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# Maritime Nuclear Applications Group (MNAG): Introductory Review of the Maritime Nuclear Regulatory Landscape

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## REVISION LOG

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## EXECUTIVE SUMMARY

The successful deployment of nuclear technology for maritime applications, including the ability to provide energy to land-based projects at ports, has the potential to assist the International Maritime Organization's pursuit of 2050 targets while simultaneously bringing low-cost nuclear power closer to where it is needed.

The benefits of low-cost nuclear power include, but are not limited to, effective resource extraction and processing, more efficient and productive industrial applications through electrification, and increased energy abundance. In addition, the maritime sector presents unique opportunities for nuclear. 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.

This work also supports the recently issued nuclear Executive Orders (EOs). Specifically, EO 14299, "Deploying Advanced Nuclear Reactor Technologies for National Security", and EO 14300, "Ordering the Reform of the Nuclear Regulatory Commission," by ensuring the rapid development, deployment, and use of advanced nuclear technologies; and increasing the deployment of new nuclear reactor technologies, such as Generation III+ and IV reactors, modular reactors, and microreactors to support America leading the commercialization of affordable and abundant nuclear energy.

However, the new technologies being developed must meet the requirements that are particular to the various types of maritime applications.

Whether nuclear technologies for maritime applications are successfully implemented will depend on how the regulatory frameworks for the nuclear and maritime sectors enable their use and deployment. The frameworks must simultaneously and effectively address safety, environmental, and security considerations, while enabling developers to propose the use of proven, innovative approaches from both sectors to be proposed.

While there are existing regulations and guidelines for both commercial nuclear power plants and the maritime sector, the combining

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of these two sectors to deploy next-generation nuclear reactor technologies, including advanced nuclear reactors in marine environments, will result in specific challenges related to siting, compliance with transportation requirements, waste management, and the conduct of decommissioning. Addressing these issues will require coordination between nuclear and maritime regulators.

The preliminary conclusions of the Maritime Nuclear Applications Group (MNAG) review emphasize the need to conduct work to adapt/evolve regulatory requirements and guidance to address the unique challenges associated with maritime nuclear applications. This review identified key gaps in the regulatory and licensing landscape for floating nuclear power plants (FNPPs), which are summarized below. Adaptations and evolved practices should emphasize ways to advance:

- Clarity on how to complete consistent licensing at national and international levels, reducing the cost and duration through convergence and, where possible, harmonizing overlapping and contradictory regulatory requirements
- The integration of maritime security with nuclear security
- The integration of the International Nuclear Transportation Framework with nuclear maritime applications
- Acceptable methodologies and practices for implementing an emergency planning basis for maritime-based nuclear facilities that considers unique design characteristics and site-specific issues
- Clarity on an appropriate end-of-life framework for FNPP projects
- The clarification and potential removal of restrictions on port access for FNPPs
- A resolution on uncertainties regarding jurisdiction.

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## ACRONYMS

ACPPNM	Convention on the Physical Protection of Nuclear Material and Its Amendment
AEC	Atomic Energy Commission
BDBT	beyond design basis threat
BRC	Blue Ribbon Commission
CANDU	Canadian deuterium-uranium
CFR	Code of Federal Regulations
CNS	Convention on Nuclear Safety
CNSC	Canadian Nuclear Safety Commission
DBT	design basis threat
DOE	Department of Energy
EPA	Environmental Protection Agency
EPZ	emergency planning (or preparedness) zones
EU	European Union
FNPP	floating nuclear power plant
GDA	generic design assessment
HLW	high-level waste
IACS	International Association of Classification Societies
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
INF Code	Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships
INL	Idaho National Laboratory
ISPS	International Ship and Port Facility Security
LLW	low-level waste
LWR	light-water reactor
MANP	Maritime Applications and Nuclear Propulsion
MNAG	Maritime Nuclear Applications Group
MNPP	mobile nuclear power plant

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NM	nuclear module
NNSA	National Nuclear Safety Administration
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
ONR	Office of Nuclear Regulation (U.K.)
SMR	small modular reactor
SOLAS	Convention for the Safety of Life at Sea
SUA	Convention for the Suppression of Unlawful Acts Against the Safety of Maritime Navigation
TNM	transportable nuclear module
TNPP	transportable nuclear power plant
TRANSSC	IAEA Transport Safety Standard Committee
TTEG	technical expert group
U.K.	United Kingdom
U.S.	United States
WG	working group
WNTI	World Nuclear Transport Institute

## 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, 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 maritime applications. MNAG fulfills this mission through strategic studies of potential maritime applications, by identifying domestic and international legal and regulatory hurdles, by cataloging and sharing relevant information resources, and by collaborating and coordinating with global stakeholders of all types. MNAG aims to support near-term field demonstrations of advanced reactor technologies in maritime settings by partnering with the United States (U.S.) Department of Energy's (DOE) NRIC. This document prioritizes a U.S.-centric approach while actively incorporating international perspectives to ensure a there is a comprehensive understanding and application of nuclear technologies for maritime applications.

MNAG's membership includes representatives of organizations and firms from the:

- Nuclear industry: structure and system designers, vendors, national laboratories, policy nonprofits, academia
- Maritime sector: vessel owner/operators, classification, maritime law, insurance, flag states
- U.S. government: independent regulatory organizations and executive branch departments
- Environmental sector: 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, and identifies the key parties that will be involved in future regulations. Current applicable rules have been described, and the regulatory requirements for both nuclear and maritime industries have been examined. This 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 established 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 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 maritime deployment technologies, including shoreside stationary systems, offshore stationary platforms, 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 this process is developing requirements and licensing structures that ensure safety and security measures remain highly reliable without unreasonably hindering advanced nuclear deployments. The current efforts, for the most part, focus on land-based facilities. Efforts for maritime-based nuclear technologies and projects have not yet begun in earnest.

International collaboration and funding will play a role in realizing the potential of nuclear technologies in a maritime deployment environment. Given the global nature of maritime activities, it is vital for nations to work together to harmonize or leverage common regulatory requirements and industry standards to the extent practicable. This collaboration can, as a start, facilitate knowledge sharing, the exchange of best practices, and the development of internationally recognized guidelines. Adequate funding (government and commercial), both for R&D efforts and to drive regulatory developments, will be crucial to reaching these goals.

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

In addition, this work supports the recently issued nuclear Executive Orders (EOs). Specifically, EO 14299, “Deploying Advanced Nuclear Reactor Technologies for National Security”, and EO 14300, “Ordering the Reform of the Nuclear Regulatory Commission,” by ensuring the rapid development, deployment, and use of advanced nuclear technologies; and increasing the deployment of new nuclear reactor technologies, such as Generation III+ and IV reactors, modular reactors, and microreactors to support America leading the commercialization of affordable and abundant nuclear energy.

### 1.3 New IAEA Terminologies and Proposed Definitions

An IAEA Transport Safety Standard Committee (TRANSSC) technical expert group (TTEG) developed and proposed the following definitions in April 2023 to assist the agency in upcoming work to explore the interpretation of nuclear safety and security standards for transportable, mobile, and floating nuclear power plants. Various departments at the IAEA are working to define various maritime applications, including FNPPs, with no consensus at the time of this writing; the work is ongoing.

The IAEA has a process for instituting new terms into its glossary for use in publications, and this process will determine how the proposed terms will be addressed. In the interim, the proposed terms are:

- Transportable nuclear module (TNM): 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): A nuclear power plant permanently mounted on or integrated into a conveyance other than a maritime vessel to produce energy. This definition also applies to a nuclear power plant that only provides energy to the conveyance.
- Floating nuclear power plant (FNPP): A nuclear power plant permanently mounted on or integrated into a maritime vessel to produce energy. This definition also applies to a nuclear power plant that only provides energy to the conveyance.

The following IAEA-recommended definitions continue to apply (definitions stem from the *IAEA Nuclear Safety and Security Glossary* [IAEA 2022c]):

- Nuclear power plant (NPP): An installation designed to produce energy from a controlled nuclear reaction.
- Nuclear module (NM): A component of a nuclear reactor that contains nuclear material or radioactive waste.
- Nuclear material: Nuclear material or radioactive waste that is packaged in accordance with Special Safety Requirements No. 6 is out of the scope of this study (IAEA 2012). Nuclear batteries, such as a radioisotope thermoelectric generator, are also out of the scope of this report.

In addition to the work already being done at the IAEA, the following considerations and conditions of maritime applications will need to be addressed:

- Conduct of operations for TNMs, FNPPs, and MNPPs
- Use of on-site refueling versus use of site-replaceable factory-fueled sealed reactors
- Use of systems and components that are necessary for the proper functioning of safety and security features at the site of operation.

## **2. REGULATORY OVERVIEW**

This report focuses on regulatory considerations, and the evolution of relevant protocols in the U.S. and internationally. This report covers topics relevant to nuclear safety, security, and transport; traces the development of nuclear regulations in the U.S.; and investigates the current structure of costs and timelines within the regulatory process. Additionally, it discusses the regulatory framework, compares aspects of nuclear regulations worldwide, and explores the specifics of licensing nuclear-powered maritime systems. The report provides an overview of the maritime classification process (i.e., not the nuclear industry classification) and the IMO Safety Code for Nuclear Ships and examines the security implications associated with FNPPs.

Central to the discussion of nuclear regulations in the U.S. are the Code of Federal Regulations (CFR) titles that govern NPPs and equipment: Title 10 CFR Part 50 (10 CFR 50) and 10 CFR 52. Part 50, “Domestic Licensing of Production and Utilization Facilities,” outlines the licenses, certifications, and regulatory approvals required for the operation and construction of NPPs. Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants,” provides a framework for the U.S. Nuclear Regulatory Commission (NRC) to issue licenses for the construction and operation of an NPP under a combined license, which references standard design certifications and early site permits. These regulatory structures play a pivotal role in shaping the nuclear regulatory landscape, offering a detailed process for ensuring safety and compliance in the nuclear sector.

### **2.1 Nuclear Reactor Safety**

The safety performance of a nuclear reactor system relies on a set of overlapping and reliable provisions to support the fundamental safety functions of control, cool, and contain, which are to be met always. These safety functions must be met during the normal operation of the facility, when there are malfunctions in the facility, when external events trigger adverse events in the facility, and during malevolent acts. The ultimate objective of meeting these safety functions is to demonstrate that the radiological consequences for workers, the public, and the environment are appropriately prevented or mitigated to an acceptable level. In most, if not all countries, the limitation of risks can also extend to consequences from exposure to hazardous materials. The characteristics of acceptable or reasonable risk are normally captured in law and

enforced through a regulatory framework that is focused on the safe conduct of activities subject to regulation. For more information regarding security and safeguards, refer to Section 3.

The key safety functions of control, cool, and contain are described further:

- Control: Reactor power (i.e., reactivity and heat generation) must always be under control within acceptable limits during startup, operation, shutdown, and refueling operations.
- Cool: The heat generated by the reactor must always be managed to prevent failure of the fuel or failure of other features that are important to safety. This means that multiple reliable heat removal paths must exist to reject heat to a designated heat sink. Under normal operation, one of these heat sink paths passes through a power conversion system such as a turbine generator. The ultimate heat sink will be either a large body of water or the atmosphere (or a combination of both).
- Contain: A series of nested and robust physical barriers must be maintained such that radioactive substances are contained even if an energetic event causes barriers to fail. In many advanced reactors, the fuel itself is specifically engineered to provide some of these barriers through increased failure tolerance. The objective of well-designed containment features is to ensure that any uncontrolled releases to the environment are prevented or mitigated below regulatory limits.

To ensure a predictable and adequate level of safety, a qualified operator must demonstrate that safety functions will be met through a combination of reliable design features and control measures. To reduce both the need for human intervention and the potential for human error, preference is normally given to well-designed and well-maintained engineering features that have been proven to be reliable and effective. Engineered design features are normally supported by other reliable systems, such as electric power, cooling, and pressurized air, which may be required for the safety functions to be carried out or for the state of systems to be controlled and monitored. Other common practices in nuclear design that support system reliability include having systems physically separated, safety features independent of one another in case one fails, a diversity of methods and equipment, and a redundancy of systems to reduce the risk of common-cause failures that could impede the performance of a safety function. These techniques emphasize systems that are important to safety, but they can also be applied to support systems for which reliability is desired. In addition, designs must incorporate defense-in-depth combined with sufficient engineering and operating margins to account for potential safety performance uncertainties that may arise from an incomplete understanding of reactor system behavior. These design principles are focused on ensuring that the objectives of safety functions are achieved, which is consistent with regulatory requirements. This approach underlines that those seeking to deploy nuclear energy technologies are committed to meeting established safety standards through thoughtful design and operational guidelines.

Regulating the use of nuclear materials and the production and use of nuclear energy is the responsibility of the regulatory body that a government forms and authorizes to issue licenses and compel compliance with requirements. As part of its function, the regulator independently assesses (and, in certain cases, independently verifies) how a given nuclear reactor system design has been demonstrated to perform the necessary safety functions with reasonable assurances to protect public health, safety, and the environment (Beckjord et al. 2003).

Approximately 80% of all commercial nuclear reactors in operation are light-water reactors (LWRs) that use low-enriched uranium fuel (3.5 to 5% U-235) and are cooled with water (IAEA 2022a). Some water-cooled designs can use natural uranium at 0.7% enrichment. Critical safety functions in water-cooled reactors, as part of a comprehensive defense-in-depth strategy, are achieved through a combination of active and passive features and systems. These include

reactor shutdown, cooling, and electrical systems, as well as the actions of highly qualified operators.

Safety always comes first. Advanced (or modern) Generation-IV reactor technology is increasingly leveraging inherent and passive safety features to reduce the degree of human intervention needed if an event occurs in the reactor. However, these safety features in conjunction with a well-trained staff will maintain the highest operational safety standards.

## **2.2 Regulation of Nuclear Energy Around the World**

### **The Role of the International Atomic Energy Agency and Its Impact on Member States**

The IAEA is an independent, intergovernmental, science- and technology-based organization in the United Nations family that serves as the global focal point for nuclear cooperation.

The IAEA works with its member states and multiple partners worldwide to promote the safe, secure, and peaceful use of nuclear energy. Through technical cooperation programs the IAEA assists its member states and promotes the exchange of scientific and technical information between them. The IAEA's work also includes setting the framework for cooperative efforts to build and strengthen an international nuclear safety and security regime and verifying states' fulfillment of their nonproliferation undertakings under the Treaty on the Non-Proliferation of Nuclear Weapons, which designates the IAEA as its verification agency.

In accordance with the IAEA's significant role in promoting nuclear safety and nonproliferation, it is important to note the unique position of the U.S. While the U.S. conducts its own rigorous nuclear verification activities and maintains a comprehensive national framework for nuclear security and safety, it actively engages in most IAEA programs and international efforts. This dual approach underscores the commitment the U.S. has to global nuclear safety standards while also ensuring its national interests and security protocols are upheld. The collaboration between the U.S. and the IAEA exemplifies a balance between national sovereignty in nuclear matters and the benefits of international cooperation and oversight.

The IAEA promotes adherence to and implementation of international legal instruments on nuclear safety that are adopted under its auspices. These include the Convention on Nuclear Safety (CNS) and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, as well as the two conventions that are the basis for the international emergency preparedness and response framework: the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency.

Specific to the CNS, member states are strongly encouraged to commit to participating as a matter of transparency and commitment to the goals of the CNS, which aims to commit contracting parties operating *land-based* civil NPPs to maintaining a high level of safety by establishing fundamental safety principles to which the states subscribe. The CNS is based on the parties' common interest in achieving higher levels of safety that will be developed and promoted through regular meetings. It obliges parties to submit reports on the implementation of their obligations for peer review at meetings that are normally held at IAEA headquarters. This mechanism is the main innovative and dynamic element of the CNS. The national report submitted to the CNS includes elements from all parties in the member states that have reported on how their activities are consistent with the CNS.

Over and above the broader conventions, a major support the IAEA provides member states—to strengthen nuclear safety and security—is its peer review and advisory services (IAEA 2022b). These peer reviews and advisory services aim to help countries in their application of IAEA safety standards and security guidance, which serve as the global reference for achieving and maintaining a high level of nuclear and radiation safety and security in all fields, such as energy generation, medicine, agriculture, industry, and research.

## Overview of the IAEA Safety Framework

The typical IAEA Safety Standards and Guides have this as part of their forewords (IAEA 2018a):

*The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property, and to provide for their application.*

*IAEA safety standards establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur.*

*The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories:*

**Safety Fundamentals:** *present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements.*

*It is important to understand that Safety Fundamentals apply to all parties in a Member State, such as government, regulators and the organizations conducting activities that introduce radiation risks.*

**Safety Requirements:** *requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework.*

**Safety Guides:** *provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety.*

The forewords also include how IAEA safety standards and safety guides are used:

*Regulating safety is a national responsibility, and many States have decided to adopt the IAEA's standards for use in their national regulations. For parties to the various international safety conventions, IAEA standards provide a consistent, reliable means of ensuring the effective fulfilment of obligations under the conventions. The standards are also applied by regulatory bodies and operators around the world to enhance safety in nuclear power generation and in nuclear applications in medicine, industry, agriculture and research. Safety is not an end in itself but a prerequisite for the purpose of the protection of people in all States and of the environment—now and in the future. The risks associated with ionizing radiation must be assessed and controlled without unduly limiting the contribution of nuclear energy to equitable and sustainable development. Governments, regulatory bodies and operators everywhere must ensure that nuclear material and radiation sources are used beneficially, safely and ethically. The IAEA safety standards are designed to facilitate this...and the IAEA "encourages" all Member States to make use of them.*

It is important to understand that the consensus nature of developing safety standards and safety guides limits precision in the way requirements and guidance are articulated. Thus, for the purposes of regulatory assessment and decision making in each member state, the standards and guides are generally not detailed enough. They must be supplemented with the local requirements and guidance necessary to meet member state statutory requirements. The additional details also consider locally accepted practices such as industry standards.

## **The Evolution of Nuclear Regulation in Specific Member States**

Over the course of several decades, nuclear regulation in most nations has undergone substantial change to clarify the licensing processes and requirements for a small range of reactor technologies. Many countries rely on large LWR technologies; however, many countries also have significant experience employing non-LWR technologies. For example, the United Kingdom (U.K.) developed and operates advanced gas reactors, and countries of the Canadian deuterium-uranium (CANDU) Owners Group collaborate in the long-term operation of pressurized heavy water reactors. As another example, the Russian Federation has developed indigenous sodium- and lead-cooled fast reactor technologies and integrated key aspects of these technologies into their regulatory framework. In each case, 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 using guidance derived from real-world operating experience. This approach includes supporting pathways for alternate proposals with a credible and relevant body of evidence that demonstrates that the performance of the proposed technology will be equivalent to or better than the status quo.

Significant nuclear accidents, such as Three Mile Island, Chernobyl, and Fukushima, have significantly impacted the safety objectives underpinning regulations around the world. These accidents reinforced that nuclear safety is a global issue; radiation, being invisible and poorly understood by most people, instills a specific apprehensiveness in the public that influences their support for projects, especially if they feel they cannot trust the operator of the facility. These accidents have had a lasting effect on the entire industry, which emphasizes community

engagement and a strong safety culture as key factors to change public perception. The IAEA established the CNS in 1994 to address the issue of safety. 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 in the places where NPPs operate. 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 (International Nuclear Safety Advisory Group 1999).

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 both philosophically and practically. Philosophically, there are diverse approaches to implementing nuclear safety, such as by utilizing a technology-specific or technology-neutral framework, which impacts how risk is factored into decision making, in addition to how prescriptive versus performance-based requirements are involved. On the other hand, member states have practical variations in their regulatory implementations; for example, there are varying frequencies for the license renewal of nuclear reactors. For instance, license durations in Canada are set by their regulator and were based on the historic performance of the licensees, but now their NPP license durations are becoming standardized to occur every 10 years to coincide with a 10-year periodic safety review frequency. France has a 10-year renewal for this reason. The U.S. has a 20-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 if member states agreed on and employed international best practices, enabling greater alignment and cooperation among national regulators. Historically multiple nations - such as the United States, France, Japan, Russia, Canada, the United Kingdom, and South Korea - have collaborated on the design, construction, and deployment of nuclear reactors. Despite this cooperative effort, there has been a profusion of design concepts. Streamlining the design process would reduce costs, shorten development timelines, and alleviate certain licensing burdens. Also, vendors could then be licensed to sell a standardized design used globally. Nonetheless, to achieve a standardized international deployment paradigm, and to prevent the need for unnecessary duplicative review efforts, there needs to be greater understanding, agreement, and eventually alignment between diverse nuclear regulators. This can be achieved through greater leveraging of the IAEA safety standards and guides, and by supplementing them with details that regulators agree upon regarding specific regulatory requirements and guidance.

### **United Kingdom—Nuclear Regulation**

In the U.K., the Office for 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. Through the consolidation of several government agencies that previously managed nuclear installations, security, and safeguards, the ONR aims to effectively license new NPPs and supervise the expanding nuclear industry in cooperation with other government agencies.

The ONR employs a primarily objective-based regulatory strategy supplemented by prescriptive industry standards set by the authorized entity. This approach is designed to maintain the safety of nuclear facilities within the U.K., which aids operational and safety guidelines in meeting stringent requirements for protection and reliability. The ONR sets high-level regulatory expectations while allowing applicants flexibility 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 duty holders permission to perform 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 examine updates to the safety case based on new information from design and safety assessments. 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 nonbinding, the GDA significantly contributes to the ONR's evaluation of an applicant's safety case. However, only a recommendation from the U.K. Department for Energy Security and Net Zero, based on reasonable knowledge that a project will proceed at a specific site, can trigger a GDA.

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

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. Other nation states, including the British Overseas Territories, are in the process of passing similar legislation to support the advancement of floating nuclear power as a component of decarbonizing 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 (Beckjord et al. 2003).

The CNSC's regulatory framework is, to the extent practicable, technology neutral but draws from domestic and global experience, as well as from 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 several projects involving both next-generation water-cooled reactors and advanced reactor designs. The licensing process uses the existing requirements, and the proponent can propose and justify alternative approaches for achieving the requirements.

The 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 the importance of 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 preclicensing vendor design review. It is important to note that the findings of the vendor design review 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)<sup>1</sup> 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 the operation of CANDU facilities and supplemented with U.S. practices and key requirements and guidance from IAEA safety standards and guides.

Since the framework's establishment, various practices from each country China has imported technologies from have been incorporated into it and adapted, and these practices have been honed 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.

### **Russia—Nuclear and Maritime Regulation**

In Russia, the regulation of nuclear energy is overseen by the Federal Environmental, Industrial, and Nuclear Supervision Service, also known as *Rostekhnadzor*. This agency enforces compliance with safety standards and regulations, ensuring the safe operation of nuclear facilities within the country. Russia's approach to nuclear regulation emphasizes both the development of advanced nuclear reactor technologies, including sodium- and lead-cooled fast reactors, and the integration of these technologies within its regulatory framework. Russia has actively participated in international nuclear safety conventions and with the IAEA. Furthermore, Russia's unique position in having deployed commercial atomic ships and FNPPs highlights its experience in utilizing nuclear energy. This aspect of Russia's nuclear industry reflects a broader strategy to harness nuclear power for diverse applications while incorporating regulatory oversight to maintain safety and security standards (IAEA 2013).

## **2.3 Distinguishing Between Regulatory Frameworks**

In general, regulatory frameworks used to evaluate the safety of NPPs and grant licenses for new plants can be categorized by three main characteristics: technology, risk, and the

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<sup>1</sup> Please note the distinction between China's Ministry of Environmental Protection's National Nuclear Safety Administration (NNSA) and the U.S. Department of Energy's National Nuclear Security Administration.

degree to which requirements are prescriptive or performance based (Beckjord et al. 2003). This categorization applies to many other industries where risk can have broad societal impacts.

## **Technology**

Some frameworks are applicable to all types of nuclear reactor technologies, whereas some are specific to a subset. Technology-specific regulatory requirements are tailored to a specific reactor technology, establishing performance standards against which applications are evaluated. This type of framework ensures regulations are applied uniformly and reduces the decision-making burden on regulators. However, a technology-specific framework limits a country's ability to efficiently adopt new technologies.

## **Risk**

When establishing requirements commensurate with risk, the probability and potential consequences of key events are assessed. In some cases, regulators also require risks to be addressed deterministically because they are deemed to be particularly important to safety in the design of the plant. For example, station blackout and malevolent acts are risks assumed to have a probability of one (100% chance of occurring). Regulatory frameworks consider risk factors to ensure that public health and safety are adequately protected, and these risk factors can be articulated as qualitative safety goals and objectives or can be quantified, such as dose limits to vulnerable members of the public.

## **Performance-Based or Prescriptive Requirements**

Performance-based requirements establish outcomes that must be achieved, but there are many ways to achieve them, if there is sufficient evidence to support that the proposed method will perform commensurate with safety requirements. For example, a regulator may specify that a reactor must have the ability to achieve a controlled shutdown within a specified timeframe after an event occurs. A performance-based requirement offers designers latitude to use different approaches to achieve this goal, such as using 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 would be available.

A prescriptive requirement establishes an outcome to be achieved but also prescribes what method is acceptable to achieve that outcome, as well as the 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 using shutoff rods within a specified time limit. In this case the designer has fewer options for selecting an approach, unless they make a specific case to the regulator seeking an exception to the requirement.

In the U.S., 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. 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. When developing each framework, it is crucial to consider the implications of wording, structure, readability, and eloquence in terms of intended 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 maritime-based nuclear facilities, all the above factors need to be considered such that the requirements are readily understood but also provide the necessary safety assurances to the public and key stakeholders.

## **2.4 Development of Nuclear Regulation in the United States**

Since the establishment of the Atomic Energy Commission (AEC) in 1946 and the enactment of the Atomic Energy Act in 1954, nuclear regulation in the U.S. has experienced significant transformations. These changes have been shaped by advancements in NPP design and operational knowledge, as well as 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 several strategies to ensure reactor safety in the early nuclear reactor designs:

- Using 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.
- Using multiple overlapping layers of prevention and mitigation (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 if other engineered barriers failed during an accident.
- Utilizing significant conservatisms, such as robust engineering design margins, to accommodate for uncertainties in the performance of the design.
- Siting in sparsely populated areas to reduce the 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 the 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 the technology chosen for commercialization. This shift toward 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 DOE, while nuclear regulation was assigned to the newly formed and independent U.S. 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 (Beckjord et al. 2003).

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 U.S. In the decades following, safety practices were refined based on experience and lessons learned and applied to nuclear reactors in a controlled manner. This refinement in safety practices was further influenced by the expansion of reactor capacities and the evolution of siting policies that have impacted the regulatory requirements for nuclear power facilities.

In the context of new advanced reactor designs that do not necessarily apply to existing reactor standards, in 2018 Congress tasked the NRC with developing an additional rule in the form of 10 CFR 53, “Risk-Informed, Technology-Inclusive Regulatory Framework for Commercial Nuclear Plants.” 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.

## **2.5 Licensing in Consideration of Floating Nuclear Power Plants**

In some cases, it is likely that a stationary maritime-based nuclear facility could be deployed at the shore in a single country using the existing licensing process for land-based facilities, with a few adjustments for the site characteristics. Licensing, defined as the written authorization by regulatory bodies for the conduct of regulated activities such as construction and operation, ensures that facilities meet safety and environmental standards. Currently, the licensing process for maritime-based facilities, such as an FNPP, is not clear, particularly where such a facility will need to operate between international boundaries. Uncertainty regarding the licensing process is an impediment to the timely deployment of nuclear technology for maritime applications. Concerns specific to FNPP licensing include:

- The absence of a recognized process a country can use to adopt or accept the results of a country-of-origin regulator’s decision or mechanism to approve, license, supervise, and enforce requirements upon the FNPP, which hampers the ship’s acceptance in foreign ports. This points to a likely preference for bilateral arrangements between countries for FNPP deployment.
- The absence of a specific licensing mechanism for civilian reactors installed on commercial ships. Some licensing efforts have occurred, with a notable example in the U.S. from the NS *Savannah*, which was launched in 1959 and operated until 1972, visiting 45 foreign and 32 domestic ports over its operating timeframe. Additionally, in 1982 the NRC approved a manufacturing license for Westinghouse to build up to eight Offshore Power System plants, but Westinghouse abandoned the effort in 1984.
- Uncertainty with navigating new licensing approaches, such as those proposed in 10 CFR 53 in the U.S.

In the U.S., the proposed NRC regulations in 10 CFR 53 are 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 the use of Part 53 in real-life projects:

- Include special applications of nuclear power explicitly in Part 53, such as floating nuclear power and maritime propulsion, to expand the technological scope of the licensure procedure.
- Collaborate with the IMO to align the maritime propulsion requirements in Part 53 with the commercial maritime 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 FNPP 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 the 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.

## 2.6 Overview of Maritime Regulations

Domestic maritime trade and international shipping have been ongoing since the time of early human civilizations; however, the international regulatory regime used today, known as the Convention for the Safety of Life at Sea (SOLAS), was first established by the United Nations IMO in 1914 in response to the 1912 sinking of the RMS *Titanic*. SOLAS addressed the uniform standards of ship designs and equipment to protect life and property from hazards related to international shipping. Since then, many other international conventions have been organized for the harmonization of international shipping codes. The IMO develops and maintains international codes by the regular assembly of signatory member states.

It is the responsibility of the member states to adhere to the IMO codes they ratify, implement them into statutory law, and enforce those established requirements within their jurisdictions.

Ships are registered by national or state administrations, known as flag administrations, whose flag the vessel is entitled to fly. If ships engaged in international voyages do not comply with flag administration requirements, the vessel's certificate of registry may be revoked. Ships carried on heavy-lift vessels may be considered cargo and may need to be included in different regulatory requirements.

Not every flag administration is a member state of the IMO. It is the responsibility of the IMO member states to enforce the compliance of their flagged ships, as well as international vessels that visit, with the maritime law established there. As member states recognize them, the IMO safety codes and standards are generally accepted globally. Port states that find a vessel out of compliance with their established statutory rules have the right to detain the vessel, preventing further operations until the provisions are met.

In addition to the requirements established by the flag administration and port states, any jurisdictional authority may impose design or operational requirements that a maritime unit must

comply with, depending on its operations or activity. It is therefore necessary to understand the scope of operations when considering maritime regulations, as the port states, flag states, or other maritime authorities may impose different or additional requirements. For example, vessels intending to pass through the Suez Canal or Panama Canal must be designed to meet the dimensions of the route, as well as other specific design and operational requirements, according to the Suez and Panama Canal Authorities.

Classification societies are often involved in the effort of verifying compliance with flag administration requirements, otherwise known as statutory requirements. Additionally, regional agreements may be the starting point for international cooperation and subsequent treaties.

### **Maritime Classification**

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 maritime facilities, including ships and offshore structures (IACS 2022). These organizations establish a framework of rules to ensure the structural and operational integrity of vessels and offshore structures, contributing to their safety at sea.

While national authorities, also known as flag authorities, bear the ultimate responsibility for ensuring the safety of ships registered under their flag, many countries have delegated inspections and surveys to authorized classification societies, referred to as recognized organizations. Many flag administrations require their registered vessels to hold a certificate of classification. Classification societies also impose their own set of rules or offer additional, optional standards to which vessels must comply. Vessels meeting all requirements for classification may receive and hold a certificate of classification from the recognized classification society, which may similarly be revoked if classification requirements are not met (Maritime Institute of Technology and Graduate Studies 2023).

Receiving a classification from a society means that a vessel or offshore structure has been evaluated against established rules and standards and met a level of safety and integrity deemed acceptable. However, it is crucial to understand that classification societies are not regulators. Their certification indicates that a design, if constructed and maintained according to approved standards, has the potential to achieve an adequate level of safety performance. For the actual operation, the owner must demonstrate that the construction and ongoing maintenance align with these approved methodologies, ensuring the vessel's physical state continues to meet safety standards. This demonstration of ongoing maintenance to meet safety standards is essential for a vessel if it is to continue to be permitted to operate, reflecting a commitment to maintaining high safety and performance levels throughout its service life.

The IACS is a collection of member classification societies that have met certain criteria of credibility. Its mission is to “establish, review, promote and develop minimum technical requirements in relation to the design, construction, maintenance and survey of ships and other maritime related facilities” (IACS 2022). It carries this out by establishing unified interpretations of statutory regulations and industry standards, or unified requirements, that all IACS members are to incorporate. The IACS is the only nongovernmental organization at the IMO that can contribute its technical expertise to the development and application of rules.

The eleven members of the IACS are listed below. Other classification societies may exist but are not members of the IACS:

- American Bureau of Shipping (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)

Maritime classification standards affecting the design, construction, operation, and inspection of a nuclear facility should be integrated into the overall design and arrangement of its structures, systems, and components before the safety case to be presented to the nuclear regulator is finalized. 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. In this arrangement, it is expected that the national maritime authority and nuclear regulator will share responsibility or otherwise devise authority over the nuclear maritime application to verify and validate both nuclear and maritime safety functions.

In the complex landscape of Russian nuclear maritime operations, the regulation of nuclear ships involves a specific nuclear regulator that collaborates closely with the Russian Maritime Register of Shipping. The process of licensing nuclear vessels, including icebreakers such as those of the *Arktika* class and the cargo ship *Sevmorput*, is intricate and governed by stringent nuclear regulatory standards. The design and approval of new ships undergo a lengthy process, as illustrated by the Akademik Lomonosov FNPP, which faced years of rigorous scrutiny from multiple organizations. Additionally, all of Russia's nuclear icebreaker vessels are managed by Atomflot, a division of Rosatom, which is Russia's state corporation that specializes in nuclear energy, nuclear nonenergy goods, and high-tech products, highlighting the state's direct involvement. This unique structure of state corporation in Russia, introduced in 1999, emphasizes the noncommercial, nonmembership nature of such entities, underscoring the nuanced distinction between commercial usage and state ownership in the context of international maritime conventions.

## 2.7 Plans for Future Classification

Ship classification is an important input into the design, construction, and operation of novel floating maritime and ship designs. A flag administration's input is a necessity for establishing an internationally recognized classification regime or authority for nuclear-powered ships, which will enhance FNPP viability. An internationally recognized classification regime or authority for nuclear powered ships would be harmonized with regulatory processes for nuclear power use. Classification will not only aid in securing investment funding and insurance (protection and indemnity) but also support business opportunities by demonstrating safety certification from recognized organizations.

While global experience in classifying nuclear-powered vessels is limited, the American Bureau of Shipping and Lloyd's Register stand out due to the historical role the U.S. and U.K. have played as pioneers in the development of maritime nuclear technology.

In 2021, the U.K.'s Maritime and Coast Guard Agency initiated a consultation to establish a regulatory framework to support the idea of using nuclear-powered ships to combat air pollution.

The objective was to align this framework with established international standards, such as the IMO's Chapter VIII of the 1974 International Convention for the SOLAS and the 1981 Code of Safety for Nuclear Merchant Ships (or Nuclear Code).

## **2.8 The Nuclear Code of the International Maritime Organization**

The IMO Resolution A.491 (XII) Safety Code for Nuclear Ships (the Code) is recognized internationally for setting safety standards covering a wide spectrum of nuclear merchant ship operations, including design, construction, operation, maintenance, and inspection. While the Code is comprehensive in these areas, it is less clear regarding the salvage and disposal of nuclear ships. This ambiguity highlights the need for further clarification or additional guidelines to fully address these aspects within the framework of nuclear maritime safety. Despite its initial emphasis on light-water pressurized water reactors (PWRs), the Code was purposefully designed to have a periodic review to accommodate evolving reactor technologies, although as of 2023 it had not been updated. This approach ensures that technical advancements in ship design, safety analysis improvements, adaptations to new ship types, adjustments for changing risk levels (such as an increase in nuclear ships in a single port), future codes and conventions, and internationally agreed-upon revised safety standards are incorporated into the Code's framework (IMO 1981).

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 stipulating a requirement to always keep the Code relevant, but it has been neglected since its adoption in 1981; however, Russian nuclear vessels still meet the requirements of A.491 (XII). Proposals to include nuclear power in the agenda of IMO safety committees are expected in 2024. These committees 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. The ability of the Code to evolve facilitates incorporating changes in regulatory practices, such as 10 CFR 50 and 52. The Code specifies system designs to meet safety requirements, specifically for PWRs. Opportunities exist to update the Code to include international standards for FNPPs with advanced reactor designs.

For the Code to be applied to FNPPs, its scope would need to be expanded, and it would need to be reconciled with the applicable safety, security, and safeguards requirements established by the IAEA, which reflect a consensus among its member states.

## **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 considering the maritime components adequately. Given the dynamic nature of siting FNPPs, traditional nuclear security approaches alone cannot ensure their protection. The feasibility of maritime-based facilities will hinge on their ability to adhere to IAEA guidelines for land-based NPPs, their site characterizations, and the path of travel for the facilities to be delivered to

respective sites. This section explores the areas where security protocols in the nuclear and maritime industries need to be linked (Fialkoff 2020).

### **3.1 On-Site Facility Security**

When an FNPP is stationed at a shoreside location or port or is secured offshore in territorial waters, the security elements resemble those used for maritime infrastructure, such as port facilities, or for conventional land-based NPPs; 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. Of near-term importance in the deployment of small modular reactors (SMRs), including those placed in maritime environments, is the need for regulators and the security establishment to clarify what they consider acceptable security-by-design measures. These measures can be combined with an approach that permits facility security to be commensurate with the potential consequences from a malevolent act on workers, the public, and the environment.

### **3.2 Security During Transport**

In its 2013 report on transportable nuclear power plants (TNPPs), the IAEA emphasized the distinctions between fixed-site and transport security. An operable nuclear reactor, particularly one that contains used fuel under transport, represents a different set of security risks and potential consequences from malevolent acts compared to a more traditional transport package containing fuel. 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 more participants there are involved in security, the more complex the security procedures become.

To ensure the highest level of security for FNPPs, it is essential for future international frameworks to incorporate both maritime and nuclear security guidelines, but they should do so in a manner that maximizes effective security performance. This use of multiple guidelines will not only provide a comprehensive safeguarding mechanism but also strengthen international cooperation and shared responsibility in FNPP operation and conveyance. At this point, further efforts are needed to define how this would be done in practice such that both sets of regulations will be met.

### **3.3 Nuclear and Maritime Security Frameworks**

In addition to safety, security and safeguards work is already underway for SMRs and microreactors in general and would need to be expanded to include maritime applications once member states are prepared to meet and share information to inform current work. The Convention on the Physical Protection of Nuclear Material and Its Amendment (ACPPNM) emphasizes the significance of safeguarding nuclear materials and facilities against the potential for proliferation. The ACPPNM also addresses domestic utilization and storage, including additional domestic transportation requirements.

The ACPPNM, via Fundamental Principal G, mandates that security requirements be adaptable based on the 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, preventing theft or sabotage, and efficient incident response. Additional guidelines cover computer security, personnel dependability, and contingency planning (Fialkoff 2020). For member states, security

is an important area of consensus that needs to be reflected, to the extent practicable, in domestic requirements to enable the greater standardization of SMRs and maritime-based facilities, and to ensure regulatory certainty in the licensing processes for these facilities.

Nuclear Security Series No. 13 provides recommendations for preventing the unauthorized removal of nuclear material during transport (Fialkoff 2020). It has been acknowledged and incorporated into the United Nations Model Regulations, which in turn influence the International Maritime Dangerous Goods Code; this code mandates that maritime transporters of nuclear materials comply with the Nuclear Security Series No. 13 standards. Important requirements include (Fialkoff 2020):

- Limiting the duration and frequency of transfers of nuclear materials
- Ensuring protection during transit and that 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.

Nuclear Security Series No. 26-G provides insight 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 that outlines security measures and stakeholder responsibilities (Fialkoff 2020).

Several existing international frameworks and analyses provide partial but relevant guidance for the security of floating nuclear power plants (FNPPs) and maritime nuclear transport. While none offers comprehensive coverage, the following sources highlight current practices and gaps:

1. **IAEA Nuclear Security Series:** While *Nuclear Security Series No. 13* offers limited information on maritime transport, *Nuclear Security Series No. 26-G* delves deeply into the topic while focusing predominantly on Category I nuclear materials (Fialkoff 2020).
2. **Design Basis Threats (DBT):** Nuclear facilities must be designed to withstand malevolent acts, including those specific to maritime threats. Current DBT and beyond design basis threat (BDBT) for maritime facilities need to be updated to reflect these threats.
3. **WNTI Gap Analysis:** A gap analysis of the Code performed by WNTI includes a comprehensive review of security requirements for FNPPs, which were not included in the Nuclear Code of the IMO.
4. **ISPS Code:** The International Ship and Port Facility Security (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 managing nuclear or radioactive materials in port facilities. When FNPPs are stationed at terminals or when atomic ships are involved, regardless of their operational status or location, it is imperative to implement a blend of nuclear and maritime security protocols. This ensures comprehensive security measures are maintained not only when these assets are in port but also during their operational activities at sea or while docked.

Part A, Section 7, of the ISPS Code provides guidance on vessel response strategies for varying maritime security (MARSEC) levels and preventive measures for prospective security incidents. Included in this guidance is the following (Fialkoff 2020):

- 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
- Including 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 (the 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 does 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 (Fialkoff 2020).

## **4. EFFORTS UNDERWAY TO SUPPORT REGULATION OF MARITIME-BASED NUCLEAR FACILITIES**

This section provides a summary of some of the activities underway to support maritime regulations at key international working groups and organizations. Additionally, this section highlights key domestic activities that address topical areas that impact maritime nuclear development, siting, construction, operations, and operational environments.

### **4.1 Transport Safety and Security**

There have been several maritime efforts over the past few years through the IAEA TRANSSC, which established a working group (WG) in 2022 under the TRANSSC TTEG on Package Performance and Assessment. The WG was tasked with creating a position paper to support the process of establishing consensus within the transport community with respect to the requirements for the safe transport of a TNM, an MNPP, and an 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; for the “applicability of transport safety requirements” of a TNM, an MNPP, and an FNPP; as well as for capturing characteristic “classification items” properties. However, these terms were not accepted by consensus.

Because the global ocean transportation industry is seeking a new generation of nuclear-powered ships that are nuclear-electric rather than being powered by a direct nuclear steam cycle, the WG's position was that the proposed definitions for an FNPP should be combined with those of a nuclear-powered ship. The combining of the proposed definitions would highlight the benefits of reliable zero-carbon-emission propulsion and the ability to provide electric power in ports and terminals during port calls. However, current regulations only address a steam-driven propulsion system.

The IAEA planned 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 on Package Performance and Assessment WG position paper will be approved by TRANSSC in its entirety. However, the position paper will be updated regularly by the TRANSSC TNPP WG 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.

Starting in October 2023, the IAEA Division of Nuclear Installation Safety, partnering with the Division of Radiation, Transport and Waste Safety and the Division of Nuclear Security, began working on a technical document (TECDOC) focused on the design basis for the safety and security of FNPPs. The focus of this joint effort is to evaluate whether the IAEA's Safety Standards and Nuclear Security Series publications adequately answer questions involving FNPPs. The finalized TECDOC discussing these issues has a proposed release date of 2026.

## 4.2 World Nuclear Transport Institute

British Nuclear Fuels Ltd (U.K.), Cogema (France), and the Federation of Electric Power Companies (Japan) founded the WNTI in 1998 to represent the collective interests of the nuclear transport industry. WNTI has observer status at the IAEA and consultative status at the IMO. WNTI's traditional mandate was focused on the safe transport of nuclear materials such as spent fuel, and it was not involved in the safe operation of NPPs.

However, in 2021 WNTI established a Maritime Applications and Nuclear Propulsion (MANP) WG 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 references 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, in nearshore environments, and in ports
- Review and evaluate issues related to the liability of a civilian operator of a floating nuclear power reactor.

The MANP WG coordinates work with a select number of nuclear and maritime regulators. Currently the MANP WG is focusing efforts on the U.S. NRC and U.S. Coast Guard and the ONR and the U.K. Maritime and Coastguard Agency.

A technical gap analysis is being developed with global technical experts. The purpose of the analysis is to provide regulators with information regarding the proposed language for a revised Code, with a scheduled completion date of 2025.

## 4.3 U.S. Nuclear Regulatory Commission

### NRC Licensing

The U.S. NRC regulates certain activities associated with commercial NPPs as well as other uses of nuclear materials and waste. Following the passing of the Nuclear Energy Innovation and Modernization Act in 2018, it 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 the NRC to collaborate with its international counterparts regarding relevant operating experience for different designs, international codes and standards, and computer modeling techniques and programs.

### NRC Licensing Considerations

A siting challenge for FNPPs is that they can be installed on a mobile floating or offshore structure at a deployment site but that structure can then 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 52, Subpart F) that authorizes a reactor to be installed at sites not identified in the manufacturing license application, and to 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 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 their ability to comply with applicable transportation requirements contained in 10 CFR 71 and consider lessons learned from the Offshore Power Systems manufacturing license process (a manufacturing license was issued in 1982 for the 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 53—“Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors” (NRC 2025b). For 10 CFR 53, the NRC proposes to establish a *technology-inclusive* regulatory framework to be used 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, these results are yet to be seen because this framework has not been implemented yet. As maritime nuclear reactors would fall under the NRC classification of advanced reactors, the proposed 10 CFR 53 may help developers make decisions about advanced reactors in commercial maritime nuclear facilities. A

draft for 10 CFR 53 was published in March 2023, and it is expected that the final rule will be issued no later than the end of 2027.

## 4.4 Siting, Construction, and Operation

To further inform the different parameters necessary to site a maritime-based nuclear facility, it is imperative that the technology can meet the commercial and operational requirements of industries that might benefit from reliable zero-emission power, such as oil and gas, floating wind, offshore processing (e.g., oil and gas separation, gas dehydration, or water treatment), synthetic fuels production, ocean transportation operators, ports, and coastal industries. However, the technology 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 maritime environment must undergo a site suitability assessment that follows the same principles and safety objectives outlined in IAEA Specific Safety Requirements No. SSR-1. However, a site in a maritime environment will naturally have differences that need to be identified and assessed to confirm that the facility's design 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 maritime environment must be considered. The detailed approach will also need to consider activities near the facility, which could present additional external challenges to the facility and its ability to exercise emergency plans both in the facility and where off-site assistance is required. Proximity to or large distances from population centers will impact the types of safety and control measures used for the facility. Maritime facilities can be more self-sufficient from an emergency response perspective, but they are not infallible.

A maritime-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 considered. A maritime 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.

### NRC Siting Requirements

To provide a perspective from the U.S. as an illustration, the siting requirements set out in 10 CFR 100 establish approval requirements for sites proposed for the construction and operation of stationary power and test reactors under 10 CFR 50 or 10 CFR 52. Gaps exist when considering a license for siting an FNPP and reactors used for propulsion, as their geographical location would not be constant.

10 CFR 100 states that site evaluations must consider factors that relate to the proposed reactor design and the peculiar characteristics of 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, security, and environmental protection. In addition:

- The main nuclear hazard to be considered in port or a nearshore environment would be an accident that is severe enough to cause an appreciable release of gaseous or volatile

radioactive materials from the ship—iodine isotopes and noble gases being of particular significance. Such an accident is highly unlikely. The ship's design and care in navigation should address any DBT and BDBT concerns, which traditionally include aircraft crashes for land-based commercial nuclear plants. For the maritime environment DBT and BDBT could be expanded to include design against maritime collisions and grounding.

Normal operations in ports and at berth will not create levels of radioactivity in and around the ship that are higher than what is specified for routine operation.

It is the view of some organizations within MNAG that safety, security, and environmental protection objectives can be achieved if a vessel is designed, constructed, and operated in accordance with the best practices for nuclear ships and within the framework of IMO's SOLAS Convention. Additional work will need to be completed to demonstrate this against prevailing nuclear requirements.

In addition, the site location and the engineered features included as mitigation measures for the hazardous consequences of an accident, if one were to occur, should ensure a low risk of public exposure. A small probability remains that accidents could lead to off-facility releases of radioactive materials. While an offshore FNPP is unlikely to have as many civilians in its emergency planning (or preparedness) zone (EPZ) compared to a land-based reactor, hazards to facility workers and the environment are still of concern and should be addressed when siting is being considered. Proponents in the U.S. should therefore work with the U.S. NRC, DOE, Coast Guard, Environmental Protection Agency (EPA), and other expert maritime agencies to consider the following in assessing the acceptability of a proposed site and/or the location of a floating nuclear power reactor:

- Population density
- Proximity to land
- The local maritime environment
- Proximity to manmade hazards
- The physical characteristics of the site, including seismology, meteorology, geology, and hydrology.

## Construction and Operation Considerations

Collaboration between the nuclear industry, the manufacturer of maritime-based systems, and installation companies will be necessary so they together can interpret and apply regulatory requirements and successfully navigate the available licensing frameworks to manufacture the nuclear facility components, manufacture the maritime-based platform, and integrate the two for deployment to the site. These entities may require separate certifications or approvals from regulators to handle nuclear material and operate or test nuclear facilities. The nuclear-maritime industry should also engage regulators early and regularly to identify interpretation issues, gaps, or conflicts and participate in their resolution.

Further work may be needed to understand how 10 CFR 50 could be used to create a multistep construction permit and operating license approach, or if 10 CFR 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 53 for licensing once NRC rulemaking is finalized in 2025, which would necessarily require extensive engagement with NRC.

Maritime nuclear industry stakeholders will need to complete a thorough review of the National Environmental Policy Act (NEPA) requirements outlined in 10 CFR 51, which mandates

the NRC to prepare environmental impact statements for all reactor license applications. This industry review will need to include a comprehensive analysis of alternative sites. Given the complex nature of licensing processes, especially for reactors on floating vessels, it is crucial to differentiate between the “site” (the physical location of the reactor on the vessel) and the “location” (where the vessel itself is situated), taking into account all relevant local and maritime regulations. This distinction should be carefully considered throughout the multistep NEPA process to ensure all environmental, regulatory, and logistical aspects are addressed.

Currently, the proposed NRC *Generic Environmental Impact Statement* (NRC 2024b) for advanced nuclear reactors uses a plant parameter envelope and site parameter envelope approach, which does not address maritime-based facilities, though data and precedence do exist from previous floating nuclear applications in the U.S. The industry needs to engage with NRC and propose an appropriate plant parameter envelope 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, Clean Water Act), which, in some cases, must be shown before NRC can issue a license.

Existing NRC operation requirements include the following:

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

Other applicable state and federal laws and regulations:

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

Many other federal and state agencies are also likely to be involved (e.g., Department of Interior’s Bureau of Ocean Energy Management, U.S. Army Corps of Engineers, U.S. Coast Guard, National Oceanic and Atmospheric Administration, EPA, Department of Defense, Federal Energy Regulatory Commission, state public utility commissions, state environmental agencies).

## 4.5 Maritime-Based Nuclear Facility Operating Environments

The reactor and all safety-related components could 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 associated means of containment would also be located partially below the waterline, offering

additional protection on all sides and proximity to water as an ultimate heat sink if needed. However, it is noteworthy that, depending on their specific design and operational requirements, not all reactors will require this configuration.

For the most part the facilities could be built and integrated within a specially qualified shipyard, which needs to be appropriately qualified to meet supply chain requirements, and delivered to the site, which may be located at the shore or in relatively deep water (more than 100 meters) within either national waters or a country's exclusive economic zone. Therefore, each facility will fall under the purview of the host country's nuclear regulators, who will have their own requirements.

### **Viable Use Cases**

It is envisaged that FNPPs could be deployed to serve one or more specific functions, including:

- Mobile water desalination
- Offshore processing and production
- Clean energy provision for offshore drilling and production
- Flexible power for coastal industry and communities
- Reducing pollution at ports and shoreline installations
- Hydrogen production and low-carbon fuels
- Clean energy provision in support of maritime green corridors
- Offshore industries and for load balancing intermittent offshore energy.
- Heavy payloads, energy transportation, and resilient mobile power for the U.S. Department of Defense (i.e., dredging vessels for the Army Corp of Engineers).

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

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

- 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.
- The fueled FNPP is transported, towed, or relocated in shutdown or hold-down condition to an approved operating location at the shore or offshore, transiting through coastal waters and passing landmasses and maritime traffic.
- For servicing and maintenance, the FNPP reverses its journey back to its home yard; hence, this may become a repeat voyage, even though some level of servicing and maintenance can be performed without moving it back to the home yard.
- The fueled FNPP is a self-propelled vessel using electricity generated by its onboard NPP. From its home yard it navigates waterways and nearshore waters to preapproved ports or licensed deployment sites, 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 that rotates on and off the vessel in ports or offshore.
- The FNPP may vary in size and capacity, from a microreactor to a gigawatt-scale reactor.

- The FNPP may be permanently moored at shore, supplying the land-based grid, or far offshore, transmitting electric current through cables to offshore facilities or the shore. Large FNPPs may be serviced, maintained, and refueled at sea or shoreside (at the site of deployment or at the home yard). The offshore FNPP carries an operating crew that rotates on and off the vessel via helicopter or boat.

## Emergency Planning Provisions and Planning Zones

In the U.S., like other countries around the world that license and operate NPPs, emergency preparedness, both inside the facility and in the region around the facility, is required as part of an effective defense-in-depth strategy. EPZs are areas established around an NPP by off-site emergency planning authorities. Emergency measures are planned for these zones in case an accident overwhelms the on-site accident prevention and mitigation measures, including the on-site emergency response. In the U.S., like many other countries, the emergency planning strategies and associated EPZ sizes are predominantly based on the source terms and accident-progression characteristics from existing large facilities.

On-site and off-site measures start with the operational response of the workers and escalate to a graduated off-site response established by criteria that consider accident progression and associated predictions of consequences over time and area. Measures serve to protect vulnerable people (normally members of the public) by establishing shelter-in-place or evacuation orders, as well as by limiting the consumption of drinking water and certain foodstuffs. The shape of the EPZ is usually circular with the NPP at the center, but it 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 different government emergency planning functions that work with the proponents of projects and nuclear regulators to establish the 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 (16.1-km) plume exposure EPZ and a 50-mile (80.5-km) ingestion exposure EPZ, both of which are imposed by the NRC. In Canada, EPZs are established by provincial emergency planning agencies in consultation with the nuclear regulator, the CNSC, Public Safety Canada, Health Canada, and local governments that are responsible for land-use planning.

Low- or ambient-pressure reactors are, by design, equipped with physical measures to prevent high-energy accidents that can lead to significant off-site consequences. Examples of design measures include lower- or ambient-pressure systems, accident-tolerant fuels, and a functional containment system with multiple barriers to prevent radiological releases. For these types of reactor systems that are currently being designed and tested, these features are being established to reduce the extent of the EPZ around the facility and, as a result, better define the liability of the operator in case of an accident or mishap. New nuclear technologies could allow for very small EPZs, and future design activities will seek to demonstrate whether all emergency responses could be carried out within the facility.

Nuclear developers are proposing that the EPZs of current and future plants using advanced reactors be limited to the site boundary of the power plant, which they suggest is the appropriate size. According to 10 CFR 50, "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 250 MW thermal" (Moe 2014).

According to IAEA's *SMR Regulators' Forum Pilot Project Report: Report from Working Group on Emergency Planning Zone*, "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” (IAEA 2018c).

The IAEA-coordinated research project “Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for Emergency Planning Zone for Small Modular Reactor Deployment” attempted to identify suitable repeatable methodologies that many regulators will accept (IAEA, n.d.).

The size of the EPZ will ultimately be established through the licensing process, initially on a case-by-case basis until sufficient technical and legal precedent are established.

The use of accident-tolerant fuels, inherent safety characteristics, passive safety features, and other features such as lower operating pressures can eliminate the possibility of large releases from the plant and significantly lower the source term and its consequences over time and for the area around the facility. This means that nuclear developers will be able to show that the off-site consequences for advanced reactors will be orders of magnitude smaller than the emergency thresholds for sheltering and evacuation. However, these claims must be evaluated through the licensing process, which will require sufficient design information and associated safety analyses.

This reduction in off-site consequences is the case for the NRC-approved methodology of the NuScale SMR (Rempe, 2022) and the methodology followed by the Shidao Bay high-temperature reactor plutonium-management plant in China and other SMR designs. Because an FNPP will be similar to a land-based NPP, the general framework for calculating the appropriate EPZ will need to follow these steps:

1. Determine the possible accident sequences that are needed to calculate the EPZ (a select set of design-based accidents and representative design-based accidents with characterized consequences), along with their occurrence frequency, using the outputs of a systematic safety assessment supported by a probabilistic risk assessment. Estimate source term
2. Calculate the maximum effective dose and contamination level of food and drinking water at different distances from the reactor for the most serious accident sequences using appropriate models and weather parameters for both the atmospheric and aquatic dispersion in the maritime environment.

If the levels calculated in step 2 for beyond the boundaries of the FNPP are much lower than the regulatory intervention levels identified, it is possible that the EPZ of the maritime asset could be limited to the boundary of the facility; however, the off-site emergency planning organization may impose further buffer zones commensurate with legal requirements.

To be able to have the boundary of the FNPP designated as the EPZ, FNPPs must utilize a sufficiently robust defense-in-depth strategy that provides multiple complementary prevention and mitigation measures to eliminate off-site 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 design-based accidents and mitigating the exposure of personnel, the public, and the environment.

This two-step approach ultimately impacts off-site measures in time and distance from the facility. Using a robust defense-in-depth approach allows a safety case to demonstrate that the consequences of accidents can be limited in time and area to the boundary of the plant, thereby reducing the need for off-site response measures.

## Nearshore Operations in Ports and Waterways

Departments and agencies involved with maritime nuclear, in conjunction with project proponents, should evaluate and determine the general conditions for how an FNPP—whether self-propelled or not—can approach and depart a safe port call and engage NRC with methodologies for performing these evaluations. They should specifically reference the safety and security characteristics of available and planned new nuclear technologies and operating/safety procedures for round-voyage nearshore approach and port canal entry, navigation, maneuvering, and docking.

### Factors in the Selection of Berths

Below are several proposed key areas for consideration if a nuclear ship is to make berth; they are grouped from a safety viewpoint:

- Factors influencing the relative probability of an accident caused by external factors such as shipping channels (frequency and speed), tidal and meteorological conditions, the type of goods/materials handled at neighboring berths and the risk they pose, the location of airports and flight paths, etc.
- Factors influencing the dispersibility of radioactive material to the environment, such as frequencies and times of prevailing and extreme meteorologic, tidal, and water flow conditions, and seasonal variations
- Factors influencing the potential consequences of accidents, such as surrounding land use, the availability of services, and the ease of towing and radiation monitoring.

### Operational Considerations for Port Use

It is imperative to consider how a maritime-based nuclear facility will interact with ports or its berth. FNPP developers should think about the following operational considerations and suggestions related to an FNPP entering and using a port:

- Notifying the port of the ship's intention to call.
- Determining conditions such as poor weather before making a port of call.
- Having remote anchorage options:
  - A designated location for nuclear ships in case there is a change in port conditions that would preclude the ship's entry to the port
  - A location the ship can be taken to 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, such that nuclear vessels could be diverted 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.

### Conditions While in Transit to and from Berth

Maritime regulations don't handle ships based on the type of power system they have; the pilotage requirements for nuclear ships should be no different from those of conventional ships, including no privilege right-of-way. In port waters, tugs can accompany the vessel to assist with maneuvering, and where this assistance is provided is a matter for individual port authorities to

consider. The presence of tugs also ensures that the ship can be moved to a safe location in case of emergencies.

## Conditions at the Berth

Upon reaching the berth, FNPP developers should think about the following berth considerations and suggestions:

- The provision of power and special lighting arrangements as required by the ship or security forces.
- A water supply for in-ship firefighting and possible connections to ship fire mains.
- Communication facilities: ship-to-shore telephone connections, port network access, and radio facilities.
- Security arrangements: Enhanced security measures compared to conventional vessels, security personnel at access points/gangways, and special surveillance during off-hours. While these measures will not fall under class requirements, we foresee the port state requiring such provisions be put in place prior to berthing.
- The presence and availability of dosimetry equipment, although the port should be responsible for this.
- 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 with consideration for complications that may arise if the nuclear vessel is involved.
- Access to the ship in the port area must be considered so emergency action is not impeded.
- In addition to current practices, while the ship is at berth it should have available a senior officer in charge, a crew on board sufficient to take 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 the handling of large quantities of hazardous material in the vicinity of the ship. Provisions to help maintain controlled access to the regions around the berth by authorized personnel only.

## Administrative Arrangements for Emergencies

Similar to what would be put in place for a land-based facility, a set of administrative arrangements should be established as precautionary measures for dealing with emergency conditions. They should include:

- *Control and operation of the vessel:* This would be an integral part of the facility's safety and security case. The specific assigned roles within the licensee's organization (e.g., vessel captain) must demonstrate competence in dealing with vessel-related accident conditions involving the release of radioactive material, including the safety of the reactor installation.
- *Port authority's responsibility:* To define executive responsibility for actions concerned with the safety of the port, including if/how the port would support the emergency response provisions of the nuclear facility.
- *Public safety and health:* Prior to designating a port as safe for use by nuclear ships, there should be full consultation with appropriate bodies for a clear definition of responsibilities, interfaces, and accompanying procedures to execute a timely and coordinated response.

These bodies may include police, health officials, and those concerned with agriculture and food. Arrangements should be made for control, evacuation, and medical treatment in case of contamination.

- *Environmental hazard:* Arrangements should be made to communicate with civil authorities and government bodies in a timely manner commensurate with the progression and severity of the accident and with the predicted off-site consequences in consideration of changing conditions.
- *Expert assistance:* Timely involvement of qualified people to support information gathering for environmental monitoring, meteorology, health physics, and engineering for assessing hazards.
- *Captain's licensee's accident management reporting structure:* Responsible for immediately and accurately reporting abnormal reactor conditions, timely updates on the progress of accident management activities, and the evolution of potential consequences. In a traditional maritime-based facility, this primary responsibility would fall to the captain.

## 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 the purpose, design, licensing, classification approval, and proximity of the FNPP.

Multiple touchpoints exist between the nuclear and maritime regulations governing FNPPs. For example, in the U.S. 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
- Shipping regulations for territorial waters
- Compulsory Pilotage Decree 1995
- Decree on Pilot Exemption Certificate Holders Shipping Traffic Act
- Regulations for licensed (maritime) pilots
- Regulations for the prevention of pollution from ships
- Regulation on the Transportation of Dangerous Substances, 2007
- Port management bylaws
- Regulations for communication and pilot requests sea shipping
- Regulations for seagoing vessels required to notify port authorities
- Regulations for notifications and communication shipping

- U.S. Coast Guard guidelines and statutes
- Other U.S. regulations.

In addition, consideration should be given to nonenvironmental rules such as the Submerged Lands Act of 1953, Rivers and Harbors Act, and Outer Continental Shelf Lands Act. Boundary conditions that pertain to environmental acts, such as the Clean Water Act, Maritime Mammal Protection Act, Coastal Zone Management Act, Magnuson-Stevens Fishery Conservation and Management Act, National Historic Preservation Act, National Maritime 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 and constructing a facility offshore and in a coastal setting. These approvals will also be needed for accessing transmission lines and may include leases, easements, and rights-of-way, among numerous others.

## 5. END-OF-LIFE CONSIDERATIONS

End-of-life operations—decommissioning, handling of spent nuclear fuel or nuclear waste—is a thorny issue when it comes to public acceptance, but it is also a significant issue identified by port operators. Thus, it is important to address these operations through informative communication about safe nuclear waste handling, as well as through thoughtful design measures. For example, by designing new nuclear energy systems that run with long fuel cycles, we can avoid refueling and removing spent nuclear fuel in commercial ports. This is true both for FNPPs operating offshore or in nearshore environments and for nuclear-powered ships. However, if properly designed, on-site refueling can still be a very safe and viable option, although such refueling is only likely to occur at a designated nuclear shipyard.

Individually, the lists of regulatory considerations for decommissioning nuclear reactors and decommissioning maritime vessels are 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. Contamination should not be able to get 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 the amount of costly and hazardous waste that is generated, which must be managed and disposed of in special facilities, can be reduced.

To explain how these different regulatory regimes currently exist, this section will explore the topic from three perspectives using the U.S. 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.

### 5.1 Existing Considerations for Managing Nuclear Waste in the United States

The NRC currently regulates four categories of nuclear waste (U.S. NRC 2020a):

## Introductory Review of the Maritime Nuclear Regulatory Landscape

- Low-level waste (LLW): includes radioactively contaminated protective clothing, tools, filters, rags, medical tubes, and many other items
- Waste incidental to reprocessing: certain waste by-products that result from reprocessing spent nuclear fuel, which DOE distinguishes from high-level waste
- High-level waste (HLW): irradiated or used nuclear reactor fuel, including commercial spent nuclear fuel
- Uranium mill tailings: the residue remaining after the processing of natural ore to extract uranium and thorium.

As is the case for existing commercial NPP operators, LLW and HLW are likely to be of the highest concern for future maritime reactor owners. LLW is classified as groups A, B, and C according to the NRC (U.S. DOE 2019):

- 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 overseen by the NRC and the four agreement states that host the four LLW disposal facilities in the U.S. *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 (U.S. NRC 2024a). These four LLW facilities are (U.S. NRC 2020a):

- Energy Solutions Barnwell Operations, located in Barnwell, South Carolina, is 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, is licensed by the State of Washington to dispose of Class A, B, and C waste from the Northwest and Rocky Mountain compacts.
- Energy Solutions Clive Operations, located in Clive, Utah, is licensed by the State of Utah to dispose of Class A waste from all regions of the U.S.
- Waste Control Specialists LLC, located near Andrews, Texas, is 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 (NRC, n.d.), 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. 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 (EPA 2020). However, sustained opposition from neighboring local communities and the Nevada state government have prevented any progress on the project, and today it seems highly unlikely that Yucca Mountain will open.

In 2021, DOE restarted a siting effort to identify potential new locations for an HLW facility in the U.S. The effort has built upon findings from a previous Blue Ribbon Commission (BRC) on America's Nuclear Future, which published multiple recommendations and expressed the need for a new approach to siting and building nuclear waste facilities.

The commission suggested that 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 an HLW facility will be built and operating before 2030.

Leading up to this point, DOE's focus had been on identifying one or more interim storage sites that would act as temporary locations for consolidating the HLW located at 80 sites around the country (Congressional Research Service 2020).

Until a repository is operating, existing NPPs are committed to the 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; it 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 (BRC 2011).

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

## 5.2 Existing Considerations for Decommissioning Vessels

To the extent practicable, the proposed path for decommissioning a nuclear vessel will need to be established in a graduated manner based on the nature of the contaminants that remain following removal of the fuel, reactor, and wastes resulting from the decontamination of the structures, systems, and components. The general approach to decommissioning a vessel will need to be presented up front in environmental assessments and during licensing in most countries; this will be subject to public comment during the decision-making processes. Where the vessels will be decommissioned and what will happen to any residual hazardous/radioactive wastes will be an important part of the public's acceptance of these technologies. The current process for NPPs is that most wastes are the responsibility of the country where the nuclear facility was located. Whereas large components are sent for processing and recycling, the resultant radioactive wastes are normally returned to the country from which the wastes originated, excluding spent nuclear fuel, which would remain in the U.S. per the McClure Amendment.

Of the ships that are ultimately broken down and recycled (a process referred to as "shipbreaking"), roughly 90% of them go through this process in either India, Pakistan, Bangladesh, or Turkey.

Because shipbreaking is notoriously dangerous and harmful to the people and environments where it takes place, several key international treaties have helped raise the environmental standards of the practice, including:

- The decision at the 2004 Conference of the Parties 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 (Basel Convention, n.d.)
- 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 (IMO 2009)
- The European Union's (EU's) adoption of the Ship Recycling Regulation in November 2013, which mandates that EU-flagged commercial vessels above 500 gross tons must be recycled in an approved ship-recycling facility that maintains safe and environmentally sound practices (NGO Shipbreaking Platform, n.d.).

Although the bulk of commercial shipbreaking takes place in the countries listed above, the U.S. does have several ship-recycling facilities that primarily service vessels from the U.S. Navy and U.S. Department of Transportation Maritime Administration (U.S. NRC 2020b). This also includes the dismantling of the U.S. Army Corps of Engineers' STURGIS, the first-ever floating nuclear power station. Between 2015 and 2018, the corps decommissioned the deactivated nuclear reactor and vessel and safely removed all associated radioactive waste. At the end of 2018, the vessel was towed to the Port of Brownsville where its entirety was recycled (Maritime Executive 2019).

The Corps model for end-of-life operations brings up some key questions, such as where a commercial maritime reactor would be sent after decommissioning if the vessel it served could be recycled normally. Or, who would pay for vessel decommissioning. In the U.S. and U.K., commercial reactors transfer operational costs, including decommissioning, to ratepayers. It is conceivable that in maritime environments, these costs would be borne by the vessel's owner and operator. Alternatively, similar to land-based reactors in the U.S., decommissioning funds could be accumulated over the reactor's operational life.

## **6. SUMMARY OF REGULATORY AND LICENSING GAPS**

Table 1 presents a preliminary summary of the key gaps and corresponding recommendations resulting from the introductory review of the regulatory and licensing landscape for FNPPs conducted by MNAG. The preliminary conclusions emphasize the need to conduct work to adapt regulatory requirements and guidance to address the unique challenges posed by maritime nuclear applications.

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Table 1. Summary of key gaps and corresponding recommendations emerging from the initial examination of the regulatory framework for civil maritime nuclear applications.

Gaps	Description	Recommendation
Need to reduce licensing cost and timeline	<p>Costs and licensing timelines are heavily influenced by the readiness of the applicant, the state of design completion, and the ability/authority of the regulator and its framework to assess the design.</p> <p>The track record for past nuclear projects shows that 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 several years.</p> <p>The period of licensing could be reduced if a complete design with the associated research results and evidence supporting the application was submitted.</p>	<p>FNPP proponents need to engage with regulators early and use prelicensing processes to better understand how requirements and guidance would be applied to FNPP projects. Engagement with regulators is necessary to understand how some of the novel approaches for FNPPs can be proposed in an effective manner such that there is reasonable certainty that they would be accepted. This includes demonstrating equivalencies in practices used in marine engineering and operations and the nuclear industry.</p>
Need for clarity on how to complete consistent licensing at an international scale and in a cost-effective manner	<p>Future owners and operators of nuclear-powered maritime vessels may have to navigate a complex web of national regulations. 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 noncompliant by another. A framework is needed such that countries can better work together to reach consensus on what is needed for similar licensing outcomes in different countries.</p>	<p>Continue to work with the IMO to collaborate with various nuclear regulatory organizations, such as the IAEA and national regulatory agencies, to develop an international licensing framework for sharing and using information and practices that the various member states can leverage—to the extent practicable—in ways that are consistent with their responsibilities under the IAEA safety and security framework.</p>
Internationally recognized classification authority and procedure for civil maritime nuclear applications	<p>The classification of FNPP technologies represents a crucial stage in demonstrating to the international community the commercial viability of a system.</p>	<p>Partner with classification societies to foster the development of a maritime classification framework for FNPPs.</p> <p>This framework will serve as a valuable reference for other classification societies, guiding their future classification FNPP efforts.</p>
Integrating maritime security with nuclear security	<p>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 significant environmental, political, and human consequences. By ensuring the convergence, if not harmonization, of both maritime and nuclear security protocols, a comprehensive approach can be taken to proactively address and respond to potential threats. This will reinforce the safety and security of international waters and the global nuclear landscape.</p>	<p>Engage with the IMO and the IAEA on the ACPPNM, INF Code, and the ISPS Code to further clarify the possible gaps in the international legal framework for the physical security of civil maritime nuclear applications.</p>

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Gaps	Description	Recommendation
International nuclear transportation framework integrated with maritime nuclear applications	Many civil maritime nuclear applications may present unique challenges due to their mobility, particularly in cases where they are proposed to operate in international waters. International nuclear transportation practices need to be established to further enable standardized safety, security, and environmental protection provisions. The intent is to facilitate seamless cross-border transportation, refueling, waste management, and decommissioning activities, while effectively preventing or appropriately addressing potential maritime nuclear incidents.	As a starting point for civil maritime nuclear applications, FNPP proponents and technology developers should increase engagement with the IAEA Transport and Nuclear Safety Standards Committees through applicable platforms (e.g., the Nuclear Harmonization and Standardization Initiative [NHSI]). The industry community should leverage examples of existing project work as the basis for engagement on specific issues to be addressed.
Clarity on emergency planning requirements considering appropriate methodologies to enable risk-informed EPZs commensurate with specific design characteristics and site-specific considerations	There are already discussions underway in many countries, including the U.S. and Canada, on what constitutes appropriate approaches to establishing the basis for EPZs for SMRs based on their operating characteristics, their safety claims, the results of hazards assessments, site conditions, and the degree of supporting evidence concerning the prevention and mitigation of accidents. A lack of clarity or consensus remains for how emergency planning authorities will implement this information to decide on risk-appropriate EPZs. This issue extends to maritime-based reactor facilities, which can encounter different challenges and emergencies and have different off-site effects. The EPZs will be based on approved analytical methods that consider design parameters such as operating pressure, core fuel inventory, and the probabilistic safety assessment.	Work with the IAEA so they include civil maritime nuclear applications in the overall effort to define acceptable approaches for developing a planning basis that off-site emergency planning decision-makers can use to establish EPZs. This work should include impacts on water and marine ecosystems but also consider the implications of: <ul style="list-style-type: none"> <li>● Facilities that are not located near organizations that can respond in a timely manner</li> <li>● Specific maritime security challenges</li> <li>● Legal requirements when operating in international waters.</li> </ul>
Clarity on an appropriate end-of-life framework for FNPP projects	Individually, decommissioning either a nuclear reactor or a maritime vessel involves lists of regulatory considerations. These regulatory processes address critical issues such as vessel scrapping, how the vessel would be decontaminated and disassembled, and how the material resulting from those processes would be handled (e.g., nuclear waste management and the release of recycled materials).	Engage with the IAEA and existing practitioners of nuclear vessel decommissioning to collect and analyze experience and lessons learned. Use this to develop a “design for decommissioning” guidance document that also proposes efficient frameworks that member states can use in planning nuclear programs and accommodating FNPPs.
Clarity on and potential removal of restrictions on port access for civil maritime nuclear applications	Port access is an important logistic issue that could impact the profitability and utilization of civil maritime nuclear applications.	Engage the IMO and the IAEA to establish a modern international framework. This framework will serve as a comprehensive guideline, outlining safety, security, and environmental benchmark requirements for civil maritime nuclear applications. By doing so, it will enable ports worldwide to consistently assess and grant access to civil maritime nuclear applications.

## 7. CONCLUSION

The successful deployment of nuclear technology for maritime applications, including the ability to provide energy to support land-based applications, has the potential to assist the IMO's pursuit of 2050 targets while simultaneously bringing low-cost nuclear power closer to where it is needed. Potential energy off-takers include, but are not limited to, industries focused on resource extraction and processing, industries interested in more efficient and productive sources of process heat and electricity for industrial applications, and energy service providers that need to bring energy to areas that are currently energy poor. Whether nuclear technologies for maritime applications are successfully implemented will depend on how the regulatory frameworks for the nuclear sector and the maritime sector enable their use and deployment.

The regulatory landscape must effectively address safety, environmental, and security considerations while simultaneously fostering proven innovative approaches from both sectors. While regulations and guidelines exist for both commercial NPPs and the maritime sector, these sectors have had limited interaction. The deployment of next-generation nuclear reactor technologies, including advanced reactors into marine environments, will require new and unique approaches to address various challenges. These challenges include siting, compliance with transportation requirements, waste management, and conduct of decommissioning, all of which will require coordination between nuclear and maritime regulators.

The siting factors for civil maritime nuclear applications that need to be considered, including commercial demand, environmental concerns, and safety and security, have already been identified (IAEA Safety Series, etc.). They will need to be carefully reevaluated to determine how they can be addressed in a cost-effective manner. Various deployment scenarios for civil maritime nuclear applications, including transportation, maintenance, and refueling, will need to be documented in a more detailed fashion to identify how existing requirements and guidance can be applied and how demonstrably effective safety and control measures for these facilities can be achieved.

The EPZ for nuclear facilities remains important, even in offshore operations, to ensure the safety and preparedness of communities surrounding the floating nuclear asset throughout its life cycle. However, because technology has advanced, the appropriate size of EPZs is now being reevaluated, particularly for advanced reactor technologies that have many inherent and passive safety features. Similarly, as technology advances for civil maritime nuclear applications, the established regulatory frameworks for waste management and decommissioning should be reviewed and adapted accordingly.

Many reactor designs that could be suitable for marine environments are being developed in the U.S., and therefore it is expected that first-of-a-kind licensing cases will be submitted to U.S. regulatory bodies. For the international deployment of civil maritime nuclear applications, international collaboration between the U.S., other nuclear regulators, and maritime regulators will be critical to the efficient near-term deployment of such technologies that will be standardized to the extent practicable. In the long term, the industry is encouraging like-minded regulators to increase collaboration to converge the criteria and guidance for acceptable ways to meet regulatory requirements. This includes participating in the development of codes and standards that can be applied in many countries where civil maritime nuclear applications may be deployed. These activities can establish the foundation for an effective and supportive regulatory environment, allowing the full potential of maritime nuclear technology to be realized.

As the international shipping industry modernizes its fleets, it will need to leverage cost-effective technological innovation to maintain its margins while keeping costs to consumers

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reasonable. Unlike all other options for modernizing shipping, advanced nuclear can provide real benefits to the shipping industry. With strong leadership and the proposed actions herein, the challenges associated with maritime nuclear technology can be effectively addressed, leading to its successful deployment and operation while ensuring safety and improving vessel performance.

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