for the reactor design and safety analysis is submitted according to a predetermined schedule.

To streamline the review process for standard reactor designs and provide early regulatory feedback, the ONR has developed a generic design assessment (GDA) process. Although non-binding, the GDA significantly contributes to the ONR’s evaluation of an applicant’s safety case. However, a GDA can only be triggered under the recommendation of the U.K. Department for Business, Energy and Industrial Strategy to the ONR based on reasonable knowledge that a project will proceed at a specific site.

By ensuring robust regulation and effective oversight, the ONR plays a crucial role in maintaining the safety and integrity of nuclear facilities in the United Kingdom.

In 2022, the U.K. Government passed the Merchant Shipping (Nuclear Ships) Regulation to establish a regulatory framework for commercial (i.e., Merchant) nuclear ships. It is MNAG’s position that these regulations include, by inference, the types of facilities captured by the proposed IAEA definition of FNPPs.

Other nation states including British Overseas Territories are in the process of passing similar legislation to support the advancement of floating nuclear power as a component of decarbonizing both coastal communities, industries, and the heavy transportation sector.

**Canada – Nuclear Regulation**

The Canadian Nuclear Safety Commission (CNSC) is an independent federal decision-making tribunal responsible for regulating nuclear power facilities in Canada. It regulates the development, production and use of nuclear energy and the production, possession and use of nuclear substances, prescribed equipment, and prescribed information.

The CNSC’s regulatory framework is, to the extent practicable, technology-neutral but draws from domestic and global experience as well as any credible supporting evidence to support a proposal. Requirements are a mix of performance-based and, where necessary, prescriptive elements, and they require the licensee to adopt and utilize proven practices such as accepted codes and standards to demonstrate that requirements are met. Any decisions concerning NPP projects follow a risk informed approach that considers, in addition to public input, both deterministic and probabilistic elements as well as the level of evidence needed to provide sufficient confidence in safety performance. Licensing is currently in progress for a number of projects involving both next generation water-cooled reactors and advanced reactor designs. The licensing process uses the existing requirements with the ability of the proponent to propose and justify alternative approaches for achieving the requirements.

Licensing of nuclear facilities in Canada involves separate evaluations and approvals for each phase of regulated activities, including site preparation, construction, operation, decommissioning, and abandonment. The CNSC conducts its assessment commensurate with importance to safety, taking into account the level of design detail needed to conduct each of the phases.
To enable vendors to better identify and resolve issues that could impede licensing, the CNSC offers a voluntary pre-licensing vendor design review (VDR). It is important to note that the findings of the VDR do not compel or influence subsequent plant design licensing reviews.

China – Nuclear Regulation

China’s commercial nuclear power facilities are licensed and regulated by the National Nuclear Safety Administration (NNSA) under the Ministry of Environment Protection. The NNSA is responsible for nuclear safety, civilian nuclear material usage, and coordination with the China Atomic Energy Authority and the National Energy Administration. The regulatory framework has been domestically developed in consideration of its original framework for operation of Canada Deuterium Uranium (CANDU) facilities, supplemented with U.S. practices and key requirements and guidance from IAEA safety standards and guides.

The framework has since incorporated and adapted various practices from each country it has imported technologies from while honing those practices as part of developing indigenous water-cooled and advanced reactor technologies. The Chinese Nuclear Industry is supported by robust internal research and development capabilities and the NNSA has successfully licensed a vast array of new build projects that span multiple reactor designs, demonstrating efficient internal processes based on technology-neutral requirements. The regulator conducts thorough safety assessments and verification activities to ensure compliance with regulations and nuclear quality assurance programs.

2.6. Licensing the Nuclear Power Maritime Systems

In some cases, the deployment of a stationary marine based nuclear facility at shore in a single country can likely be achieved with the existing licensing process for land-based facilities, with a few adjustments for the site characteristics.

However, for other types of marine based facilities, the licensing process for a Nuclear Power Maritime System (NPMS) is currently not clear, in particular, where the facility will need to operate between international boundaries. Uncertainty regarding the licensing process is an impediment to timely deployment of nuclear technology for maritime applications. Concerns specific to NPMS licensing include:

- The absence of a recognized process for a country to adopt or accept the results of the country-of-origin regulators’ decision or mechanisms to supervise the NPMS, which impedes the ship’s acceptance in foreign ports. This points to a likely preference for bi-lateral arrangements between countries for deployment of FNPPs.
- Absence of a specific licensing mechanism for civilian reactors installed on commercial ships in the United States, though precedence exists from the NS Savannah which was launched in 1959 and operated till 1972 visiting 45 foreign and 32 domestic ports over its operating timeframe. 
- Licensing for advanced reactor designs (ARDs) has limited experience using new licensing approaches such as the proposed 10 CFR Part 53.

The proposed Part 53 of the NRC regulations in Title 10 of the U.S. CFR is designed to resolve a number of these concerns. Consequently, the following remedies could potentially help address all identified problems, but experience needs to be obtained from use of Part 53 in real-life projects:

- Include special applications of nuclear power explicitly in Part 53, such as floating nuclear power and marine propulsion, to expand the technological scope of the licensure procedure.
- Collaborate with the IMO to align the marine propulsion requirements in Part 53 with the commercial marine industry, thereby enhancing the likelihood of international recognition and adoption.
- Utilize historical licensure documents, such as those for the NS Savannah licensed by the AEC, to establish a baseline and incorporate NPMS requirements into Part 53.
• Urge and facilitate collaboration between
the IMO and various nuclear regulatory
organizations, such as the IAEA and
national regulatory agencies, to develop
an international licensing process. The
IAEA’s extensive experience in regulating
the safety and security of international
transportation of radioactive materials makes
it a valuable resource for this endeavor.

Experts from both the nuclear and maritime
industries support the idea of an international
licensing process, and preliminary
implementation steps are underway to
address the scope of work required.

2.7. Overview of
Classification Procedure

To obtain a license for a vessel, FNPPs, like
other commercial ships, are required to undergo
classification by a classification society. Because
classification affects the design and arrangement
of structures, systems, and components within
the nuclear facility as a whole, classification
requirements should be integrated into the overall
design before completing the safety case to be
presented to the nuclear regulator. The nuclear
regulator will review all evidence used to support
the safety case and will engage with any expert
organizations to support its assessment work.
The International Association of Classification
Societies (IACS) defines classification societies
as organizations responsible for establishing
and enforcing technical standards for the design,
construction, and inspection of marine facilities,
including ships and offshore structures.

Twelve members of the IACS:
• ABS
• Bureau Veritas (BV)
• China Classification Society (CCS)
• Croatian Register of Shipping (CRS)
• Det Norske Veritas (DNV)
• Indian Register of Shipping India
• Korean Register (KR)
• Lloyd’s Register (LR)
• Nippon Kaiji Kyokai (Class NK)
• Polish Register of Shipping (PRS)
• Registro Italiano Navale (RINA)
• Russian Maritime Register of Shipping (RS)

While national authorities, also known as flag
authorities, bear the ultimate responsibility
for ensuring the safety of ships under their
flag, many countries have delegated this task
to authorized classification societies, referred
to as Recognized Organizations (ROs). The
classification of an NPMS represents a crucial
stage in demonstrating to the international
community the commercial viability of a system.

Given Russia’s operation of the Sevmorput
and several icebreakers of the Arktika class,
the Russian Maritime Register of Shipping
possesses unparalleled expertise in the
classification of nuclear ships. However, it
is important to note that the line between
what is considered to be commercial and
state property is not clear in these cases.

2.8. Plans for Future Classification

Ship classification is a crucial input into the
design, construction and operation of novel
floating, marine and ship designs. To improve
the viability of NPMS, it is essential to establish
an internationally recognized classification
regime or authority for nuclear-powered ships.

While global experience in classifying nuclear-
powered vessels is limited, ABS and LR stand
out due to the United States’ and United
Kingdom’s historical role as pioneers in the
development of marine nuclear technology.

In 2021, alongside ABS, the United Kingdom’s
Maritime and Coastguard Agency initiated a
consultation to establish a regulatory framework
supporting nuclear-powered ships as a means
to combat air pollution. The objective was to align
this framework with established international
standards, such as the International Maritime
Organization’s 1981 Code of Safety for Nuclear Merchant Ships (or Nuclear Code) and Chapter 8 of the 1974 International Convention for the SOLAS. This demonstrates the United Kingdom’s intention to introduce nuclear power to the commercial maritime sector.

2.9. The Nuclear Code of the International Maritime Organization (IMO)

The Safety Code for Nuclear Ships (the Code) [6] is a comprehensive document that provides internationally acknowledged safety standards for a wide range of nuclear merchant ship-related aspects. It includes design, construction, operation, maintenance, inspection, salvage, and disposal. Despite its initial emphasis on light-water PWRs, the code was purposefully designed to accommodate evolving reactor technologies, although it has yet to be updated. Anticipating the need for periodic review, this approach ensures the incorporation of technical advancements in-ship design, safety analysis improvements, adaptation to new ship types, adjustments for changing risk levels (such as an increase in nuclear ships in a single port), compatibility with future codes and conventions, and adherence to internationally agreed-upon revised safety standards [6].

The Code is under review by the World Nuclear Transport Institute (WNTI) in coordination with member states of the IMO. The review includes a comprehensive gap analysis to identify how the Code may be modernized to reflect advances in nuclear and maritime safety and nuclear security since being written in the 1970s. The Code contains a mandatory review clause which stipulates a requirement to always keep the Code relevant, but which has been neglected since its adoption in 1981. Proposals for inclusion of nuclear power on the agenda for IMO safety committees are expected during 2024 which would formalize the work to modernize the Code.

The Code serves as a robust foundation that can be revisited and updated to incorporate new technologies. This facilitates the development of modern regulations, similar to the NRC Parts 50 and 52. It specifies system designs to meet safety requirements, especially for PWRs. Although this approach poses challenges for developing an NPMS with ARDs, the listed design considerations still offer valuable guidance for the NPMS’s design specifications, including the following [6]:

- The evaluation of local meteorological conditions, population density, and land use factors on a nuclear ship.
- Consequences of natural phenomena, such as unusual sea currents, tornadoes, tsunamis, hurricanes, gusts, snow, and ice.
- Inertial forces acting on the vessel in a rough sea.
- The effects of collision, grounding, or explosion-induced shock loading on reactor plant components.
- Ship motion effects on reactor controls and dynamic behavior.
- Capacity of a ship’s reactor safety systems to function without malfunction under specific conditions.
- Radiological requirements, with an emphasis on minimizing exposure and staying within applicable dose-equivalent limits.
- Requirements concerning damage stability, floodability, fire safety, expected reactor casualties, radiation safety, waste management, operating and survey requirements, and quality assurance.
3. Security Implications for FNPPs: A Combined Evaluation of the Nuclear and Maritime Domains

Existing literature focuses predominantly on the nuclear security aspects of FNPPs without recognizing the maritime components adequately. Given the dynamic nature for siting FNPPs, traditional nuclear security approaches alone cannot ensure their protection. In addition to adhering to IAEA guidelines for land-based NPPs, site characterization and the path of travel for delivery of the facility to a site location will play an important role in deciding on the feasibility of marine based facilities. Dangerous Goods (IMDG) and International Ship and Port Facility Security (ISPS) protocols into their maritime security regulations. This section explores the areas where security protocols in the nuclear and maritime industries need to be linked [7].

3.1. On-site Facility Security

When a FNPP is stationed at a port or anchored offshore in territorial waters, the security elements resemble those used for maritime infrastructure, such as port facilities, or conventional land-based nuclear power plants; however, the technologies used to support those elements may differ, such as use of radar, antisubmarine nets etc. The maritime and nuclear industries each have distinct recommendations for on-site security.

3.2. Safety During Transportation

In its 2013 report on Transportable Nuclear Power Plants (TNPPs), the IAEA emphasized the distinctions between fixed-site and transport security. Transport security is uniquely complex due to its multifaceted character; it is multimodal, often operates across multiple jurisdictions, and involves a multitude of stakeholders. Whether viewed through a nuclear or maritime lens, the multiple participants in the security procedures increase their complexity.

To ensure the highest level of security for FNPPs, it is essential for nations to incorporate both maritime and nuclear security guidelines. This not only provides a comprehensive safeguarding mechanism, but also strengthens international cooperation and shared responsibility in FNPP operation and conveyance.

3.3. Nuclear Security and Safeguards Framework

The Convention on the Physical Protection of Nuclear Material and its Amendment (ACPPNM) emphasizes the significance of safeguarding nuclear materials and facilities against potential for proliferation. The Convention on the Physical Protection of Nuclear Material (CPPNM) only addressed international transport, whereas the ACPPNM also addresses domestic utilization and storage.

The ACPPNM, via its Fundamental Principal G, mandates that security requirements be adaptable, based on current threat analysis and the potential repercussions of unauthorized nuclear material interactions. In addition, the Nuclear Security Series documents from the IAEA provide detailed security protocols, such as early intruder detection, postponing theft or sabotage, and efficient incident response. Additional guidelines cover computer security, personnel dependability, and contingency planning [7].

3.4. Nuclear Security

The CPPNM and its Amendment (ACPPNM) are foundational legal frameworks aimed at assuring
the security of nuclear material during transport. While the original CPPNM was predominantly concerned with international transportation, the ACPPNM added additional domestic transportation requirements. Notably, neither of these conventions provide specific instructions on how to accomplish this security. This information is available in Nuclear Security Series No. 13, which provides recommendations for preventing the unauthorized removal of nuclear material during transport [7].

However, the recommendations of Nuclear Security Series No. 13 have been acknowledged and incorporated into the U.N. Model Regulations, which in turn influence the IMDG Code, mandating that maritime transporters of nuclear materials comply with these standards. Important suggestions include the following [7]:

- Limiting the duration and frequency of transfers of nuclear materials.
- Ensuring protection during transit and interim storage is commensurate with the category of nuclear material.
- Avoiding predictable patterns by varying travel itineraries and schedules.
- Evaluating the credibility of all personnel involved.
- Employing a material transport system with adequate physical protection measures based on threat assessments.

While Nuclear Security Series No. 27-G provides implementation guidance for nuclear facilities, Nuclear Security Series No. 26-G provides insights for transportation security. This guidance emphasizes the importance of recognizing responsibilities when passing through the territorial waters of another state. In addition, it stresses the importance of advanced notification protocols and the development of a transport security plan (TSP) that outlines security measures and stakeholder responsibilities [7].

Intriguingly, while Nuclear Security Series No. 13 provides limited information on maritime transport, Nuclear Security Series No. 26-G delves deeply into the topic while focusing predominantly on nuclear materials in Category I [7]. Nuclear facilities must be designed to withstand specific malevolent acts, including marine threats. The design basis threat (DBT) and beyond design basis threat (BDBT) for marine facilities need to be updated to reflect these threats.

The gap analysis of the Code performed by WNTI includes a comprehensive review of security requirements for FNPPs, originally not included in the Nuclear Code of the IMO.

### 3.5. Maritime Security

The ISPS Code mandates vessel security requirements that closely resemble those for facilities. The ISPS Code proposes a comprehensive anti-terrorism maritime strategy, emphasizing tiered security from the point of origin to the ultimate destination. However, the ISPS Code does not outline procedures for the management of nuclear or radioactive materials in port facilities. When FNPPs are nonetheless stationed at terminals, a combination of nuclear and maritime security protocols should be implemented.

Part A, Section 7 of the ISPS Code provides guidance on vessel response strategies for varying MARine SECurity (MARSEC) levels and preventative measures for prospective security incidents. Included in this procedure are the following [7]:

- Assessing ship security to identify potential hazards.
- Developing a vessel security plan that includes measures such as restricting unauthorized access, security protocols, auditing and updating security measures, and delineating the role of the ship security officer.
- The ISPS Code requires the presence of a ship security officer on each vessel, who is responsible for assuring vessel security, conducting inspections, and coordinating with shippers for the transportation of nuclear materials.

Given the interdependence of maritime and nuclear security for FNPPs, collaboration between
security experts from both domains is crucial. It is essential to align vessel security plans with transport security plans and vice versa to ensure safe and seamless transportation.

In 1993, the IMO introduced the voluntary Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel [INF Code]), complementing the IAEA regulations. This voluntary Code introduced recommendations for the design of ships transporting radioactive material and addressed such issues as stability after damage, fire protection, and structural resistance. In January 2001, the INF Code was made mandatory and renamed the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Waste on Board Ships.

Conventions such as the Suppression of Unlawful Acts against the Safety of Maritime Navigation (SUA Convention) and its protocols emphasize broader aspects of vessel security than the ISPS Code. These protocols are intended to protect against illegal acts against ships and platforms. According to the 2013 IAEA Report on TNPPs, enforcement and implementation of the SUA Convention, particularly its 2005 Protocol, are the responsibility of maritime law enforcement agencies rather than state nuclear security agencies [7].
4. Case for Marine Based Nuclear Power in the Energy Transition

The past few decades have seen huge growth in global energy demand which also creates an increasing strain on energy generation capacity, whether process heat or generation of electricity. Simultaneously, the energy sector is being compelled to exercise leadership in the drive towards net-zero and encouraging rapid electrification of numerous end-users. Despite significant improvements in energy efficiencies in the face of population and industrial growth, global energy demand is expected to triple by 2050 [8].

A marine based nuclear power platform offers a complementary way to deploy reliable and sustainable nuclear power close to where it is needed, particularly where traditional land-based facilities are not economically feasible.

In addition to direct power consumption, the production of e-fuels will also contribute to an increase in power demand since it requires substantial electricity or process heat production, which must originate from cost competitive zero-carbon sources. The growth in demand is beginning to outpace electricity supply in major markets. Although there have been significant efforts made to introduce renewable and clean energy sources, many sources produce variable power, presenting energy security issues that need to be rectified with fossil fuel backup generators. A marine based nuclear facility can be deployed in a manner that can service different types of energy demands and can be integrated with renewables to balance out energy variability and eliminate the need for fossil fueled backup facilities.

Doing this reduces dependence on fossil fuels at a time when increasing fossil fuel prices have led to price escalations in wholesale markets, impacting several industries, with cost increases often passed onto the consumer.

Nuclear power has been a mainstay of powerful navies since the 1950s. Nuclear submarines, aircraft carriers and warships have proven that it is feasible to operate reactors at sea, tolerating pitching, rolling, and heaving, while travelling millions of miles without refueling. Commercial nuclear ships were also tested back in the 1960s and 70s, but issues existed related to commercial insurance and economic viability when compared to traditional vessels that utilized bunker fuel when fossil fuels were priced at $2 per barrel. Climate change and global warming were not significant issues at that time.

Floating nuclear power generation is not a new idea, with the earliest examples dating back to 1968 when the U.S. Army used a FNPP at the Panama Canal called the STURGIS. This project was one of many parallel land-based projects that arguably used the world’s first true SMRs, designed to be modular, compact, and be equipped with robust and reliable safety features. These reactors were transportable, fueled locally but designed to be operated and maintained with simple tools. In the modern context, there is only one active example of a FNPP, the Akademik Lomonosov, a Russian-built nuclear power facility situated off the coast of Pevek in Siberia, which was successfully deployed in 2019. The reactors in that facility are mildly adapted icebreaker reactors with extensive Arctic Sea experience. The FNPP at Pevek was specifically placed to permit for the retirement of another first generation SMR-like facility, the 4-unit Bilibino Nuclear Plant.

The utility offered by small Pressurized water reactors (PWRs) made implementing the first FNPPs the most viable solution to meet energy needs in remote regions. Advanced nuclear technologies offer significant promise to expand the utility of FNPPs into the future for different energy generation applications.
5. Efforts Underway to Support Regulation of Marine Based Nuclear Facilities

The first MNAG report [10], published in 2022, expressed an opinion that many viable reactors that would be suitable for the marine environment are being developed in the USA under the US Department of Energy’s Advanced Reactor Demonstration Program Risk Reduction (ARDP RR) awards and as such will likely pursue first-of-a-kind (FOAK) licensing through the U.S. NRC. There are an increasing number of designs being developed around the world that may be suitable for use in different marine deployment projects. This section provides a summary of some of the activities underway to support regulation of those marine development projects.

5.1. Transport Safety and Security

The IAEA Transport Safety Standard Committee (TRANSSC) set down a working group (WG) in 2022 under the TRANSSC Technical Expert Group on Package Performance and Assessment (TTEG PPA). The WG was tasked with creating a position paper to support the process of establishing a consensus within the transport community with respect to the requirements for the safe transport of a TNM, an MNPP and a FNPP. The focus of the position paper was transport safety, with interface issues also addressed as necessary.

In April 2023, the WG set out recommendations for “definition and classification”, as shown in Section 1.3 above, a section for the “Applicability of transport safety requirements” to TNM/MNPP/FNPP as well as capturing characteristic “classification items” properties.

The position of the TTEG WG was to combine the definitions for an FNPP with that of a nuclear-powered ship on the basis that a new generation of nuclear-powered ships now sought by the global ocean transportation industry would be nuclear-electric, rather than powered by a direct nuclear steam cycle. This combined the benefits of reliable zero carbon emission propulsion with the ability to provide electric power in ports and terminals during port calls. However, current regulations only address a steam-driven propulsion system.

Going forward, the IAEA plans to establish three subgroups under a higher-level TRANSSC TNPP WG in 2023, focused on sea mode, land mode, and nearshore and port conditions. It is not anticipated that the TTEG WG position paper will be approved by TRANSSC in its entirety. However, the position paper will be updated regularly by the new TRANSSC WG TNPP, if new items need to be added or the status of items changes. For new designs, the positions will be reviewed and adjusted as needed.

5.2. World Nuclear Transport Institute

The WNTI was founded in 1998 to represent the collective interests of the nuclear transport industry by British Nuclear Fuels Ltd (U.K.), Cogema (France) and the Federation of Electric Power Companies (Japan). WNTI has observer status at the IAEA and consultative status at the IMO. Their traditional mandate has been limited to the safe transport of nuclear materials such as spent fuel and have not been involved in the safe operation of nuclear power plants.

However, in 2021, WNTI established a Marine Applications and Nuclear Propulsion WG (MANP) to work with IMO member states to revise and modernize the International Convention for the SOLAS Chapter VIII, Resolution A.491 (XII) – Safety Code for Nuclear Ships (1981) with the following aims:

- Bring the Code up to date with
correct reference to IAEA and IMO safety and security standards.
• Introduce nuclear technology agnosticism (not limited to any specific technologies) to allow for advanced reactors at sea.
• Review and recommend requirements for security and safeguarding at sea, nearshore environments and in ports.
• Review and evaluate issues related to the liability of a civilian operator of floating nuclear.

The MANP group coordinates work with a select number of nuclear and maritime regulators. At this point in time the MANP group is focusing efforts on the U.S.-NRC and U.S. Coast Guard in the USA, and the ONR and the U.K. Maritime and Coastguard Agency (UKMCA).

A technical gap analysis is in process with technical experts from the IAEA, Oak Ridge National Laboratory, LR, and the ABS. The purpose of the analysis is to provide regulators with information regarding the proposed language for a revised Code, with a scheduled completion date in mid-2024.

5.3. U.S. Nuclear Regulatory Commission (NRC)

5.3.1. NRC Licensing

The U.S. NRC regulates certain activities associated with commercial nuclear power plants as well as other uses of nuclear materials and waste and, following the passing of the ‘Nuclear Energy Innovation and Modernization Act’ in 2018, is preparing to review and regulate a new generation of nuclear facilities, including both water and non-water-cooled reactors.

As a result, the NRC now operates in an environment where potential applicants for power plant projects are considering a wider range of technologies, including advanced reactors and have a wide and varied range of technical, business, and regulatory experience. Additionally, the nuclear power industry has become more globalized, and many reactor designs are being developed, constructed, and operated abroad. This international activity provides opportunities for collaboration between the NRC and its international counterparts about relevant operating experience for different designs, international codes and standards, and computer modelling techniques and programs.

As stated in its Vision and Strategy: Safely Achieving Effective and Efficient Non-LWRs Mission Readiness [11], the NRC needs to be effective and efficient as it conducts its safety, security, and environmental protection mission, without imposing unnecessary regulatory burden. This includes licensing reviews associated with fuel fabrication, storage, transportation, and disposal. This strategy is being applied more broadly across all reactor design reviews as evidenced with increasing U.S. collaboration internationally on GE-Hitachi BWR-300 reviews.

Participants from both the nuclear and maritime industries must now start work on the evaluations and recommendations for licensing activities where nuclear reactors are proposed to be used in marine based facilities. A project group is being established in the U.S. with participation from reactor designers, FNPP designers, U.S. Government agencies and industry operators. The aim of the project group is to produce a study focused on developing a framework for NRC certification or licensing and how the industry may help inform the regulator on the key issues in designing, licensing, building, and deploying a marine based facility in U.S. territorial waters.

5.3.2. NRC Licensing Considerations

At first, the study will evaluate the feasibility of leveraging from NRC-certified designs or designs that are referenced in a U.S. licensed facility, given any modifications necessary to accommodate deployment and operation in a marine environment.

Siting challenges have been identified from the nature of FNPPs, where the reactor is installed on a mobile floating or offshore structure at a
deployment site, but where that structure can be transported (towed or lifted) to and from a deployment site. It is therefore important to evaluate the need for an NRC manufacturing license (10 CFR Part 52, Subpart F) authorizing a reactor to be installed at sites not identified in the manufacturing license application and consider changes to the manufacturing license process promulgated in 2007 NRC rulemaking.

Future regulatory studies should evaluate the need for a possession license under 10 CFR Part 70 if the reactor is going to be fueled at the place of manufacture (i.e., the reactor will be transported fully assembled and fueled to the site of deployment). Furthermore, for reactors that are going to be fueled at the place of manufacture, studies should evaluate compliance with applicable transportation requirements contained in 10 CFR Part 71 and consider lessons learned from Offshore Power Systems manufacturing license process (ML issued in 1982 for manufacture of eight floating nuclear power reactors).

In cases where the FNPP is self-propelled or propelled by electric power generated by the onboard reactor(s), the boundary conditions between NRC licensing and the maritime safety regime of the U.S. Coast Guard and others, must be evaluated carefully.

Future licensing will include new options with the anticipated implementation of the proposed 10 CFR Part 53 – “Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors”[12]. Here, the NRC proposes to establish a “technology-inclusive” regulatory framework for use by applicants for new commercial advanced nuclear reactors. The new regulatory requirements would utilize multiple risk informed methods and performance-based objectives that are more adaptable to a variety of advanced reactor technologies. Such a review process is intended to be better optimized and enable applicants to meet their scheduling and cost needs; however, this is yet to be seen, as it has not been implemented yet. As maritime nuclear reactors would fall under the NRC classification of advanced reactors, the proposed 10 CFR Part 53 may assist in commercial decisions for advanced reactors in maritime nuclear facilities. A draft for 10 CFR Part 53 was published in March 2023, and it is expected the final rule will be issued in June 2025.

5.4. Siting, Construction, and Operation

To determine the parameters of siting a marine based nuclear facility it is imperative that the technology can meet the commercial and operational requirements by industries such as oil and gas, floating wind, offshore processing and synthetic fuels production, ocean transportation operators, ports, and coastal industries, which may benefit from reliable, zero-emission power. However, they must also meet the operational requirements of the licensee, who is responsible for safety under their nuclear facility license.

Under current requirements, including those of the IAEA, the siting of a nuclear facility in a marine environment will need to go through a site suitability assessment process following the same principles and objectives as those documented in IAEA SSR-1. However, a site in a marine environment will naturally have some differences that need to be identified and assessed to confirm that the design of the facility is sufficiently robust from a safety, environmental, and security perspective for a given site. For example, the depth of water required for effective mooring and the type of marine environment must be considered. The in-depth approach will also need to consider activities in the vicinity of the facility, which could present additional external challenges to the facility and the ability to exercise emergency plans both in the facility and where offsite assistance is required. Proximity or large distances from population centers will impact the safety and control measures used for the facility at the site. Marine facilities do have an ability to be more self-sufficient from an emergency response perspective, but they are not infallible.
A marine based nuclear facility will need to be protected from the environment it operates in and from external impacts resulting from activities in the surrounding area. Proximity to shipping lanes, military facilities and tribal or indigenous lands or resources must be taken into consideration. A marine facility may also face different types of malevolent acts, including the threat of piracy.

In the case of permanently moored FNPPs, the proximity to transmission lines and required infrastructure will dictate whether new cables and transmission lines will be required.

5.4.1. NRC Siting Requirements

To provide a perspective from the United States as an illustration, siting requirements as set out in the U.S. Code of Federations (CFR) Title 10, Part 100 [13] establishes approval requirements for proposed sites for the purpose of constructing and operating stationary power and test reactors under 10 CFR Parts 50 or Part 52. When considering a license for siting an FNPP, the NRC must consider the case of mobile FNPPs, where the reactor is used for propulsion, as the geographical location of the facility would not be constant. The concept of a site has not been defined for nuclear propulsion in IAEA safety standards and remains a subject to be resolved.

10 CFR Part 100 states that factors considered in the evaluation of sites include those relating both to the proposed reactor design and the characteristics peculiar to the site. It is expected that reactors will reflect through their design, construction, and operation an extremely low probability of accidents that could result in the release of significant quantities of radioactive fission products.

Nuclear merchant ships and moored FNPPs will be expected to be designed and built to achieve a high degree of safety and security. If a vessel is designed, constructed, and operated in accordance with the best practices for nuclear ships and within the framework of the IMO SOLAS Convention, it can be reasonably assumed that:

- The main nuclear hazard to be considered in port or a nearshore environment would arise from the occurrence of a highly unlikely accident of sufficient severity to cause an appreciable release from the ship of gaseous or volatile radioactive materials, of which the iodine isotopes and noble gases are of particular significance.
- The ship’s design and care in navigation should address the Design Basis and Beyond Design Basis Threat (DBT/BDBT), which traditionally includes design against aircraft crash for land-based commercial nuclear plants. The marine environment could expand the DBT/BDBT to design against marine collisions and grounding.
- Normal operations in ports and at the berth will not give rise to levels of radioactivity in and about the ship more than those specified for routine operation.

In addition, the site location and the engineered features included as safeguards against the hazardous consequences of an accident, should one occur, should ensure a low risk of public exposure. There remains a small probability that accidents might be experienced which could lead to off facility releases of radioactive materials. While an offshore FNPP is unlikely to have as many civilians in its EPZ compared to a land-based reactor, hazards to facility workers and the environment are still of concern and should be addressed during siting considerations. Proponents in the U.S. should therefore work with the NRC, U.S. Department of Energy (DOE), the U.S. Coast Guard, the U.S. Environmental Protection Agency (EPA) and other expert maritime agencies to consider:

- population density,
- proximity to land,
- the local marine environment,
- proximity to manmade hazards, and
- the physical characteristics of the site, including seismology, meteorology, geology, and hydrology,

in assessing a proponent’s proposal acceptability of a site, and/or location of a floating nuclear power reactor.
5.4.2. Construction and Operation Considerations

The nuclear industry should collaborate with the facility that is planned to manufacture the unit, and the facility or company involved in the installation, if different from the manufacturer, to interpret and apply regulatory requirements and successfully navigate available licensing frameworks to manufacture the nuclear facility components, manufacture the marine based platform and integrate the two for deployment to the site. These entities may require separate certification or approvals from regulators to handle nuclear material and operate/test nuclear facilities. The industry should also engage early and regularly with regulators to identify interpretation issues, gaps or conflicts and participate in their resolution.

The industry should engage with the U.S. DOE and the NRC to propose and discuss how 10 CFR Part 50 could be used to create a multi-step construction permit and operating license approach or if 10 CFR Part 52 could be adapted for a one-step combined license approach that could reference certified or approved designs, or Early Site Permits. Another option would be to use 10 CFR Part 53 for licensing once that NRC rulemaking is finalized in 2025, which would necessarily require extensive engagement with NRC.

The industry should also lead an initiative to review and comment on the NRC environmental (NEPA) review requirements (10 CFR Part 51), where the NRC prepares environmental impact statements (EIS) for all reactor license applications, including detailed alternative sites analysis. In a multi-step process, as discussed above, the distinction between the ‘site’ of the reactor on a floating vessel and the ‘location’ of that floating vessel, considering all boundary conditions with local and maritime rules, should be considered.

Currently, the proposed NRC Generic Environmental Impact Statement (GEIS) [14] for advanced nuclear reactors uses a plant parameter envelope (PPE) and site parameter envelope (SPE) approach, which does not address marine based facilities, though data and precedence do exist from previous floating nuclear applications in the United States. The industry needs to engage with NRC and propose an appropriate PPE methodology for this. Discussions will need to clarify how the NRC would consider applicant compliance with other federal/state requirements (e.g., Coastal Zone Management Act [CZMA], Clean Water Act [CWA]), which, in some cases, must be shown before NRC can issue a license.

Existing NRC operation requirements include the following:

**Significant NRC Operational Requirements**

1. Operator staffing (remote or autonomous operations)
2. Security and safeguards (10 CFR Part 73)
3. Emergency planning (10 CFR Parts 50 and 52)
4. Transportation packaging (10 CFR Part 71)
5. Financial protection (10 CFR Part 140) (Price-Anderson Act coverage; private insurance)
6. NRC Annual Fees

**Other Applicable State and Federal Laws**

1. Will depend on location of facility, i.e., distance from shore in nautical miles.
2. Relevant state laws and regulations, depending on location
3. Non-Environmental (e.g., Submerged Lands Act of 1953, Rivers and Harbors Act, Outer Continental Shelf Lands Act)
4. Environmental (e.g., Clean Water Act, Marine Mammal Protection Act, the Coastal Zone Management Act, Magnuson-Stevens Fishery Conservation and Management Act, National Historic Preservation Act, National Marine Sanctuaries Act)
5. Identify specific approvals that may be required from other federal, state, and local agencies for siting a facility offshore and/or in coastal setting and construction/access to transmission; may include leases, easements, or rights-of-way, among numerous others.

Many other federal and state agencies are likely to be involved (e.g., DOI’s Bureau of Ocean Energy Management, Army Corps of Engineers, U.S. Coast Guard, National...
5.5. Marine Based Nuclear Facility Operating Environments

The deployment of facilities housing reactors rated from 20 MW electric up to 1.2 GW electric with a capacity factor of up to 95% is possible. The reactor and all safety-related components would be housed in the hull, with ample compartmentalization and buffer spaces, reinforced structures, and shielding to protect them from collision and flooding and to support effective emergency response. The reactor and containment could also be located partially below the waterline, offering additional protection on all sides and allowing the use of seawater as a virtually infinite final heat sink.

The facilities could be built and integrated for the most part within a shipyard and delivered to the site, which may be moored or anchored in relatively deep water (>100m) within either national waters or within a country's exclusive economic zone (EEZ). Therefore, each facility will fall under the purview of the host country's nuclear regulators, who will have their own requirements.

5.5.1. Viable Use Cases

It is envisaged that FNPPs could be deployed to serve U.S. ocean transportation including:

- heavy payload, energy transportation and resilient mobile power for the U.S. Dept. of Defense,
- mobile water desalination,
- offshore processing and production,
- clean energy provision for offshore drilling and production,
- flexible power for coastal industry and communities,
- decarbonizing ports and shoreline installations,
- hydrogen production and low carbon fuels,
- clean energy provision in support of maritime green corridors, or
- offshore industries and for load balancing intermittent offshore energy.

Such facilities could also be connected to major national grids via subsea power transmission cables, helping to alleviate current stress on global electricity systems, providing a reliable baseload and cost competitive source of sustainable electricity.

Several high-level theoretical scenarios should be considered and evaluated:

1. An FNPP hull is fitted with its reactor and power systems in a licensed yard before being fueled for operation, potentially in a different yard.
2. The fueled FNPP is transported, towed, or relocated in shut down or hold-down condition to an approved operating location offshore, transiting through coastal waters, past landmasses and passing marine traffic.
3. For servicing and maintenance, the FNPP reverses the journey back to its home-yard, hence this may become a repeat voyage.
4. The fueled FNPP is a self-propelled vessel using electricity generated by its onboard NPP. From its home-yard, it navigates waterways, nearshore waters and into pre-approved ports, where it connects its electric supply to the port's grid, providing clean power during its call. The self-propelled FNPP carries an operating crew which rotates on and off the vessel in ports or offshore.
5. The FNPP may vary in size and capacity from small; generating no more than 10–20 MWe to large; generating grid-scale electric power more than 1 GWe.
6. The FNPP may be permanently moored far offshore, transmitting electric current through cables to offshore facilities, or to shore. Large FNPPs may be serviced, maintained, and re-fueled at sea. The offshore FNPP carries an operating crew which rotates on and off the vessel via helicopter or by boat.
5.5.2. Emergency Planning Provisions and Planning Zones

In the United States, like other countries around the world that license and operate an NPP, emergency preparedness is required. The emergency planning (or preparedness) zone (EPZ) is the area around an NPP inside of which offsite emergency measures are planned in case an accident progression overwhelms the onsite accident prevention and mitigation measures, including onsite emergency response.

Onsite and offsite measures start with the operational response of the workers and escalate to graduated offsite response established by criteria that take into consideration accident progression and associated predictions of consequences over time and area. Measures serve to protect vulnerable persons (normally members of the public) by establishing shelter in place or evacuation as well as the limitation of consumption of drinking water and certain foodstuffs. The shape of the EPZ is usually circular with the NPP as the center but is also reflective of the population distributions and land use around the facility. The EPZ size is defined as the distance from the NPP (radius of the circle). Different countries have government emergency planning functions who work with the proponents for the projects and nuclear regulators to establish appropriate zone types and EPZ sizes and zoning systems. It is common to see two or more planning zones for a single reactor. For example, U.S. reactors have a 10-mile (16.1km) Plume Exposure EPZ and a 50-mile (80.5km) Ingestion Exposure EPZ, which is imposed by the NRC. In Canada for example, EPZs are established by Provincial emergency planning agencies in consultation with the nuclear regulator, CNSC, Public Safety Canada, Health Canada and information from local government who are responsible for land use planning.

In the United States, like many other countries, the EP strategies and associated zones EPZ sizes are predominantly based on the source terms and accident progression characteristics from existing large facilities. Low or ambient-pressure reactors are, by design, equipped with physical measures to prevent high energy accidents that can lead to significant offsite consequences. Examples of design measures include lower or ambient-pressure systems, accident tolerant fuels and multiple barriers to radiological releases as a functional containment system. These features are being established to achieve a reduction in the extent of the emergency planning area around the facility and, as a result, better define the liability of the operator in case of an accident or mishap. The liability of the operator must be understood and mitigated. New nuclear technologies could allow for very small EPZs, and future design activities will seek to demonstrate whether all emergency response could be carried out within the facility.

In the case of current and future plants using advanced reactors, the appropriate size of the emergency planning zones is being proposed to be limited to the site boundary of the power plant. This will ultimately be established through the licensing process, initially on a case-by-case basis until sufficient technical and legal precedent is established.

1. According to 10 CFR Part 50 (2011), ... the size of the EPZ may be determined on a case-by-case basis for gas-cooled nuclear reactors and for reactors with an authorized power level less than 250MW thermal.” [27]
2. According to IAEA’s SMR Regulators’ Forum Pilot Project Report: Report from WG on EPZ: “There is a need to consider that the EPZ size for SMRs can be scaled based on the specific design characteristics and site-specific considerations.” [28]
3. IAEA Coordinated research project (02/2018) “Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for EPZ for Small Modular Reactor Deployment.” This document attempts to identify suitable repeatable methodologies that many regulators will accept.

The use of accident tolerant fuels, inherent safety characteristics, passive safety features and other features like lower operating pressure can be used to eliminate any large releases from the
plant and significantly lower the source term and its consequences over time and area around the facility. This means that offsite consequences can be shown to be orders of magnitude less than emergency thresholds for Sheltering and Evacuation. However, these claims must be evaluated through the licensing process, and this requires sufficient design completion and associated safety analysis to be completed.

This is the case for the NRC-approved methodology of the NuScale SMR [9], the methodology followed by the Shidao Bay HTR PM Plant in China and other SMR designs [Table 1].

In the case of an FNPP, a general framework for calculating the appropriate EPZ will need to take the following steps:

1. Employing outputs of systematic safety assessment supported by Probabilistic Risk Assessment (PRA), the possible accident sequences that are needed for the EPZ calculation (a select set of Design based accidents (DBAs) and representative DBAs with characterized consequences) are determined along with their occurrence frequency.

2. Source term estimation.

3. Calculation of the maximum effective dose and contamination level of food and drinking water at different distances from the reactor in case of the most serious accident sequences using appropriate models and weather parameters for both the atmospheric and aquatic dispersion in the marine environment.

If the levels calculated in Step 3 beyond the boundaries of the FNPP are much lower than the regulatory intervention levels identified, the EPZ of the marine asset might be capable of being limited to the boundary of the facility, however, the offsite EP organization may impose further buffer zones commensurate with legal requirements.

To achieve this, FNPPs must utilize a sufficiently robust defense-in-depth strategy that provides multiple complementary prevention and mitigation measures to eliminate offsite consequences to the extent practicable. This would greatly minimize the magnitude and consequences of radioactive release, effectively ensuring that radioactive material is localized and does not escape the nuclear island in DBAs, mitigating the exposure of personnel, the public and the environment.

This is the approach that ultimately impacts offsite measures in time and distance from the facility. According to Figure 1 below, stronger measures for Levels 1-4 buy you relief in Level 5 when considering defense-in-depth for integrated accident management.

Using a robust defense-in-depth approach allows a safety case to demonstrate that consequences from accidents can be limited in time and area to the boundary of the plant, thereby reducing the need for measures for offsite response.
Table 1: Examples of advanced nuclear reactors designs with proposed reduced EPZ [15].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BWRX-300</th>
<th>NuScale</th>
<th>IMSR</th>
<th>MMR</th>
<th>MCFR</th>
<th>eVinci</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developer</td>
<td>GE-Hitachi Nuclear Energy</td>
<td>NuScale Power Inc</td>
<td>Terrestrial Energy Inc</td>
<td>Ultra Safe Nuclear Corp</td>
<td>TerraPower LLC</td>
<td>Westinghouse Electric Corp</td>
</tr>
<tr>
<td>Reactor Type</td>
<td>Boiling water</td>
<td>Pressurized water</td>
<td>Thermal spectrum molten salt</td>
<td>High temperature gas</td>
<td>Fast spectrum molten salt</td>
<td>Heat pipe</td>
</tr>
<tr>
<td>Thermal Power (MW)</td>
<td>870</td>
<td>200</td>
<td>400</td>
<td>10</td>
<td>180</td>
<td>15</td>
</tr>
<tr>
<td>Pressure</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Ambient</td>
<td>Ambeient</td>
</tr>
<tr>
<td>Source Term</td>
<td>Conservative appr. Scaled large BWR</td>
<td>Conservative appr. Scaled large BWR</td>
<td>Molten Fuel, only noble gases released</td>
<td>Robust PRISM</td>
<td>Closed cycle, integrated waste management</td>
<td>TRISO inventory</td>
</tr>
<tr>
<td>EPZ Claim (m)</td>
<td>1000 (site boundary)</td>
<td>500 (site boundary)</td>
<td>&lt;500 (site boundary)</td>
<td>30-50</td>
<td>10-20</td>
<td>10-20</td>
</tr>
</tbody>
</table>

Figure 1: Defense-in-Depth: Integrated Accident Management [16].
5.5.3. Nearshore Operations in Ports and Waterways

In collaboration with DOE and maritime agencies, proponents should evaluate and determine the conditions for the approach and departure of a safe port call of an FNPP, whether self-propelled or not, and engage NRC with methodologies for performing these evaluations. They should make specific reference to the safety and security characteristics of available and planned new nuclear technology and operating/safety procedures for round-voyage nearshore approach, port canal entry and navigation, maneuvering and docking.

5.5.4. Factors in the Selection of Berths

Below are several key areas which must be considered if a nuclear ship is to make berth. Suggestions and considerations have used past IAEA safety studies [17] as a foundation. It will be important that future work makes progress towards a framework that addresses the points below. There must be overarching factors which should be considered in the selection of viable berths. These factors from a safety viewpoint might be grouped as:

- Factors influencing the relative probability of an accident caused by external factors such as shipping channels (frequency and speed), tidal and meteorological conditions, location of airports and flight paths etc.
- Factors influencing the dispersal capability to the environment, such as frequencies and times of prevailing and extreme meteorologic, tidal and water flow conditions, and seasonal variations.
- Factors influencing potential consequences of accidents, such as surrounding land use, availability of services and ease of towing and radiation monitoring.

5.5.5. Practices to be Considered for Port Use

When considering a marine based nuclear facility, it is imperative to consider how this nuclear asset will interact with ports or at berth. Below are arrangements which must be considered prior to entry and use of ports by FNPPs, using IAEA safety series [17] documents as a basis.

- Prior Notification of the ship’s intention to call at the port.
- Vessel must be inspected and granted an entry certificate by the receiving government before entering port waters.
- Arrival condition considerations, such as poor weather.
- Remote anchorage:
  - Designated location for nuclear ships in case there is a change in port conditions which would preclude the ship’s entry to the port.
  - A location the ship can be taken as an emergency measure in the unlikely scenario that the ship experiences an accident.
- Adequate surveillance and communication facilities must be provided by the port, to divert nuclear vessels to remote anchorage if poor visibility or adverse weather arises. In ports without such facilities, the vessel is permitted to proceed at the captain’s discretion.

5.5.6. Conditions While in Transit to and from Berth

In maritime regulation, the handling of the ship is not affected by the type of power systems, and therefore, the pilotage requirements for nuclear ships should be no different from those of conventional ships, including no privilege right of way. In port waters, tug(s) can accompany the vessel to assist with maneuvering, with the location at which this assistance is provided a matter for individual consideration by port authorities. The presence of tugs also ensures that the ship can be moved to a safe location in case of emergencies.
5.5.7. Conditions at the Berth

Upon reaching the berth, it is important to consider the following suggestions and considerations:

- Provision of power and special lighting arrangements as required by the ship or security forces.
- Consideration of water supply for in-ship firefighting and possible connections to ship fire mains.
- Communication facilities: ship-to-shore telephone connections, port network access, and radiotelephone facilities.
- Security Arrangements: Enhanced security measures compared to conventional vessels, security personnel at access points/gangways, and special surveillance during off-hours. While this might not fall under class requirements, we foresee the port state requiring such provisions to be put in place prior to berthing.
- Presence and availability of Dosimetry equipment.
- Appropriate arrangements for adequate fire cover (could be land-based fire stations, military fire support, air-based fire support) while the vessel is at berth while considering complications that may arise if the nuclear vessel is involved.
- Consideration must be given to access to the ship in the port area so emergency action is not impeded.
- For manning of the ship while at berth, in addition to current practices, the IAEA safety series [17] suggests the availability of a senior officer-in-charge, a sufficient crew on board to man the ship capable of taking her outside port limits if required, and a continuous fire patrol.
- Any necessary pilots should be available on short call for the duration of time at berth.
- Facilities adjacent to the berth:
  » No handling of explosives and careful consideration given to handling of large quantities of hazardous material in the vicinity of the ship.

5.5.8. Administrative Arrangements for Emergencies

There also must be a set of administrative arrangements that should be established as precautionary measures for dealing with emergency conditions which should include:

- Control and Operation of the vessel: Captain’s competence in dealing with vessel-related accident conditions involving the release of radioactive material, including the safety of the reactor installation, which remains the responsibility of the captain.
- Port Authority’s Responsibility: To define executive responsibility for action concerned with the safety of the port.
- Public Safety and Health: Prior to arrival, there should be full consultation with appropriate bodies for a clear definition of responsibilities. These may include police, health officials and those concerned with agriculture and food. Arrangements should be made for control, evacuation, and medical treatment in the case of contamination.
- Environmental Hazard: Arrangements should be made to warn civil authorities and government bodies about potential radioactive material spread.
- Expert Assistance: Involvement of experts in environmental monitoring, meteorology, health physics, and engineering for assessing hazards.
- Captain’s Responsibilities: Responsible for immediate reporting of abnormal reactor conditions and assessment of the situation.

5.5.9. Boundary Conditions Between Nuclear Licensing and Maritime Regulations

Rules governing the location or navigation of an FNPP in national waters and nearshore environments will depend on purpose, design, licensing, classification approval, and proximity location of the FNPP.
Multiple touchpoints exist between the nuclear and maritime regulations governing FNPPs. For example, in the United States these include:

- Flag State oversight
- Port State Control
- Local Environment Regulation
- National Nuclear Regulations
- The ISPS Code
- Pilot Requirements
- Tug Requirements
- Stevedore Requirements
- Shipping Traffic Acts
- Inland Navigation Police Regulations (BPR)
- Shipping Regulations for Territorial Waters (STZ)
- Compulsory Pilotage Decree 1995
- Decree on Pilot Exemption Certificate Holders Shipping Traffic Act
- Regulation for Licensed (Maritime) Pilots
- Regulation for the Prevention of Pollution from Ships
- Regulation on the Transportation of Dangerous Substances, 2007
- Port Management Bylaws
- Regulation for Communication and Pilot requests sea shipping
- Regulations for seagoing vessels required to notify port authorities
- Regulations Notifications and Communication Shipping
- USCG guidelines and statutes
- Other U.S. regulations

In addition, consideration should be given to non-environmental rules such as Submerged Lands Act of 1953, Rivers and Harbors Act, Outer Continental Shelf Lands Act. Boundary conditions with environmental acts such as the Clean Water Act, Marine Mammal Protection Act, the Coastal Zone Management Act, Magnuson-Stevens Fishery Conservation and Management Act, National Historic Preservation Act, National Marine Sanctuaries Act must be evaluated.

It is also important that work is done to identify specific approvals that may be required from other federal, state, and local agencies for siting a facility offshore and/or in coastal setting and construction/access to transmission; may include leases, easements, or rights-of-way, among numerous others.
6. End-of-Life Considerations

Reconciling end-of-life operations: nuclear waste, facility decommissioning, handling of spent nuclear fuel or nuclear waste is a thorny issue for ports, and it is important to address this through informative communication about safe nuclear waste handling as well as thoughtful design measures. For example, by designing new nuclear energy systems that run with long fuel cycles, we can avoid refueling and removal of spent nuclear fuel in commercial ports. This is true both for FNPPs operating offshore or in nearshore environments as well as for nuclear-powered ships. However, if properly designed, on-site refueling can still be a very safe and viable option.

Individually, the list of regulatory considerations for decommissioning nuclear reactors and decommissioning maritime vessels is extensive. When combined, these technologies will require new and complex end-of-life processes to address issues like nuclear waste management and vessel scrapping. While this section does not provide suggestions for how those processes should be shaped, it does outline some of the regulations and considerations as they exist today.

A commercial maritime reactor must be designed to the extent practicable to prevent and mitigate any cross-contamination or uncontrolled releases during all operational conditions. No contamination should come from the reactor into the remainder of the facility, and contamination should not be able to get from the facility into the reactor. By minimizing cross-contamination between the reactor and maritime installation, end-of-life operations for the facility can be greatly simplified and reduce the generation of costly and hazardous waste, which must be managed and disposed of in special facilities.

To explain how these different regulatory regimes currently exist, this section will explore the topic from three perspectives, using the United States as an example. First, the regulatory considerations as they exist for each sector individually; second, how these considerations are addressed within the military context of the U.S. Navy; and finally, how a commercial maritime reactor, namely the NS Savannah, was decommissioned.

6.1. Existing Considerations for Managing Nuclear Waste in the United States

The NRC currently regulates four categories of nuclear waste. According to their website, this includes [21]:

- **Low-level waste (LLW):** includes radioactively contaminated protective clothing, tools, filters, rags, medical tubes, and many other items.
- **Waste incidental to reprocessing (WIR):** refers to certain waste by-products that result from reprocessing spent nuclear fuel, which the U.S. DOE has distinguished from high-level waste.
- **High-level waste (HLW):** “irradiated” or used nuclear reactor fuel. This includes commercial Spent Nuclear Fuel (SNF).
- **Uranium mill tailings:** the residues remaining after the processing of natural ore to extract uranium and thorium.

Like existing commercial nuclear power plants, LLW and HLW are likely of highest concern for a potential future maritime reactor owner. LLW is classified into three groups: A, B, and C. According to the NRC [26]:

- **Class A LLW** contains the least radioactivity, most of which comes from relatively short-lived radionuclides that decay to background levels within a few decades.
- **Class B LLW** is also relatively short-lived but contains larger concentrations of short-lived radionuclides than Class A LLW.
- **Class C LLW** can contain larger concentrations of both short-lived and long-lived radionuclides.
In general, LLW disposal is a routine process that is overseen by the NRC and the four “agreement states” that host the United States’ four LLW Disposal Facilities. “Agreement states” are domestic states that, under Section 274 of the Atomic Energy Act, manage portions of the NRC’s authority to license and regulate by-product materials (radioisotopes); source materials (uranium and thorium); and certain quantities of special nuclear materials [22]. These four LLW facilities are (see Figure 2) [21]:

- **EnergySolutions Barnwell Operations, located in Barnwell, South Carolina:** Licensed by the State of South Carolina to dispose of Class A, B, and C waste accepted from the Atlantic compact states (Connecticut, New Jersey, and South Carolina).
- **U.S. Ecology, located in Richland, Washington:** Licensed by the State of Washington to dispose of Class A, B, and C waste from the Northwest and Rocky Mountain compacts.
- **EnergySolutions Clive Operations, located in Clive, Utah:** Licensed by the State of Utah for Class A waste from all regions of the United States.
- **Waste Control Specialists (WCS), LLC, located near Andrews, Texas:** Licensed by the State of Texas to dispose of Class A, B, and C waste from the Texas Compact generators and outside generators with permission from the Compact.

HLW presents a more complex problem. According to the NRC, HLW takes one of two forms:

1. Spent (used) reactor fuel when it is accepted for disposal.
2. Waste materials remaining after spent fuel is reprocessed.

The Nuclear Waste Policy Act of 1982 establishes the U.S. Federal government’s responsibility to provide a place for the permanent disposal of HLW and assigns the cost of permanent disposal to those who generate it. In 1987, the act was amended to designate Yucca Mountain in Nevada as the nation’s sole nuclear waste repository [32]. However, sustained opposition from neighboring local communities and the Nevada state government have prevented any progress on the project and today the possibility of Yucca Mountain opening seems highly unlikely.
In 2021, the U.S. DOE under the Biden Administration restarted a siting effort to identify new potential locations for a HLW facility in the United States. The effort has built upon findings from the Obama administration’s Blue Ribbon Commission on America’s Nuclear Future, which published multiple recommendations including an expression of the need for a new approach to siting and building nuclear waste facilities. This new approach should be adaptive, staged, consent-based, transparent, standards- and science-based, and governed by partnership agreements with local, state, and tribal leadership. Although a consent-based approach is promising, it is also time intensive, and it is unlikely that a HLW facility will be built and operating before 2030.

Leading up to this point, the Biden Administration’s focus has been on identifying one or more interim storage sites that would act as temporary locations for consolidating HLW located at 80 sites around the country (see Figure 3) [19]. Until a repository is operating, existing nuclear power plants are committed to safe on-site storage of HLW. This involves placing spent fuel rods in an on-site spent fuel pool for several years before moving them to open-air dry storage. “Dry-cask storage” is an NRC-certified method for storing and managing HLW that has been in practice since 1986. While the approach has a spotless safety record, it is not widely accepted as a final waste management solution [18].

Discussions will need to take place to determine how waste from marine based facilities will be addressed under the existing framework and using the facilities being planned. With the growth of nuclear reactor projects in the United States, including marine based facilities, waste management facilities will need to be expanded or new ones established. Clarity is also needed on whether exported facilities would be repatriated back to the United States for waste management and disposal or whether key wastes such as spent fuel will remain in the country of deployment.

Figure 3: Nuclear Waste Storage Sites in the United States [19].
6.2. Existing Considerations for Decommissioning Vessels

Compared to managing the end-of-life for a nuclear reactor and its fuel, managing a maritime vessel’s end-of-life is relatively less complicated. Of ships that are ultimately broken down and recycled (a process referred to as “ship breaking”), roughly 90% of them go through this process in either India, Pakistan, Bangladesh, or Turkey (see Figure 4).

Because ship breaking is notoriously dangerous and harmful to the people and environments where it takes place, several key international treaties have helped to raise the environmental standards of the practice. This has included:

- The decision at the 2004 Conference of the Parties (COP) to recognize old ships as waste under the Basel Convention and to collaborate with the IMO on establishing mandatory requirements for environmentally sound ship dismantling [33].
- The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, which was adopted in May 2009 and outlines a control system for ship recycling, including obligations for flag States, shipowners, recycling States, and recycling facilities [30].
- The European Union’s adoption of the Ship Recycling Regulation (EU SRR) in November 2013, which mandated that EU-flagged commercial vessels above 500 gross tons must be recycled in one of a list of approved ship recycling facilities that maintain safe and environmentally sound practices [31].

Although the bulk of commercial ship breaking takes place in the countries listed above, the United States does have several ship recycling facilities that primarily service vessels from the U.S. Navy and U.S. Department of Transportation Maritime Administration (MARAD) [23]. This also includes the dismantling of the U.S. Army Corps of Engineers’ STURGIS, the first ever floating nuclear power station, which took place from 2015 to 2019. Between 2015 and 2018, the Army Corps decommissioned the deactivated nuclear reactor and vessel and safely removed all associated radioactive waste. By the end of 2018,
the vessel was towed to the Port of Brownsville where it was able to be entirely recycled [24]. While the STURGIS provides one useful model for managing the end-of-life for a vessel integrated with a nuclear reactor, there is a key distinction between how the U.S. military disposes of its nuclear waste compared to the commercial nuclear sector. This brings up some key questions such as where a commercial maritime reactor would be sent after decommissioning, even if the vessel it served could be recycled normally. Additionally, lessons have been learned over decades of decommissioning experience that could be useful for maintaining separation between onboard nuclear and maritime systems. Finally, an essential question is who would pay for vessel decommissioning. Today, commercial reactors in the United States and United Kingdom pass these costs on to ratepayers. One might imagine that in a maritime setting, these costs would ultimately fall on the vessel owner and operator.

6.3. Existing Decommissioning for Naval Reactors

The U.S. Navy has launched over 200 nuclear-powered submarines, aircraft carriers, and cruisers. Decommissioning these vessels generally involves “defueling the reactor, deactivating the ship, removing the reactor compartment for land disposal, recycling the remainder of the ship to the maximum extent practical and disposing of the remaining non-recyclable materials.” Known as the Ship-Submarine Recycling Program (SRP), this process takes place at the Puget Sound Naval Shipyard (PSNS) in Bremerton, Washington and began in 1986. Here, reactor compartments are removed from ships, which includes the reactor vessel, steam generators, pumps, valves, and piping. Before the reactor is removed, it must be deactivated. Fuel is removed from the reactor core, fluids are drained from piping systems, pipes are sealed, and electrical components are depowered. After deactivation, the reactor compartment is cut from the hull of the ship and completely sealed with welded steel plates. The result is a compartmentalized, self-contained package that is fit for transportation to a disposal site. Once removed, reactor compartments are shipped to the Hanford Site in Washington and SNF is shipped to the Naval Reactor Facility at INL in Idaho Falls. By defueling the reactor, over 99% of radioactivity within the nuclear-powered vessel is removed. The rest of the vessel can then be further broken down and certain portions recycled [25].

Dry dock capacity has limited the ability of the U.S. Navy to keep on schedule for naval reactor decommissioning. This is particularly true regarding the decommissioning efforts for the U.S.S. Enterprise, the first U.S. nuclear-powered aircraft carrier. As a part of a 2014 Puget Sound Naval Shipyard and Intermediate Maintenance Facility (PSNS & IMF) study, the U.S. Navy proposed an alternative plan to complete the dismantling and disposal of ex-Enterprise while freeing up dry dock capacity. Under this proposal, fuel would be removed and handled by the U.S. Navy, while the remainder of the decommissioning process would be contracted out to a commercial shipyard. The U.S. Navy projects this alternative approach could reduce costs and worker radiation exposure while also improving execution schedule. A more detailed outline of this process can be found in the Environmental Impact Statement/Overseas EIS/OEIS) for the U.S. Navy's Disposal of Decommissioned, Defueled Ex-Enterprise (CVN 65) and Its Associated Naval Reactor Plants, which was published in August 2022 [29].
7. Summary of Regulatory and Licensing Gaps

The table below presents a concise summary of the key gaps and corresponding recommendations resulting from the introductory review of the regulatory and licensing landscape for FNPPs conducted by the MNAG. This review aims to highlight the important aspects of the current regulatory framework and propose actionable steps to streamline and enhance the licensing process, helping the effort for the safe and efficient deployment of FNPPs. The findings of the MNAG emphasize the necessity for evolving regulations that are robust and adaptable to the unique challenges posed by maritime nuclear applications.

Table 2: Summary of key gaps and corresponding recommendations emerging from the initial examination of the regulatory framework for floating nuclear power plants (FNPPs).

<table>
<thead>
<tr>
<th>Gaps</th>
<th>Description</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need to reduce licensing cost and timeline</td>
<td>Comprehensive design certification assessments alone have been known to incur costs of up to $100 million, while site-specific combined operating licenses range between $25 and $50 million, excluding additional expenses from NRC staff inquiries. The licensing process typically spans at least five years, and it is probable that certification for any new Advanced Reactor Design intended for maritime applications will require even more time.</td>
<td>Engage with regulatory bodies to recognize the current efforts been made to expedite this process and track future developments in this field. Further examinations could be undertaken to analyze the projected timeframe and identify the remaining key milestones required for the successful introduction of the chosen reactor technology to the market.</td>
</tr>
<tr>
<td>Absence of an international licensing authority and process</td>
<td>In the absence of a centralized international authority, nuclear-powered maritime vessels may encounter a complex web of national regulations to navigate. Each country could have its own set of criteria dictating whether these vessels are permitted to enter its waters or dock at its ports. Consequently, a situation may arise where a ship compliant with one country's regulations is deemed non-compliant by another.</td>
<td>Urge the IMO to collaborate with various nuclear regulatory organizations, such as the International Atomic Energy Agency (IAEA) and national regulatory agencies, to develop an international licensing process.</td>
</tr>
<tr>
<td>Internationally recognized classification authority and procedure for nuclear-powered ships</td>
<td>The classification of an FNPP represents a crucial stage in demonstrating to the international community the commercial viability of a system.</td>
<td>Partner with the International Association of Classification Societies (IACS) to foster the development of a Maritime Classification Framework for FNPPs. This framework will serve as a valuable reference for IACS members, guiding their future classification efforts in the FNPP domain.</td>
</tr>
<tr>
<td>Gaps</td>
<td>Description</td>
<td>Recommendation</td>
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<td>Integrating maritime security with nuclear security</td>
<td>The intersection of maritime operations and nuclear materials necessitates heightened security measures. The potential interception, theft, or sabotage of nuclear materials at sea could result in catastrophic environmental, political, and human consequences. By ensuring harmonization of both maritime and nuclear security protocols, a comprehensive approach can be taken to proactively address and respond to potential threats. This reinforces the safety and security of international waters and the global nuclear landscape.</td>
<td>Engage with the maintainers of the INF Code and the ISPS Code for further clarification on the possible gaps in the international legal framework for physical security of FNPPs.</td>
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<td>International Nuclear Transportation Framework integrated with Nuclear Maritime Applications</td>
<td>FNPPs present unique challenges due to their mobility and the fact that they operate in international waters, distinguishing them from land-based counterparts. Establishing an international nuclear transportation framework for FNPPs is crucial to ensure standardized safety, security, and environmental protocols that can be universally adopted by all nations. This framework would facilitate seamless cross-border transportation, refueling, waste management, and decommissioning activities, while effectively preventing or appropriately addressing potential maritime nuclear incidents.</td>
<td>Engage with the IAEA Transport Safety Standard Committee and the World Nuclear Transport Institute to incorporate FNPPs in their efforts.</td>
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<td>Scale EPZ size requirements based on specific design characteristics and site-specific considerations</td>
<td>Establishment of an EPZ for SMRs that can be adjusted based on various factors, such as the outcomes of a hazard assessment, the technology and its unique features, specific design criteria, and in some cases, policy considerations.</td>
<td>Analyze the IAEA safety requirements and methodology for determining EPZ size and recommend areas of improvements.</td>
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<td>End-of-life framework for FNPP</td>
<td>Individually, both decommissioning nuclear reactors and decommissioning maritime vessels involve extensive lists of regulatory considerations. However, when these technologies are combined, they necessitate the development of new and more complicated end-of-life processes. These processes aim to tackle critical issues such as nuclear waste management and vessel scrapping.</td>
<td>Collaborate with Naval Reactors, a leader in launching over 200 nuclear ships and engaging in decommissioning processes. Learn valuable lessons and establish processes to emulate with FNPPs.</td>
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<td>Restrictions of port access for FNPP</td>
<td>Port access was frequently recognized as a major logistic concern which could highly impact the FNPP’s profitability and utilization capabilities.</td>
<td>Establish a unified international framework, in close collaboration with the IMO and the IAEA. This framework will serve as a comprehensive guideline, outlining standardized safety, security, and environmental benchmarks for FNPPs. By doing so, it will enable ports worldwide to consistently assess and grant access to FNPPs based on universally accepted criteria.</td>
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The successful deployment of nuclear technology for maritime applications has major potential to assist in the pursuit of net-zero carbon emissions. Some features of the marine construction sector, such as reduced construction cost and time and flexibility in siting and redeployment, when combined with the benefits associated with nuclear, make it a near-term option for meeting future energy needs, even in some of the hardest-to-abate sectors. By leveraging modular shipyard manufacturing, the nuclear industry can achieve significant cost and schedule reductions, increased productivity, and improved quality control. However, the new tools being developed need to overcome many of the major hurdles that have historically hindered the progress of the nuclear sector.

The successful implementation of marine nuclear technology will depend on the establishment of a comprehensive and robust regulatory framework. This framework should effectively address safety, environmental and security considerations, while simultaneously fostering innovation, paving the way for the successful deployment of floating nuclear assets, and ensuring they can play their significant role in reaching decarbonization targets. The evaluation of licensing, siting, construction, and operational factors will be crucial for the successful deployment and operation of marine based nuclear facilities. While there are existing suggested regulations and guidelines, advanced nuclear reactors will require unique approaches to various challenges. These include siting, compliance with transportation requirements, and decommissioning, all of which will require coordination between nuclear and maritime regulators.

Siting factors, including commercial demand, environmental factors, and safety and security considerations, have already been identified by previous literature (IAEA safety series etc.) but require careful re-evaluation to bring them in line with modern regulations and standards. To ensure safe and efficient operation, various scenarios, including transportation, maintenance, and refueling, should be considered. The EPZ remains important, even in offshore operations, to ensure the safety and preparedness of communities surrounding the nuclear power plant throughout the lifecycle of floating nuclear assets. However, as technology has advanced, the appropriate size of EPZs is now being re-evaluated, particularly for ARDs with inherent safety features. Similarly, established regulatory frameworks for waste management and decommissioning should be reviewed and adapted considering technological advancement.

A number of reactor designs that could be suitable for marine environments are being developed in the USA (ARDR, RR, etc.), and therefore it is possible that FOAK licensing cases may be submitted to U.S. regulatory bodies. However, international collaboration between key stakeholders such as country regulators will be crucial to harmonize standards. This partnership has already begun to gain momentum and is vital for promoting knowledge sharing and driving regulatory change. By bringing essential stakeholders together to lay the foundation for an effective and supportive regulatory environment, the full potential of marine nuclear technology can be realized.

New nuclear technologies that are appropriate for maritime offers a true game changer for the international ocean transportation industry, responsible for moving over 80% of global trade. As the international shipping industry moves towards a zero emissions future it will need a technological game changer to allow it to maintain its margin while keeping costs to consumers low. Unlike all other options for decarbonized shipping, advanced nuclear can provide real benefits to the shipping industry.

By implementing the proposed action and showcasing strong leadership, the challenges associated with marine nuclear technology can be effectively addressed, leading to its successful deployment and operation while ensuring safety and sustainability.
9. References


