

Overcoming Challenges to Nuclear-Maritime Applications

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*Accelerating Commercial Maritime Demonstration
Projects for Advanced Nuclear Reactor Technologies*

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Executive Summary

This report is the fifth deliverable in a series of reports set forth by the Department of Energy (DOE), led by the American Bureau of Shipping (ABS), for the research award titled “Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies.” The report highlights guidance to bridge the gaps between innovative nuclear technologies and their practical implementation in maritime environments.

The previous reports discussed specific technical, economic and regulatory challenges that may be expected when developing and establishing advanced nuclear technologies for commercial maritime applications. This report supports the mission of the U.S. National Reactor Innovation Center (NRIC) to demonstrate projects with industry and acts as a resource for the various stakeholders associated with the development of novel applications for advanced reactors. The previous reports discuss the interest in nuclear technology applications for decarbonized energy and identify the potential demands in nuclear energy supply and price. The work in these reports 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.

The recommended strategies to address key challenges are presented in this report according to the lifecycle phase and are broken down in the following categories:

- 1) Strategies To Consider Throughout the Lifecycle
 - a) Nuclear Requirements and Licensing
 - b) Security, Safeguards, Non-proliferation, and Export Control
 - c) Public Policy / Public Acceptance
- 2) Strategies to Consider during Early Stages of Development
 - a) Demonstration and Testing
 - b) Establishing a Business Case
 - c) Integration of Nuclear and Maritime Systems
- 3) Strategies to Consider during Construction, Commissioning, and Establishing Infrastructure
 - a) Supply Chain and Fuel Availability
 - b) Support Infrastructure
- 4) Strategies to Consider during Operations and End-of-Life
 - a) Nuclear Waste Transport and Disposal, and Nuclear-Maritime Decommissioning & Vessel Recycling

To address these different areas, solution strategies were categorized and discussed in depth throughout the report. Thirteen categories of solution strategies are included in the report and presented in the context of the challenge that must be addressed. Solution strategies include: Robust Testing or Demonstration, Digital Systems, Public Engagement/Public Relations (PR), Personnel Certification & Training, Robust Design, Investment, Funding Policy, Leverage Government and Navy Experience, Establishing Fuel Supply, Operational Procedures, Novel Ownership Arrangements, Code Standardization and Regulatory Harmonization, and Leverage Land-Based Nuclear Experience. It is notable throughout the responses most of the categories emphasize technical aspects of the issue rather than the regulatory or economic.

The Nuclear Requirements and Licensing Subsection 2.1 covers design certification and different characteristics of licensing challenges. The primary solution strategies discussed in this section were Code Standardization and Regulatory Harmonization, Robust Design, Robust Testing and Demonstration, Funding Policy, and Leverage Land-Based Nuclear Experience. Guidance is presented according to existing practices and ongoing developments of regulations and policy.

The Subsection 2.2 Security, Safeguards, Non-proliferation, and Export Control discusses how requirements will be implemented to tackle the challenges and address concerns related to safety, security and safeguards. Solution strategies for

these challenges include Robust Design, Code Standardization and Regulatory Harmonization, Operational Procedures, Personnel Certification & Training, and Digital Systems

Subsection 2.3 Public Policy /Public Acceptance provides guidance on the strategies used to engage the public and campaign for public acceptance as it potential presents a challenge for nuclear projects from governments and policymakers. Solution strategies for addressing this challenge include Robust Testing and Demonstration, Public Engagement/Public Relations, and Leverage Government and Navy Experience.

The Subsection 2.4 Demonstration and Testing conveys how FOAK technology demonstration projects for the application of advanced nuclear reactors in the maritime industry may encounter challenges during the testing and demonstration phases, including some of the potential challenges related to testing and demonstration activities. Solution strategies covered in this section include: Robust Testing and Demonstration, Robust Design, Code Standardization and Regulatory Harmonization, Funding Policy and Public Engagement/PR.

The Subsection 2.5 Establishing a Business Case discusses challenges related to developing economic cases for demonstration projects and commercializing advanced nuclear products in the maritime industry. Economic viability will be particularly important to establish financial viability, the magnitude of its applicability, and how aggressively its development may be pursued. The solution strategies covered in this section include: Funding Policy, Robust Design, Code Standardization and Regulatory Harmonization, Robust Testing and Demonstration, Novel Ownership Arrangement, Leverage Land – Based Nuclear Experience, and Personnel Certification & Training.

The Subsection 2.6 Integration of Nuclear and Maritime Systems section discuss how the integration of advanced nuclear technology with maritime systems may face several difficulties that won't be present for the land-based applications. The nuclear reactors deployed on the commercial maritime units or facilities will be required to prove their ability to eliminate or address issues unique to their maritime environment. This section discussed the following solution strategies: Code Standardization and Regulatory Harmonization, Robust Design, Robust Testing and Demonstration, and Public Engagement / PR.

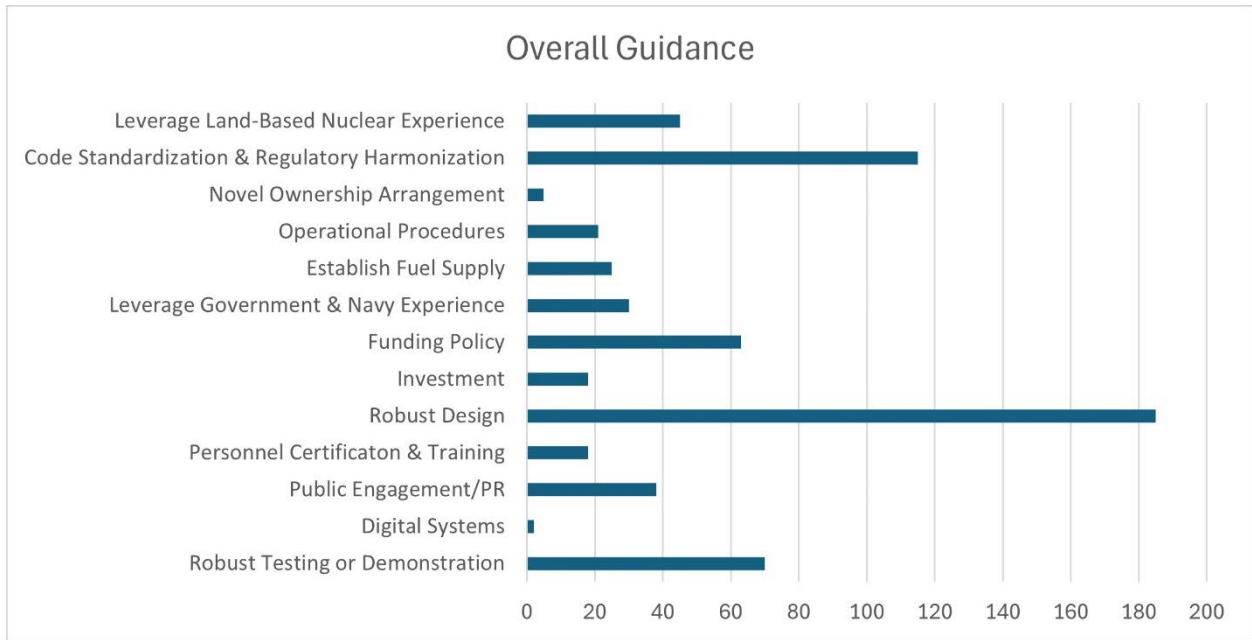
Subsection 2.7 Supply Chain and Fuel Availability elaborates on the challenges of establishing supply chains as well as ensuring the availability of fuel, materials, and components. Solution strategies discussed in this section include: Establishing Fuel Supply, Robust Design, Leverage Land-Based Nuclear Experience, Funding Policy, Investment, Code Standardization and Regulatory Harmonization, and Robust Testing and Demonstration.

Subsection 2.8 Support Infrastructure discusses the arrangements for supporting the implementation of nuclear-maritime applications, and the challenges that may affect the viability of the technology and simultaneously increase the cost of its development and deployment. This section suggests solution strategies such as Robust Design, Code Standardization and Regulatory Harmonization, Personnel Certification & Training, Leverage Land-Based Nuclear Experience, Funding Policy, Public Engagement / PR, Leverage Government and Navy Experience, Investment, Robust Testing and Demonstration.

Subsection 2.9 Nuclear Waste Transport and Disposal, and Nuclear-Maritime Decommissioning & Vessel Recycling is a sensitive topic that talks about how the nuclear waste handling and disposal will be carried out as it can provide numerous challenges to the maritime applications when compared to the traditional land-based reactors. Demonstration activities will need to be considered to showcase to the public, government and investors how the end-of-life procedures as well as effective waste management and decommissioning will be carried out. Solution strategies including Robust Design, Leverage Land-Based Nuclear Experience, Code Standardization and Regulatory Harmonization, Leverage Government and Navy Experience, Funding Policy, and Operational Procedures are discussed in this section.

This report aims to provide guidance for the successful demonstration and eventual deployment of nuclear technologies in the maritime environment by highlighting key areas of focus and action. Maritime and nuclear industry experts were asked to give their input on how the identified challenges may be resolved. All responses were gathered and incorporated into this report with solution strategies provided according to the identified challenge in each section. These responses provide a qualitative look at the most recommended strategies to address expected challenges. This report doesn't showcase every strategy, but highlights what respondents consider the most important focus areas. Additionally, it calls for collaboration between the nuclear and maritime industries alongside emphasizing efforts for investment in research and development and other

challenges to the economic and regulatory landscape. The output from the experts, as seen in the figure below, illustrates the overall guidance where the numbers represent the count of collective guidance to address the presented challenge. It can be concluded that the most widely proposed strategies to address all the issues relate to robust design as well as other related activities mostly undertaken in the initial stages of the technology development phase. The second most proposed strategy was to address issues by focusing on code standardization or regulatory harmonization across disparate regimes, regions and international frameworks. The third and fourth approaches suggested were robust testing / demonstration and funding policy activities where these can tackle the technical, regulatory, and economic challenges. Things to consider for the future would be to address primary challenges in the mid-term while also addressing lower priority strategies as appropriate.



Overall Guidance for Addressing All Challenges

ACRONYMS

The background of the page is a dark blue color with a faint, light blue technical drawing or blueprint overlay. The drawing consists of various geometric shapes, lines, and hatching patterns, typical of an engineering or architectural plan. The lines are thin and light, creating a subtle grid-like structure across the page.

ABS American Bureau of Shipping
ACRS Advisory Committee on Reactor Safeguards
CAPEX Capital Expenses
CATF Clean Air Task Force
CPPNM Convention on the Physical Protection of Nuclear Material (IAEA)
D&D Decontamination & Decommissioning
DOD U.S. Department of Defense
DOE U.S. Department of Energy
EPZ Emergency Planning Zone
FDA Food and Drug Administration
FNPP Floating Nuclear Power Plant
FOAK First-of-a-Kind
HALEU High-Assay Low-Enriched Uranium
IAEA International Atomic Energy Agency
IMO International maritime Organization
INF Code Irradiated Nuclear Fuel Code (IMO)
ISPS International Ship and Port Facility Security Code (IMO)
ITAR International Traffic in Arms Regulations
LNG Liquefied Natural Gas
NIST National Institute of Standards and Technology
NRC U.S. Nuclear Regulatory Commission
NRIC U.S. National Reactor Innovation Center
MNAG **Maritime Nuclear Application Group**
MOX Mixed Oxide Fuel
MSC Military Sealift Command
NEMO Nuclear Energy Maritime Organization
OPEX Operational Expenses
PNTL Pacific Nuclear Transport Limited
PR Public Relations
PRA Probabilistic Risk Assessment
SSC Structures, Systems, and Components
TI-RIPB Technology-Informed, Risk-Informed and Performance Base
TRISO Tri-structural Isotropic
WNTI World Nuclear Trasport Institute

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1 Introduction

This Guidance report, the fifth deliverable in a series under the DOE research award titled “Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies,” aims to provide guidance to bridge the gaps between developing innovative nuclear technologies that are nearly available or relatively mature and their practical implementation in maritime environments.

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.

Previous reports discussed specific technical and regulatory complexities that are expected to be encountered when developing and deploying advanced nuclear technologies for maritime applications. This includes specific challenges to demonstrate technology and project feasibility needed to bring a new technology to the market, as well as the challenges faced during operations and the end-of-life.

This report provides recommendations and guidance for approaching demonstration projects and overcoming challenges identified in previous reports, when designing, licensing, manufacturing, commissioning, operating, and decommissioning a nuclear-maritime application.

Recommendations and guidance span stationary or relocatable power plants (also known as Floating Nuclear Power Plants or FNPPs) and use of nuclear reactors in commercial ships. While "recommended practices" are discussed throughout this report, it's important to recognize that these are not universally "best," but are based on current knowledge and expert consensus. Decision-makers should evaluate these practices within the context of their specific regulatory, operational, and environmental conditions.

While this document is globally relevant and aims to provide guidance that transcends national boundaries, it includes specific examples from U.S. initiatives to illustrate particular points for successful implementations. Such references are intended to support DOE’s efforts through the National Reactor Innovation Center (NRIC) but are equally applicable to international projects aiming to harness advanced nuclear technologies in commercial maritime operations.

1.1 Goals and Objectives of this Research

The objective of this research is to connect the maritime industry with the nuclear industry and encourage the demonstration and commercialization of marine projects using advanced nuclear energy technologies. Initial demonstration projects may either seek to be commercially successful or generate strong evidence necessary to credibly support future commercial plans. This research project both supports the mission of the U.S. National Reactor Innovation Center (NRIC) to demonstrate projects with industry and acts as a useful resource for the various regulatory bodies and other stakeholders associated with advanced reactors.

1.2 Project Members

The American Bureau of Shipping (ABS) is a not-for-profit marine classification society for the U.S. (designated in USC §3316) and a globally recognized standards organization and research organization for the maritime industry.

The National Reactor Innovation Center (NRIC) is a DOE-funded program that provides resources and guidance for testing, demonstration, and performance assessment to accelerate the deployment of advanced nuclear energy technology concepts, including support for commercial maritime applications.

Supporting Project Advisors include the law firms of Morgan, Lewis & Bockius, LLP and Blank Rome LLP for insights into legal, licensing, and regulatory regimes.

1.3 Background

Interest in nuclear technology applications is increasing as the forecasts for future decarbonized energy identify potential gaps in energy supply and price, especially for hard-to-abate industries including some sectors of the transportation industry such as maritime transport. Additional stress is added by the simultaneous demand to scale up renewable energy installations and the projected growth in global energy demand and electrification. Furthermore, application of nuclear technologies contributes to national security by ensuring an affordable, reliable, and secure energy supply for critical commercial maritime operations and offshore energy infrastructure.

There are a growing number of advanced nuclear reactor technologies with the potential to offer solutions for these challenges, both for onshore and offshore industries, where decarbonized and sustainable heat or electrical energy production may need to be scaled up to meet demand. A number of new designs rely on proven practices of traditional water-cooled technologies but introduce new ways to deploy them in compact arrangements, using modular design and serial manufacturing practices while making major improvements to safety and operational performance.

As discussed in the first publication of this project series “Road Map for the Development of Commercial Maritime Applications of Advanced Nuclear Technology,” (1) advanced reactors are defined as:

- a. A nuclear fission reactor with improvements over the most recent generation of nuclear fission reactors, which may include
 - a. inherent safety features;
 - b. lower waste yields;
 - c. greater fuel utilization;
 - d. superior reliability;
 - e. increased resistance to proliferation;
 - f. increased thermal efficiency; and
 - g. the ability to integrate into electric and nonelectric applications, or
- b. A nuclear fusion reactor (2).

A growing number of advanced reactor designs are leveraging lessons learned from the past, using modern materials and design techniques, and progressing the development of highly versatile non-water-cooled reactor designs. This has resulted in arrangements that utilize new fuel designs, specialized coolants and a host of other features intended to make these designs more reliable, economical to

operate and offer strong safety performance. All of these technologies face the same overall challenges; where novel technologies are introduced, there is a need to test and demonstrate the technologies for safety and regulatory compliance. The more novel and complex the reactor facility design, the more analysis and testing is needed to verify the predictability of the performance under the expected operating conditions. This is not just limited to the reactors themselves but can encompass any systems or structures the reactors interface with.

Operating conditions of nuclear-maritime applications include:

- Different operating conditions where there may be complex interplay of inherent phenomena, passive and active system responses,
- Lifecycle aging conditions and varying power demand profiles,
- External influences, including operation under wind and wave motion conditions.

In the third publication of this project series, “Report on Potential Challenges and Impacts of Advanced Nuclear-Maritime Applications in the U.S.” (3), key technical, regulatory, and economic issues were introduced. To address these issues and see successful demonstration projects leading to technology deployment, stakeholders from maritime and nuclear technical and regulatory organizations and agencies must collaborate.

These recommendations and solutions presented in this document were in part obtained through the completion of a survey of industry experts who provided their views on overcoming each identified challenge. The identified challenges described for the survey are presented in Appendix 1. Issues were presented in a matrix according to technical, economic, or regulatory considerations, and responses were requested to provide insights and guidance about how to address them. Responses were categorized and tallied according to the general nature of the guidance provided, where similar advice was drawn from different respondents. Figures presented throughout this report to display the count of recommended solution strategies were derived by the categorization of survey responses. The survey responses are indicative of what strategies are considered the most relevant for specific issues, however, they are not complete or exhaustive representations of all important strategies. Additional guidance was derived from literature reviews of relevant sources including reports within this series as well as other publicly available information.

The term *demonstration* can have a different meaning depending on the interest in the work. A demonstration can be scientific, engineering or economic. It can be small scale or full scale, limited in scope or extend broadly across markets.

Recognizing that demonstration activities are a normal part of the product development cycle for any type of technology, this paper is focused more on the broader set of integrated activities that need to be conducted to convince decision makers that use of nuclear reactors for commercial maritime applications is not only viable, but also capable of being scaled up to meet modern needs for energy.

2 Recommendations to Address Key Challenges

Technology development and commercialization of advanced reactors faces a variety of potential challenges that includes demonstrating the feasibility of technologies, overcoming issues present in existing legal and institutional frameworks, paths to commercial implementation and scale-up for broad

use by end-users. Potential challenges to the adoption of nuclear technology for maritime applications are discussed in the third publication of this project series, "Report on Potential Challenges and Impacts of Advanced Nuclear-Maritime Applications in the U.S." Challenges are presented in this document according to lifecycle phase and broken down into the following categories:

- 1) Strategies To Consider Throughout the Lifecycle
 - a) Nuclear Requirements and Licensing
 - b) Overall Security, Safeguards, Non-proliferation, and Export Control
 - c) Public Policy/Public Acceptance
- 2) Strategies to Consider during Early Stages of Development
 - a) Demonstration and Testing
 - b) Establishing a Business Case
 - c) Integration of Nuclear and Maritime Systems
- 3) Strategies to Consider during Construction, Commissioning, and Establishing Infrastructure
 - a) Supply Chain and Fuel Availability
 - b) Support Infrastructure
- 4) Strategies to Consider during Operations and End-of-Life
 - a) Nuclear Waste Transport and Disposal, and Nuclear-Maritime Decommissioning & Vessel Recycling

Certain challenges and issues which are generally applicable overall, such as those related to the effort of managing proprietary information, or the implementation of AI are addressed across several categories rather than given explicit sections. This document cannot address all possible challenges but focuses on what the authors judged to be particularly important.

An example of this is the deal that Constellation Energy and Microsoft signed of a 20-year power purchasing agreement in where one of the reactors at the Three Mile Island would be brought back despite it being shut down back in 2019. The main reason that has acted upon this is due to the rising usage of energy demand as well as engaging in decarbonization. The topic of discussion that stands out is their primary use of nuclear energy to support their data centers with artificial intelligence (AI) (4). The utilization of AI is on the rise more than ever and it will only be higher by the time the FNNP are developed which leads to the question of how AI can be utilized with these FNNP through the use of automation and much more. This is a topic that can be discussed and followed up on as time passes by with the technology of nuclear industry.

To address each challenging area, multiple strategies may be implemented. Solution strategies are categorized and described below, and discussed throughout this document to address the title challenge:

Robust Testing or Demonstration:

- Strategies implemented during or related to the testing or demonstration phases of new materials or technology.
- Designing tests and demonstrations to specifically to resolve targeted issues.
- Using existing criteria and safety requirements for materials and equipment testing.
- When criteria and safety requirements do not exist for materials and equipment testing, using conservative approaches to assessing risks and holistically documenting the decision-making process.

- Performance evaluation, assessment, or verification of reactors, including supporting equipment, materials, parts, or other physical components.
- Secondary supporting aspects of manufacturing or operations, including verifying the costs of equipment or operations, establishing an understanding of reliability, or evaluating the effectiveness of supply chains.
- Verification and validation activity related to equipment and material approvals, certifications, and procedures leading up to licensing activities.

Digital Systems:

- Decisions related to digital architecture of controls or human-machine interfaces, including choosing software and designing operational controls for the use of software.
- Choosing or implementing codes or standards related to software.

Public Engagement/Public Relations (PR):

- Providing useful and informative content into the public domain and encouraging public participation
- Activities related to formal or informal education, outreach, workshops, or informational sessions for the public or directed at specific policymakers.
- Informing policy and regulatory improvements by providing credible and timely information to decision makers through their processes.
- Providing broader salient information to commercial organizations such as insurers and financial firms to enable them to formulate laws, regulations, guidance or policy.

Personnel Certification & Training:

- Differences in certification and training requirements between the reactor systems operating organization and the crew of the vessel.
- The activities of personnel related to training (before or after certification), certification requirements, and onboard drills.
- Any related training, certification, or education of non-crew or non-operating personnel, including personnel of ports, shipyards, or other land-based facilities not directly related to the operations of the nuclear-maritime application.
- Certifications and appropriate background checks or clearances for any individual, including design and review engineers, manufacturers, fabricators, inspectors, owners and operators.
- Any other personnel credentials that may be pertinent to the facility's country of origin versus country of deployment (e.g. citizenship status).

Robust Design:

- The selection of parts, materials, equipment, structures, or components. This includes the selection of suppliers or vendors.
- The selection of nuclear fuel, including the selection of suppliers or vendors over the unit's lifetime.
- The selection of appropriate locations with the right infrastructure and qualified support services to conduct maintenance activities.
- The selection of appropriate support facilities for service, repair, maintenance, and major structural inspections.

- Systematic identification and mitigation activities related to operational and technical risks, including risk identification and assessment methodologies or practices.
- Systematic overview of Safety, Security and Safeguards by design for the protection of life, property, and the environment.
- The selection of vendors or processes for nuclear systems decontamination and decommissioning (D&D) activities, including facilities, locations, and fuel/nuclear material waste management or handling processes and related equipment.
- The creation or development of supply chains for components, advanced materials, equipment, or systems necessary for the deployment of the technology with the exception of the establishment of fuel supply, which is a separate category.

Investment:

- Investment in the development and deployment of advanced nuclear technologies involves contributions from both the private and public sectors. Each plays a critical role in diversifying risks and leveraging strengths to support a robust development environment for nuclear energy in maritime applications.
- Private Sector Investment:
 - o Capital Development: Private capital is necessary for the initial development of technology, the establishment of supply chains, and the creation of necessary infrastructure.
 - o Innovation and Demonstration Support: Private funds often support concept designs, material advancements, and the demonstration of new technologies, providing flexibility and speed in responding to technological advancements.
 - o End-of-Life Management: Private investment is also dedicated to managing the end-of-life stages of nuclear applications, including decommissioning and waste management.
- Public Sector Investment
 - o Research and Development (R&D) Funding: Public funds are required for foundational research and development, often carried out in national laboratories and universities.
 - o Infrastructure and Regulatory Support: Governments can provide support for the development of necessary infrastructure and can facilitate regulatory approvals, which are critical for the deployment of nuclear technologies.
 - o Risk Mitigation: Public investment can help mitigate the financial risks associated with nuclear energy projects, making them more attractive to private investors and financial institutions.
- Collaboration Between Public and Private Sectors
 - o Joint Ventures and Partnerships: Collaborative projects between public entities and private companies can combine public oversight and standards with private innovation and efficiency.
 - o Funding Models: Hybrid funding models can be developed to share the financial burden of large-scale nuclear projects, spreading risk and leveraging public accountability with private sector agility.

Funding Policy:

- The investment of public funds towards the development of technology, the establishment of supply chains, or the creation of infrastructure.

- The investment of public funds into ownership and operating models for certain nuclear applications.
- Changes to licensing or regulatory fee mechanisms that incorporate a need for additional public funding.
- The use of public funds as collateral, insurance, or any other financial guarantee in relation to the economic liability of potential technology deployment.
- The provision of additional public funding to regulators or policymakers to support regulatory development and appropriate regulation of technology.

Leverage Government and Navy Experience:

- Government experience gained from the deployment of nuclear-maritime units.
- Experience gained by nuclear capable navies from the deployment of nuclear-maritime propulsion to the extent that such experience is relevant to commercial maritime (i.e., non-military) applications.
- Government experience gained from the study, testing, or demonstration of advanced nuclear technologies.
- Government experience gained from regulating nuclear energy or the maritime industry.
- Experience of crews or personnel familiar with Government use of nuclear-maritime applications.

Establish Fuel Supply:

- Developing fuel supplies, particularly in regard to novel fuels such as TRISO, High-Assay Low-Enriched Uranium, and Thorium.
- Developing infrastructure related to the production of nuclear fuels.
- Coordinating stakeholders to establish a robust and resilient fuel supply.

Operational Procedures:

- Operation, monitoring, refueling, maintenance, installation, and removal (for example, refueling or end-of-life) of systems composing the nuclear facility.
- Operational procedures relating to the operation of a vessel, maritime unit, or nuclear facility.
- Details of the operational profile of nuclear reactor equipped systems to be such as the geographical regions where they operate.
- Security and emergency response along with fundamental nuclear control plans.
- The decisions and choices made to establish trade routes, operating regions, or any geological operational considerations that may affect access to ports, trace and cargo availability, or any restrictions necessary for the safety or ease of operations.

Novel Ownership Arrangements:

- Implementing a leasing scheme where ownership of a reactor and the rest of the facility or vessel is separated.
- Arranging administrative responsibilities at the facility or vessel level and within the owner/operator chain of command, as well as ports or other supporting facilities for the purpose of liability.
- Implementing other innovative ownership arrangements which may not be common in the nuclear or maritime industry.

Code Standardization and Regulatory Harmonization:

- Where regulatory authorities have different technical requirements for the same subjects, the harmonization of requirements across national or international organizations refers to general efforts to provide alignment and regulatory agreement between authorities¹.
- Standardizing engineering codes and other standards applicable to the development of nuclear-maritime technology.
- Addressing or bridging regulatory gaps which may present challenges towards adopting nuclear-maritime technology.
- Creating new laws, regulations or licensing mechanisms relevant to nuclear-maritime technology.
- Creating international treaties or frameworks which may govern applications of nuclear-maritime technology.

Leverage Land-Based Nuclear Experience:

- Experience obtained from a successful land-based reactor demonstration or deployment which may be relevant in overcoming challenges associated with the deployment of the technology or a subset of that technology in maritime applications.
- Experience related to the development of land-based nuclear technology.
- Identifying challenges for maritime reactors that may have been, or reasonably would be, eliminated or overcome by previous land-based nuclear deployments.

2.1 Nuclear Requirements and Licensing

In the nuclear power sector, licensing is application-, operator- and site-specific. That is, each power plant or even research reactor is subject to a domestic licensing process that focuses on the organization conducting the activities. The conduct of activities includes, for example, the operation and maintenance of reactor systems and any other systems that could adversely impact nuclear safety and security. Licensing may apply to demonstration activities where those activities fall under specific laws or regulations. As a result, who executes the activities and how they are conducted needs to be planned in consideration of what licenses may be needed. Many countries have made efforts over the past decade to adapt licensing processes to allow for new reactor designs or lower the costs of the licensing process. Although these efforts have largely been prescriptive to large light water reactors. However, the primary challenge to conducting marine demonstration licensing is the lack of a licensing process that is independent from the site location. Currently, licensing processes in the vast majority of IAEA member states do not consider a reactor moving from one location to another by land or marine.

Design certification is a tool used by regulators in some countries either within or separate from a licensing process to allow for structured engagement that results in binding decision making and as a measure of

¹ Note the discussion about harmonization in Carson et.al.'s 2023 WNA Report *A Framework for International Regulatory Efficiency to Accelerate Nuclear Deployment*: "Often when the subject of deploying standard reactor designs throughout the world is discussed, the word 'harmonization' is used to describe the need in relation to regulatory requirements or codes and standards. However, there are many different ideas about what harmonization means, and so [that] paper introduces the term of efficiency to ensure alignment of perspectives. Efficiency refers to the continuous improvement that is desired to be achieved through bi- and multi-lateral regulatory design review activities." (6)

regulatory certainty. Certification is most useful and economic when a design is mature and is not likely to substantially change. As a result, design certification is not recommended for demonstration or even FOAK activities as any substantive changes to the design will warrant a reopening of the certification. This can be expensive and very time-consuming.

Some challenges in relation to nuclear licensing include the following:

- **Licensing or equipment certification may require re-design or additional testing and demonstration efforts.** Leading up to licensing or certification, testing and demonstration efforts may result in a modification of design and subsequent re-testing as a normal part of the design optimization process. Unforeseen or unexpected test results that require major design changes may require substantial added effort for all design, testing, and licensing parties. Nuclear licensing may require certain engineering standards or codes to be used as well as the qualification of specific new technologies. Advanced reactor designs employing new materials or equipment with low technology maturity levels may prove a hurdle, particularly to demonstration projects and early adopters of nuclear-maritime applications.
- **The period of licensing may not be expedited, resulting in severe delays.** The need to validate, verify, certify and license technologies and processes related to certain safety and regulatory requirements may require more effort to address uncertainties related with operating in the marine environment that could present safety and security risks. If unanticipated, these uncertainties would be the cause of unforeseen delays and extra expense. Costs associated with either late engagement with the regulator and other stakeholders or the premature initiation of testing, analysis and licensing activities, may affect the financial viability of nuclear power in the maritime industry and have the potential to be a disadvantage compared to alternative energy sources.
- **Licensing effort may be challenging for new or unique technology or applications without sufficient operating experience.** This is likely to be most pronounced for demonstration projects or FOAK technology, where regulations do not clearly guide the industry on the required testing or demonstration criteria for nuclear applications in the maritime industry.

A breakdown of the responses from industry experts is shown in

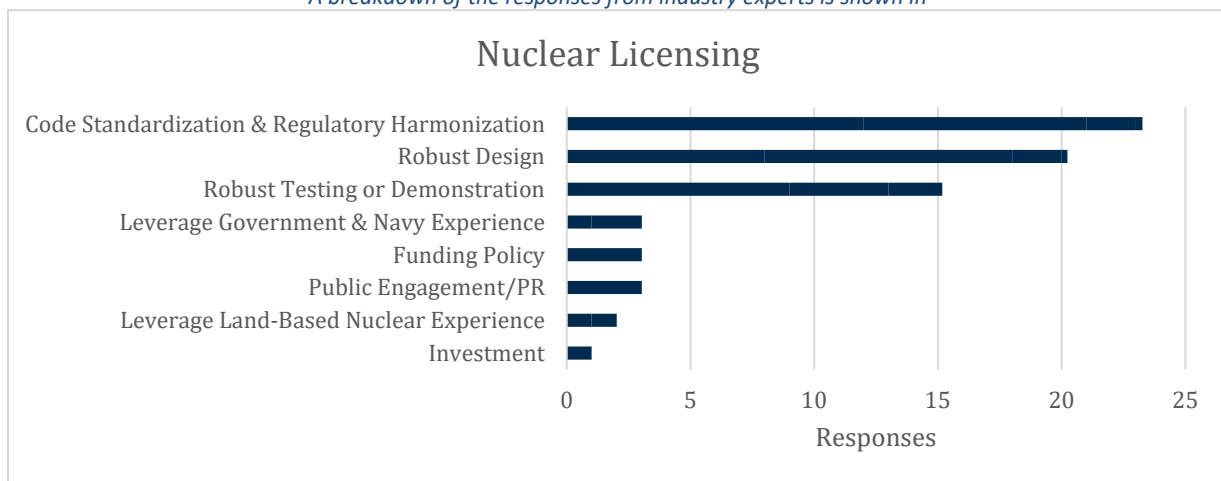


Figure 1 to understand the recommended approaches to address nuclear licensing challenges.

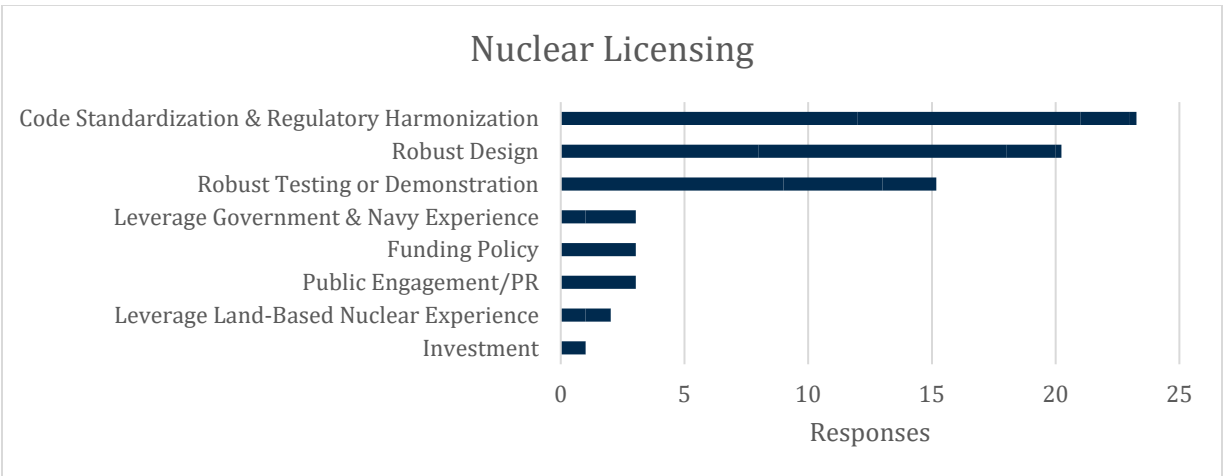


Figure 1: Addressing Challenges Related to Nuclear Licensing

While solutions related to code standardization and regulatory harmonization were naturally offered, many other solutions were provided related to the robust design and the robust demonstration or testing of the technology. That is, with appropriate design and demonstration measures addressed in the early stages of development, bottlenecks or uncertainties related to licensing nuclear-maritime activities may be better understood and more easily addressed.

Initial demonstrations and first movers have the potential to ‘clear the path’ for future activities by first navigating the licensing process and experiencing the extent of challenges and other problems. Lessons learned should be incorporated and implemented in later efforts to develop a streamlined process.

These challenges related to licensing will need to be overcome for nuclear energy to become widespread in the maritime industry. Various solutions or approaches are discussed below that may address one or more of the listed nuclear licensing challenges.

2.1.1 Code Standardization and Regulatory Harmonization

Establishing a clear and efficient process to license demonstration and deployment activities for advanced reactor technologies intended for marine applications may be a necessary first step success. Early engagement activities between stakeholders and regulators during the design and initial demonstration processes have the potential to identify and resolve issues early. Early engagement also gives the regulator time to develop substantive regulatory positions for use in licensing. These positions can inform refinement of laws and regulations, potentially resulting in more streamlined project licensing.

In the U.S., engagement with the NRC during the creation of new regulations such as 10 CFR Part 53 may be particularly beneficial in establishing and clarifying regulatory frameworks, for example, during the public comment periods of proposed regulations. Regardless, the nature of nuclear energy and its risks mean that a licensing process will exist for nuclear applications when compared to competing alternative energy sources, resulting in the possible need for unique considerations and mechanisms to allow nuclear energy to remain competitive. Preapplication engagement may be particularly useful in limiting the potential effects of regulatory licensing delays.

Where gaps in existing engineering design codes and licensing requirements exist, the application of a Technology-Inclusive Risk-Informed, and Performance-Based (TI-RIPB (5)) approach compatible with

existing guidelines may assist in ensuring the successful development, testing, demonstration, and licensing of materials, components, or systems. This highlights the importance of working with regulators to ensure the inclusion of the TI-RIPB mechanism in the licensing process for advanced nuclear technology.

2.1.2 Robust Design

The potential costs and difficulties that may be encountered throughout the licensing process must be considered far ahead of time during the design process, as understanding and incorporating these costs early on can avoid unexpected costs or delays later.

During initial demonstrations, designing for ease of approvals may be facilitated by designs incorporating known materials and components which have already been approved or those that have higher levels of technical maturity, and therefore can decrease risks or impacts of re-testing or re-design. Possible technical problems and issues must be identified and addressed in the early stages of demonstration, i.e., during pre-application, vendor design review, and pre-licensing activities, to prevent licensing delays.

The potential deployment of reactors of the same type across different environments (including internationally) may facilitate the licensing process related to design certification and manufacturing licenses and decrease the costs for individual deployments. For example, implementing modular reactor designs that may only require one certification and are suitable for various applications, such as those proposed in Carson et.al.'s 2023 WNA report "A Framework for International Regulatory Efficiency to Accelerate Nuclear Deployment" (6).

Industry stakeholders may benefit from engagements with other stakeholders and regulators to identify opportunities that can enable regulatory and licensing reviews to begin as early as possible, for example, the multilateral regulatory review activities for the GE-Hitachi BWRX-300 reactor design joint regulatory review in the U.S. and Canada, or the EDF NUWARD joint review activities in France, Finland and the Czech Republic (6).

2.1.3 Robust Testing and Demonstration

To overcome challenges which may be present during the demonstration of new technologies, testing is a necessary practice to verify the performance and effectiveness of components and materials before being implemented in final designs. Potential considerations for initial demonstration deployments may include limiting the geographical scope to a U.S. Department of Energy (DOE) reservation or a U.S. Department of Defense (DOD) site if applicable, as this could ease the licensing effort with respect to security.

2.1.4 Funding Policy

Licensing demonstration activities can be expensive and time consuming compared to the design and demonstration effort. The more novel the methods and technologies, the more complex licensing becomes. Thus, a model that could be adopted is a funding or voucher process for developers to receive relief for innovative work that requires licensing.

Respondents stated that if the U.S. Congress modifies the funding mechanisms of the NRC, then there may be potential benefits in facilitating the licensing process of advanced reactors and facilities as well as potentially lowering their associated costs. For most of its existence, Congress has required that the NRC recoup the vast majority (90%) of its operating costs through fees charged to the regulated industry, with

taxpayer dollars accounting for the other 10% (7). This is important to highlight because this balance is not the same across all U.S. regulators. The U.S. Food and Drug Administration (FDA), for example, recovers 60% of its budget through taxpayer dollars (8).

Congress addressed this issue through the “Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2024” (the “ADVANCE Act”) (9). Section 201 of the ADVANCE Act reduces—essentially by half—the hourly rate for NRC Staff that is charged to advanced nuclear reactor pre-applicants and applicants. The ADVANCE Act establishes a sunset date of September 30, 2029, for the reduced hourly rate for pre-applicants. This time limitation is intended to encourage advanced nuclear companies to prioritize resources to engage with the NRC in the near-term to receive licenses for FOAK designs.

Each of the provisions in the ADVANCE Act will have an important impact on the NRC and its ability to license novel advanced reactor technologies in the coming years. One of the most notable sections of the Act calls on the agency to update its mission statement to include efficient licensing and regulation while recognizing “the benefits of civilian use of radioactive materials and nuclear energy technology to society.” Some of the provisions could specifically support the development of maritime reactors, including:

- Majority foreign ownership: the act creates concessions concerning a prohibition on majority foreign ownership of NRC-licensed nuclear facilities such as nuclear power plants. In the past, this provision has generally stifled foreign investment in the U.S. nuclear industry. Importantly, the law would maintain national security requirements such as a restriction of licensing to the Organization for Economic Cooperation and Development (OECD) countries and India. This change in the rules could also potentially work well with a new suite of financing tools for SMRs that was recently published by the U.S. Export-Import Bank (10).
- Microreactors: The NRC will have 18 months from the Act enforcement to develop risk-informed and performance-based strategies and guidance for licensing microreactors. This is notable because the Act names some of the unique considerations of microreactors, which include safeguards and security, the transportation of fueled microreactors, and licensing mobile deployments.
- Licensing considerations for non-electric applications: The NRC will need to submit a report to congress on "unique licensing issues or requirements" relating to flexible operations, the use of reactors exclusively for non-electric applications, and co-location of reactors with "industrial plants or other facilities." Because the report will need to consider input from a wide range of stakeholders, this could present an opportunity to the maritime sector to provide feedback and considerations.
- National Environmental Policy Act (NEPA): The NRC will have to develop and submit to Congress a plan that focuses on streamlining the Agency’s environmental review process. This is important considering the weight that these reviews carry during plant siting, which itself is a key sticking point for licensing maritime reactors. Combined with a mandate to clarify the licensing of microreactors, a renewed focus on efficient environmental permitting could present another potential avenue for the maritime sector to share its unique perspective and interest in maritime reactors.

2.1.5 Leverage Land-Based Nuclear Experience

Materials, systems, fuels, and components in relation to an advanced nuclear reactor for a maritime facility or unit that has previously been used and licensed for land-based applications may have higher technology maturity levels than new systems that have not been licensed or certified. However, even with systems that have been previously licensed and used on land-based nuclear plants, some additional testing, simulation or demonstration may be needed to demonstrate suitability for use in marine applications.

While some modification may be needed to support the use of the product in the maritime environment (i.e., marinization), the licensing process for a component that is already qualified and has been used in previous applications may be simplified, with the possible exception of security-related elements, for use in initial maritime demonstration projects.



*Figure 2 Plant Vogtle in Waynesboro, Georgia
Office of Nuclear Energy (81)*

2.2 Security and Non-proliferation

To prevent the misuse of nuclear materials and technology for nuclear weapons, unsafeguarded fuel cycle activities, or nuclear terrorism, the international community has developed and agreed to a framework for nuclear security and nonproliferation. This framework, which consists of various treaties, conventions, and other regimes, supports international cooperation and facilitates the trade and information exchange needed for building land-based nuclear power plants which may not be directly applicable to civil nuclear maritime applications. In various fora, including the International Atomic Energy Agency (IAEA) and the International Maritime Organization (IMO), governments, nuclear and maritime industry, and other stakeholders are studying the particulars of civil nuclear maritime nuclear applications. They are considering how the existing frameworks for both nuclear and maritime can be applied in an efficient and effective manner to address any gaps and challenges that the various civil nuclear maritime deployment scenarios being discussed pose to nuclear security, safeguards, and the framework for civil nuclear cooperation including export controls. This will likely lead to more and specific guidance to address this aspect of the civil deployment of nuclear technologies in the maritime environment.

2.2.1 Security

Nuclear security focuses on the prevention, detection, and response to malicious acts such as theft, sabotage, unauthorized access, and illicit trafficking of nuclear and other radioactive materials. States Parties to the Convention on the Physical Protection of Nuclear Material and its Amendment (A/CPPNM) are responsible for establishing a nuclear security regime that guarantees the physical protection of nuclear material during use, storage, and transport.

The A/CPPNM applies unequivocally to civil maritime nuclear applications such as deployment of Floating Nuclear Power Plants (FNPPs) and Civil Nuclear Propulsion. While the A/CPPNM applies, questions

specific to regulatory and technical implementation of nuclear security regimes in these new operational environments need to be answered. This includes but is not limited to identifying State responsibility for FNPPs when deployed extraterritorially, design of physical protection systems, and coordinating response for civil maritime nuclear applications when they are deployed offshore.



Figure 3 PNTL Vessel Pacific Heron [8]

Designers are encouraged to engage with project proponents and regulators to understand the specific security requirements for civil maritime nuclear applications and apply these early in their design process (security by design). The U.S. government provides support and training to vendors through the Department of Energy/National Nuclear Security Administration's (DOE/NNSA's) International Nuclear Security for Advanced Reactors (INSTAR) program.

2.2.2 Safeguards

International safeguards applied by the IAEA are an important element of the global nuclear nonproliferation regime. Safeguards are a set of technical, legal, and administrative measures that are applied by the IAEA to ensure that nuclear facilities are not misused, and nuclear material is not diverted from peaceful uses.

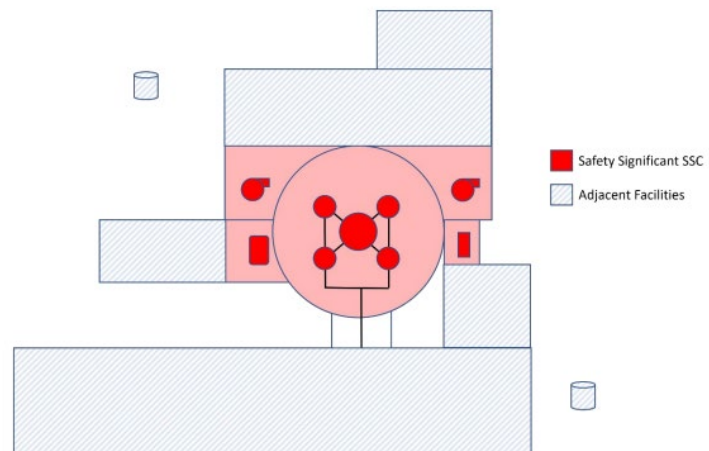


Figure 4: Concept of "Safety Significant" SSCs from a Separation Approach [17]

In the context of civil nuclear maritime applications, both fundamental and practical challenges are being considered. Fundamental challenges include questions about who has control over the nuclear material and the reactor, and how IMO rules on territory and jurisdiction relate to those in nuclear safeguards agreements. Practical challenges include the ability to apply containment and surveillance measures in the maritime environment, nuclear material accounting for novel reactor types and deployment models, and the ability of the IAEA to verify the completeness and correctness of declared nuclear materials.

Designers are encouraged to engage with customers and regulators to understand the specific safeguards requirements and apply these early in their design process (safeguards by design). The U.S. government provides support and training to developers through DOE/NNSA's Advanced Reactor International Safeguards Engagement (ARISE) program.

2.2.3 Export Controls

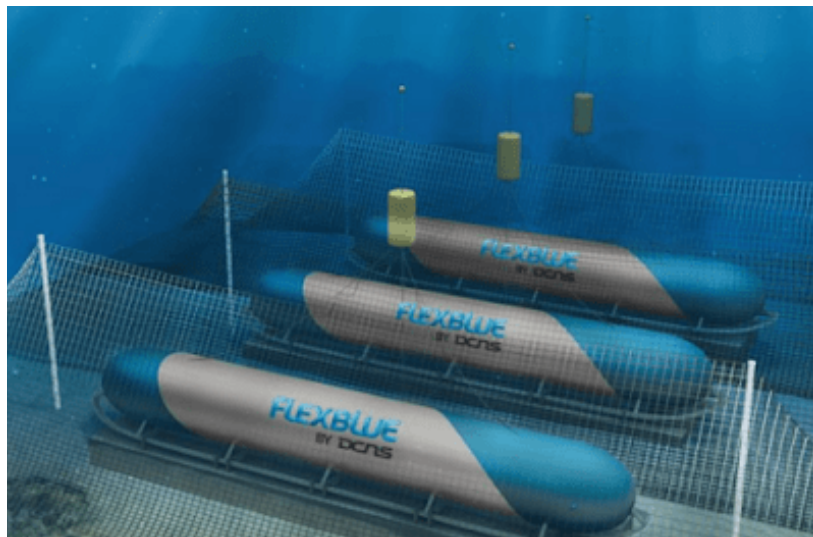


Figure 5: Flexblue Concept for Underwater Seabed Reactor Developed by France's Naval Group (Formerly DCNS)

Peaceful nuclear cooperation agreements (NCA) and export controls provide the legal and regulatory framework that facilitate the transfer of nuclear technology for peaceful applications and address, among other things, physical protection and application of international safeguards. Civil nuclear deployment in the maritime environment raises novel questions regarding the intersection of nuclear and maritime law that must be considered specific to NCAs and export controls.

In the United States, Section 123 of the U.S. Atomic Energy Act of 1954, as amended (AEA), requires the conclusion of an NCA for significant exports of nuclear material or equipment from the United States ("123 Agreement"), establishing the framework for civil nuclear cooperation. In addition to nuclear exports, these 123 Agreements facilitate cooperation in other areas, such as technical exchanges, scientific research, and safeguards discussions. In line with Section 123 of the AEA, 123 Agreements must meet nine nonproliferation criteria, thereby advancing the nonproliferation principles enshrined in the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and providing a framework for facilitating peaceful nuclear trade.

The AEA provides the statutory basis for U.S. nuclear export controls found in 10 CFR Parts 810 and 110, which cover the export of nuclear material, equipment, and technology for peaceful uses. In addition, to Part 810 and 110, consideration must be given to the broader framework of U.S. export controls as they may be applied to civil nuclear maritime applications including the U.S. Department of State's International Traffic in Arms Regulations (ITAR) and the U.S. Munitions List at 22 CFR Parts 120-130 and Department of Commerce's Export Administration Regulations at 15 CFR Part 730 et seq.

Consideration must be given to whether the current statutory basis for 123 Agreements, including "Subsequent Agreements," and nuclear export controls adequately address the novel questions raised by

civil nuclear maritime deployment. This must be done in a way that continues to facilitate trade for peaceful purposes while ensuring nuclear security and nonproliferation measures.

2.2.4 Personnel Certification & Training

Crew and personnel arrangements for any maritime unit or facility incorporating nuclear reactors is an important component of effective security, safeguards and non-proliferation. Yet, all personnel have the potential to become insider threats, either maliciously or by unintentionally creating latent vulnerabilities. Every person who interfaces with nuclear operations and maintenance needs to be security vetted by qualified authorities but also be regularly assessed by facility security staff in how they carry out their work. Because nuclear security is a national responsibility, the vetting process also includes assessment by national security authorities which may also pose restrictions based on nationality and citizenship status.

For example, maritime applications deployed solely in U.S. waters may require crewing to exclude unauthorized Foreign Nationals.

Additional security measures (i.e. need to know) are normally required for personnel depending on their need to access sensitive information, for example, necessitating acquiring government-issued clearances to access Safeguards Information (as defined in the U.S. Atomic Energy Act of 1954, as amended). According to the consequences and frequencies of the identified risks, security measures may include armed personnel permanently stationed at the unit or facility to dissuade or



Figure 6: Officers of the CNC providing protection for shipments of MOX Fuel and Plutonium

protect against a direct attack. For example, under existing regulations for land-based nuclear facilities in the U.S., the NRC requires the presence of at least 10 security personnel on site at all times, which can result in dozens of full-time security guards across all shifts. For example, a 2019 study completed by J. Conway, et al. (20) calculated that a floating nuclear power plant may require as many as 96 annual full-time employees to fulfill all necessary security roles across shifts. In other countries, laws and regulations may differ but generally prescribe specific security measures to be in place, including types of qualified security staff. Security plans are produced according to the DBT.

Shipping companies involved in international transport of nuclear material employ armed personnel on board. Vessels operated by PNTL, for example, have security personnel employed by the Civil Nuclear Constabulary (CNC) provide protection from departure to arrival for shipments of Mixed Oxide Fuel (MOX) and Plutonium (26) (note that these fuel forms are may not be used for advanced commercial reactor designs due to proliferation concerns although they are currently used in operating land-based nuclear

power plants). These personnel are armed with weapons that include rifles, pistols, and shotguns, and they also have access to protective equipment such as body armor and gas masks (17). However, the value of a marine based reactor may be quite different to security threats, requiring additional security measures. For example, nuclear power plants need to address intentional vehicle and aircraft collisions in the facility design (29). For a marine based facility, a ship collision will need to be addressed, and regulators need to clarify if the intentional aircraft crash scenario still applies. These require measures beyond what normal security contingencies address.

2.2.5 Digital Systems

The maritime sector already uses a significant degree of digital automation to operate and maintain their systems as well as optimize the economics of the crew needed to operate the vessel. The nuclear industry is highly conservative in its adoption of modern digital instrumentation systems. The primary reasons for this are:

- The safety analysis of a nuclear facility can become incredibly complex and expensive as these systems become more complex and reliable performance becomes harder to predict.
- For a facility that is expected to operate for 60+ years, rapid obsolescence of electronics makes maintenance very expensive. Upgrading equipment to newer design means costly rework of nuclear safety analysis which underpins a licensing basis.
- Increased cybersecurity risks arise as systems are expanded to gather and process more information.

Advanced reactors are being designed to implement digital tools and systems to enhance operability, maintainability and reduce personnel costs.

Digital systems that incorporate robust cybersecurity features are a highly useful tool for the successful implementation of nuclear reactors in maritime systems because they can enhance detection of threats and complement human response to mitigate the events resulting from the threats. However, the potential implications of cyberattack need to be taken into account where systems important to safety, security and safeguards can be compromised, leading to nuclear events with consequences to personnel, the public and the environment.

The above concerns apply equally to both marine-based and land-based facilities. What makes certain marine based systems different is the mobility and variability of locations (e.g. remote sites) and personnel that may be accessing the systems for maintenance (e.g. contractors in different deployment countries). The use of remote communication technologies presents a specific vulnerability if important plant systems are not appropriately firewalled.

Cybersecurity requirements will likely be the same as those in place in land-based reactors and will need to include appropriately qualified operations and maintenance staff within a strong security and cybersecurity culture. The main challenge for the design of marine facilities is agreeing on which requirements and technical standards to follow such that they will be accepted for use in a wide variety of deployment countries.

2.3 Public Policy/Public Acceptance Challenges

The history of public responses to nuclear accidents may present a hurdle for support and authorization of nuclear projects from governments and policymakers. Risks associated with political uncertainties may also introduce additional risks to investors, potentially delaying the deployment of the technology.

To successfully deploy advanced nuclear technology, the strategies employed by first movers to engage the public and campaign for public acceptance will offer a precedent to others to learn and improve upon. Proponents need to ensure that the public, and particularly communities that may be most impacted by the technology, have confidence in the safety and technical success of the units, as well as the laws and regulations that govern their use. The following are identified as potential risks to advanced nuclear-maritime deployments regarding public acceptance and public policy, especially if they occur as consequences of poor public acceptance:

- **Engineering solutions are needed to address risk reduction measures at all phases and for all components.** Analyzing and reducing risks typically begins in the design stage, but may not always consider public perception, or what the public may consider acceptable levels of risk at the early stages of project development. Public acceptance may be a major factor in determining the success of nuclear-maritime deployments.
-
- **Public perception may result in restrictive transport or trade policy, laws or regulations regionally or globally.** This may limit the operational regions for nuclear-maritime applications, as well as potentially add uncertainties and risks.
-
- **Public perception may limit investment opportunities.** The combination of potential risks and uncertainties stemming from public perception may limit public and private investment, which may consequently effect the development and adoption of the technology.
-
- **Public perception may change the number of dedicated engineers and technicians interested in supporting the development of the technology.** It is possible that there may be a fluctuation in the available workforce as perceptions of risks associated with nuclear technologies evolve. This may present different hiring landscapes for acquiring qualified personnel when compared to competing industries.

The above challenges related to public acceptance will need to be overcome for nuclear energy to become widespread in the maritime industry. Several solutions or approaches are discussed below, which, alone or in combination, may address one or more of the listed public policy and public acceptance issues.

A breakdown of the responses from industry experts is shown in Figure 7 to understand approaches to addressing issues related to public policy/public acceptance. Recommendations to address public perceptions are distributed across a few categories and focus on robust design strategies to address public concern and specific functions of funding policies to raise awareness and grow public engagement and confidence in the technology.

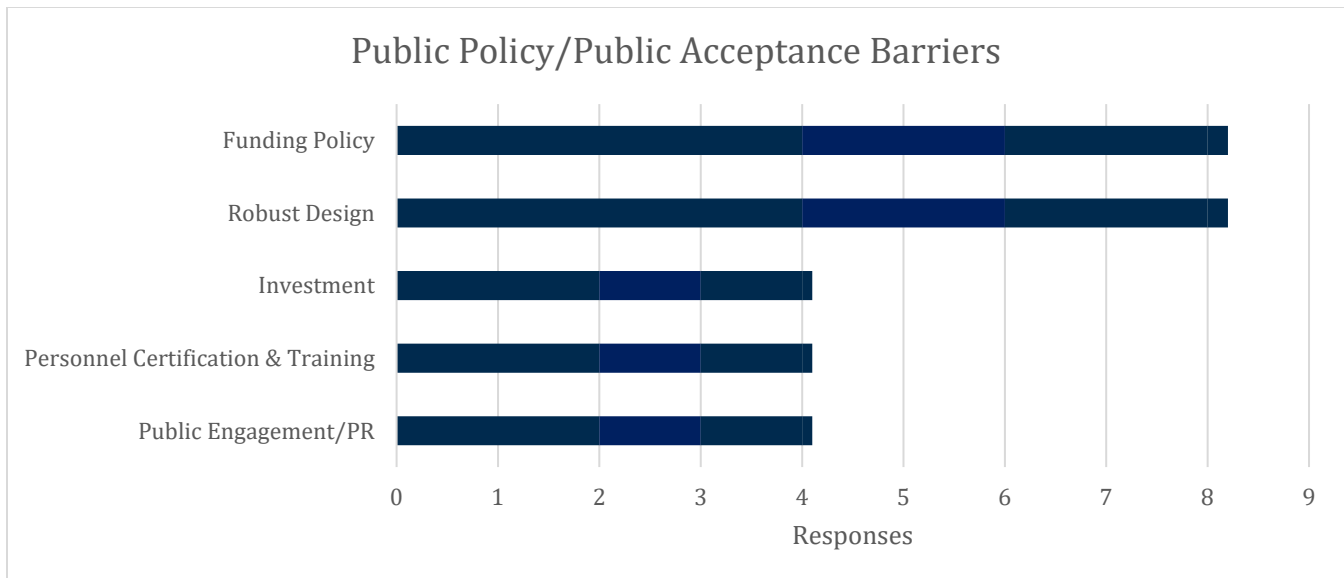


Figure 7: Addressing Challenges Related to Public Policy/Public Acceptance

2.3.1 Robust Design

Advanced nuclear technology may have many potential benefits compared to traditional technology regarding potential inherent safety features and scaling up decarbonized energy. When technological developments are leveraged to showcase reduced risk profiles and environmental benefits, there is potential for public confidence in the technology to improve.

For example, the absence of a pressurized coolant in some reactor concepts, such as those employing molten metal or salt coolants, may lower the likelihood of high pressure-related failures, and consequently lower the potential severity of a failure mode. Additionally, advanced nuclear reactors may also be designed with passive safety features including MSR drain tanks and freeze plugs, significantly higher negative reactivity feedback, or other innovative reactor arrangements compared to traditional LWRs. Showcasing how these engineering solutions reduce risk can encourage public support for the technology.

The marine environment may also provide unique benefits compared to some land-based applications which may ease public concerns, such as the potential deployment of reactors offshore and away from population centers as well as the potential for mobile applications to reduce the risks of proximity to individual communities.

2.3.2 Public Engagement/Public Relations (PR)

Efforts aimed towards the education of the public to increase the understanding of advanced nuclear technology may prove to be useful in overcoming potential challenges. Many apprehensions held by the public regarding the potential risks of a nuclear or radiation incident may be based on outdated or misconstrued understandings of radiation physics or of modern improved technology safety features.

Public outreach and education about realistic risks and potential effects of a technology failure based in modern understanding of the effects of radiation and current technological developments may assist in easing negative perceptions of nuclear energy applications (30).

Early engagement with the public as well as with institutions involved in science and technology education have the potential to obtain social license early on and be a major factor in determining the timeline and scope for adopting new technologies.

Leveraging the aspects of advanced nuclear technology in maritime applications, that may be perceived as particularly interesting or attractive, may reduce risks associated with a reduced available workforce by attracting new talent. Actively leveraging public channels such as social media sites can be impactful strategies to grow public support through sharing information, explaining technology and discussing the benefits of nuclear energy. Communication from individual public figures, celebrities, or leaders may also be impactful strategies to convey messages and engage the public.

A 2023 study published by Radiant Energy Group regarding the global public perception of nuclear energy (31) has shown that global supporters of nuclear energy may outnumber those who oppose it by a factor of 1.5, with the number being slightly higher in the U.S.. Results also showed that familiarity and knowledge regarding nuclear energy may have a correlation with supporting its implementation. These results suggest that the public may be more accepting of nuclear technology today than is often assumed, while also demonstrating the importance of education and outreach.

Additionally, it may prove beneficial to convey the role of nuclear energy to reduce carbon emissions and facilitate an energy transition. Since the turn of the century, increased environmental activism has driven the implementation of local and regional decarbonization policies and sustainable market developments. The public is generally supportive of reducing emissions and developing sustainable energy solutions. When it can be shown that nuclear power supports these initiatives, further public acceptance may be achieved.

It is important to note that support for nuclear projects at the national level and local level are earned in different ways. While support for nuclear energy can be earned at the national level through educational programs, securing social license at the local level (i.e. ports) for projects requires robust community engagement programs. These programs actively involve local elected and unelected leadership in project planning to ensure that communities accept the risks and benefits associated with advanced reactors.

2.3.3 Leverage Government, Navy, and other Experience

Investigating the PR strategies used by nuclear navies may be beneficial, as their nuclear propulsion deployments have survived public acceptance challenges.

The U.S. Navy's nuclear program may serve as a demonstration of the safety and viability of nuclear reactors. Since a minor incident related to the primary coolant leakage in 1973 on the nuclear submarine USS *Guardfish*, there have been no known radiation leaks affecting crews or the public. This track record underscores the U.S. Navy's successful operation of nuclear reactors on ships and submarines, such as the aircraft carrier USS *Gerald Ford* shown in Figure 8, demonstrate robust safety protocols and operational excellence (32). The nuclear safety record of the global Naval nuclear programs, as well as the wide deployment to various global ports may be leveraged to help with public acceptance of commercial nuclear-maritime technology.



Figure 8: USS Gerald R. Ford (26)

2.4 Demonstration and Testing

FOAK technology demonstration projects for the application of advanced nuclear reactors in the maritime industry may encounter challenges during testing and demonstration phases, including increased costs and extended schedules. These potential challenges related to demonstration and testing activities are discussed below in more detail.

- **Design may use new, innovative materials and systems not tested or approved.** The need may arise to use different materials or systems from land-based reactor designs that are more suitable for the marine environment which may not have been tested or approved.
- **Specific maritime nuclear testing equipment and platforms may need to be developed.** The possibility exists that systems and materials that may already be tested and approved for land-based applications would need to be specifically tested for viability in the marine environment. This has the potential to further delay demonstrations as well as increase costs.
- **Code cases for material may be needed.** New standards or codes may need to be developed for approving advanced materials which may require years of material testing and verification, potentially restricting the use of specific materials and components and affecting the technical quality of the product. Current LWR-based standards may be overconservative and therefore impose unnecessary costs to advanced nuclear reactors that don't need to meet the requirements due to enhanced safety features like passive cooling or negative feedback. The administrative and organizational effort to develop new codes and standards may be burdensome to the stakeholders involved. This could potentially lead to delays, increased costs, and other design constraints.
- **Technology failure may involve potentially severe environmental consequences.** Technology failure during demonstration and testing activities, ranging in severity from a small radiation leak to a catastrophic failure, could pose long term effects to the surrounding environment and communities, as well as additional consequences for the continued development of that technology.
- **Technology failure may involve potentially severe political and regulatory consequences.** Technology failure during demonstration and testing activities may also incur indirect consequences related to public perception, developing laws and regulations, or geopolitics.
- **Technology failure may involve potentially severe economic consequences.** Although major demonstration failures are unlikely to occur due to the approval controls in place, any potential costs associated with cleanup, remediation, or compensation of affected parties in the event of a failure during demonstration or testing may prove prohibitive for continued design development. Additionally, technology failure in early demonstration and testing phases may diminish investor confidence, potentially reducing available funding for future projects.

All of the above are risks that need to be addressed in the planning and execution of demonstration projects. Several potential risk mitigation solutions or approaches are discussed below, which, alone or in combination, may address one or more of the listed demonstration and testing issues.

A breakdown of the responses from industry experts is shown in Figure 9 to understand the types of approaches to addressing issues related to demonstration and testing. Specific guidance emphasizes robust testing or demonstration schemes. Other emphasis on robust design may be related to appropriate planning for demonstration and testing ahead of time, according to the needs of the design.

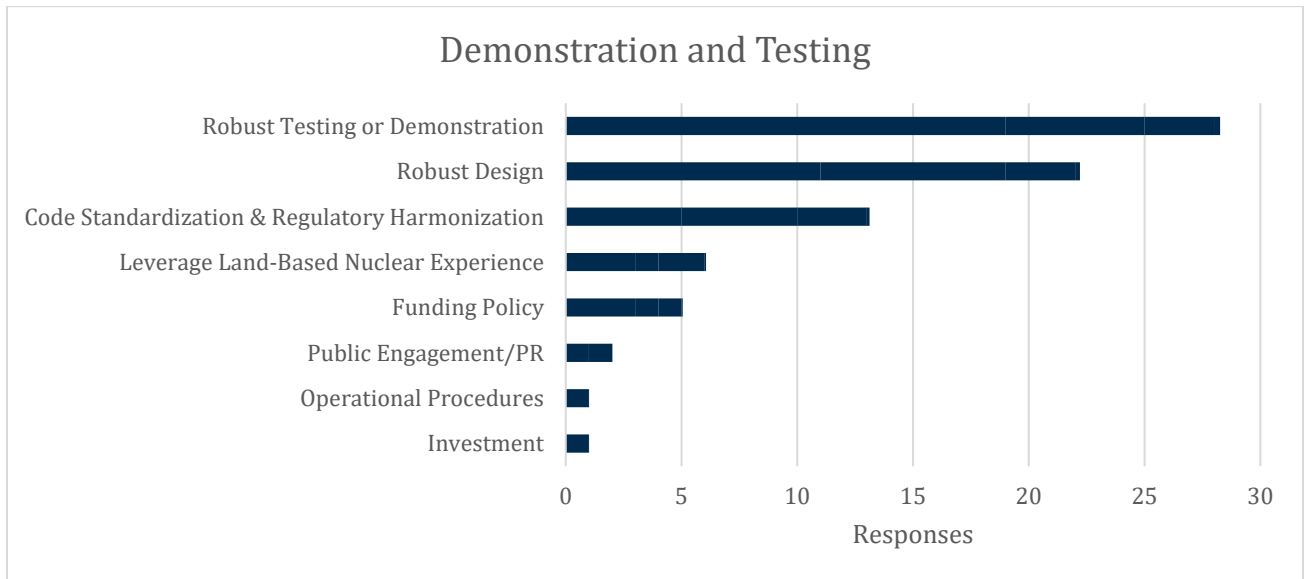


Figure 9: Strategies recommended to Address Challenges Related to Demonstration and Testing

2.4.1 Robust Testing and Demonstration

A technology demonstration project involves a certain amount of risk by default as early technology development functions as an information gathering exercise. As a result, these risks need to be understood and addressed appropriately in a Risk Informed Decision Making (RIDM) framework that includes safety, security and economic impacts of events or setbacks that could occur. Methods for accomplishing this could include having plans in place to respond to unexpected material performance tests and minimize potential resulting delays. Demonstration project timelines should account for possible delays. Additionally, the demonstration and testing process may limit costs and delays by potentially leveraging computer modeling and simulation, existing modeling, test, or prototypical testing facilities such as seismic rigs, tow tanks and model basins, where applicable. Data from tests and demonstrations of materials, components, or systems undertaken in the early decades of nuclear energy technology development may not be fully compatible, of sufficient fidelity or approved to meet quality requirements, as evidence may be insufficient or obsolete in validating their applicability (33).

Regarding the possible severity of the consequences of a failure during the demonstration, credible failure scenarios should be systematically identified, and risks ranked to inform the need for the testing and demonstration. In some cases, bounding scenarios can be proposed that encompass a group of lesser scenarios to simplify the analyses. While certain tests may be necessary to determine the limits of when a material or system might fail, design and control measures need to be implemented as part of a good safety culture to address potential failures and limit consequences during testing.

Strategic deployment of testing and demonstration activities should consider addressing issues in series according to complexity, starting with achievable engineering demonstrations and systematically increase in effort.

The demonstration of a docked FNPP is a logical first step in the deployment of advanced reactors in maritime operations due to its similarity to land-based reactors. The simplest version of this is a facility that will be stationed at a site for a long period of time and designed to generate electricity. An FNPP concept may have particular prospects for economic viability, as they may be deployed in isolated or remote areas such as island nations where constructing land-based power plants is difficult. Many existing floating power plants have dual-fuel capabilities, utilizing liquefied natural gas (LNG) as well as fuel oil to produce power. The use of traditional (non-nuclear) fuels requires significant infrastructure in addition to the power generation unit, such as a fuel storage unit which can take the form of a permanently moored tanker or LNG carrier. Land-based traditionally fueled units also require fuel availability and regular fuel deliveries sufficient for its power needs, which is difficult to achieve in many environments and conditions such as in remote arctic regions or during storm conditions. FNPP concepts may have advantages in these regards as they would not necessitate a frequent supply of new fuel or fuel storage facilities, while also eliminating carbon emissions.

A notable gap between industry testing needs and U.S. university and national laboratories' testing capability was identified in fourth report of this series, Readiness Report for DOE Support of Maritime-Related Demonstration Projects of Advanced Nuclear Technology. This is the inability to test maritime nuclear power plants in a ship motion environment. NRIC prepared a subsequent report, Ship Motion Testing Needs Evaluation that identifies the need to test for thermal-hydraulic phenomena to close the gap in understanding a nuclear plant's behavior in a ship motion environment. NRIC also prepared a second report, Engineering Requirements and Capital Cost Estimation for a Ship Motion Test Facility, that outlines the requirements for a facility capable of testing these thermal hydraulic phenomena. Government funding support for such a facility would provide testing capabilities that would benefit multiple nuclear reactor technologies and multiple maritime applications with data that is necessary for future license applications.

The next logical step, albeit with a higher level of legal complexity is the deployment of advanced nuclear technology in government sponsored or owned non-military maritime assets including strategic sealift vessels, auxiliary vessels, icebreakers, research vessels, or dredges, such as the U.S. Army Corps of Engineers (USACE) dredge *McFarland* shown in Figure 10 (34). Government deployment of nuclear-powered vessels may prove particularly effective in obtaining technical experience as well as establishing a pathway for future commercial deployments where the government is able to manage a degree of risk absorption that the commercial sector would not be prepared to take on. NRIC's ongoing efforts through the Maritime Nuclear Applications Group (MNAG) aims to develop standardized testing procedures and simulation models specifically designed for maritime applications. These efforts are critical in predicting potential challenges and preparing robust testing environments tailored to the complex dynamics of maritime nuclear reactors. For more detailed information on NRIC's current projects and their impact on maritime-related testing, maritime nuclear developers are able to participate in the MNAG R&D working group, which outlines comprehensive strategies and technological innovations currently underway. By aligning our robust testing and demonstration strategies with NRIC's proven frameworks and ongoing efforts, we ensure that the maritime nuclear technology sector is well-prepared to meet the challenges of today and tomorrow.



Figure 10: USACE Dredge McFarland (2018) (35)

2.4.2 Robust Design

Designers will need to be competent in the use of appropriate safety assessment practices including deterministic and probabilistic practices to account for the reliability and applicability of all components, in order to guarantee that they have been adequately validated by the time of the demonstration.. Additionally, for demonstration activities, systems may need to be designed utilizing conservative safety margins as well as potentially incorporate frequency-consequence criteria for the purpose of addressing credible scenarios (36).

It may also prove helpful for designers to incorporate components and materials that have previously received licenses and have operating experience into the design and testing program to lower the risks of delays and additional costs. Any additional work related to the development of specific technology options should be completed prior to the commencement of the demonstration phase (33). ASME currently has updated standards to include advanced reactors (36).

2.4.3 Code Standardization and Regulatory Harmonization

The successful demonstration of new technologies and methodologies can provide convincing case studies for the standardization of engineering and design codes that can facilitate further implementation of the technology.

The introduction of new TI-RIPB rules and guidelines by the NRC may offer alternative regulatory solutions for novel designs, such as NRC Regulatory Guide 1.242 which allows small reactors to undertake “performance-based emergency preparedness.” Applying TI-RIPB rules such the Guide 1.242 may allow, among other things, a reactor’s emergency planning zone (EPZ), shown in Figure 11, to be determined by the potential consequences of an accident as opposed to a prescribed distance. This alternative regulatory solution was utilized by Nuscale in 2022, to receive approval from the NRC to use an EPZ sizing methodology that could reduce the EPZ from 10-mile plume exposure pathway to within site boundary (37). Local environmental conditions and infrastructure are to be taken into account for an EPZ, so any installation intended to be located offshore need to consider the lack of regional infrastructure, so the

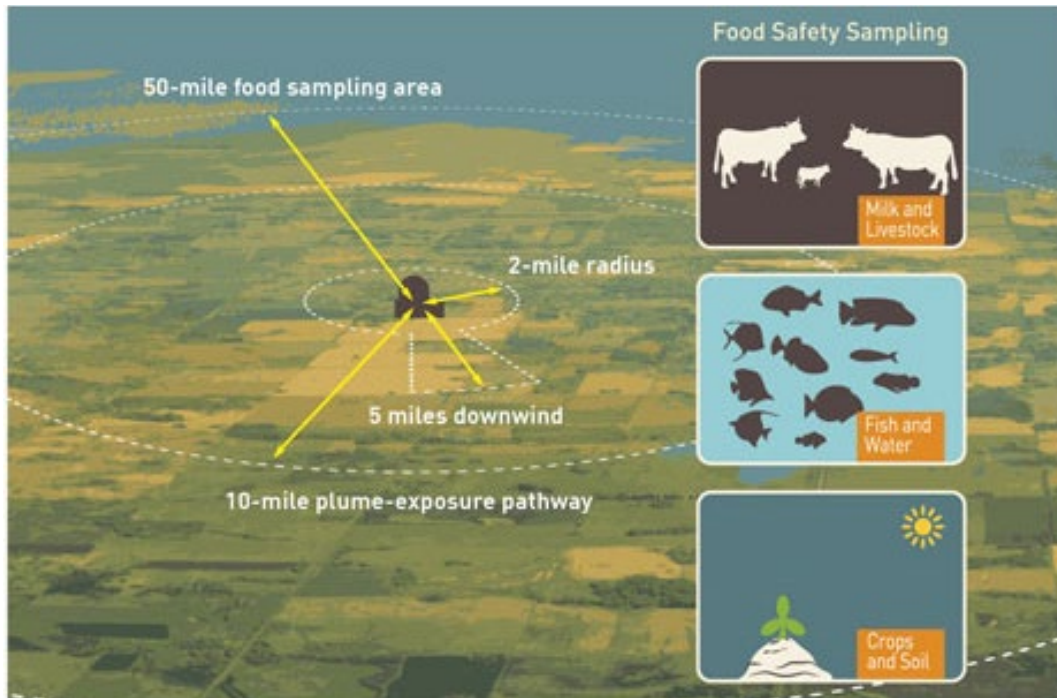


Figure 11: Emergency Planning Zones with a 2-mile ring around the plant is identified for evacuation, along with a 5-mile zone downwind of the projected release path (38).

first movers must show what alternative design and control measures will be sufficiently effective to compensate. An EPZ includes areas surrounding a nuclear reactor in which accident planning is implemented in order to protect the public in the case of an incident (38). Reducing the EPZ radius for small modular reactors may in turn limit costs and accelerate the licensing process for demonstration projects (39). The potential for a reduction in EPZ radius within the design criteria may yield positive results in overcoming regulatory hurdles (40).

Additionally, environmental impact statements (EISs) are currently required under the National Environmental Policy Act (NEPA) to be prepared by the agency before it takes a major federal action; for example, the NRC issuing a design certification, construction permit, or operating license for an advanced reactor (41). NEPA also allows agencies to prepare “programmatic” or “generic” EISs, which can be used to address generic impacts of maritime applications of nuclear energy, potentially clarifying and addressing environmental risks associated with operations and technology failure. Harmonizing the approach to maritime evaluations under NEPA can simplify the deployment of nuclear units in multiple maritime locations.

2.4.4 Funding Policy

Organizers of demonstration and testing activities are typically responsible for funding innovative work, but the industry at large and governments can put tools in place to assist with funding where suitable. Funding can include project risk reduction assistance and the use of government sponsored facilities to reduce costs.

Successful government funding of innovative energy technologies has often included a goal-based system where a government agency awards funding to projects that achieve specific goals or criteria in order to continue development. For maritime nuclear reactor technology, this may incentivize successful

deployments, while also ensuring that available funding is provided to viable concepts. Potential goals may include benchmarks for business and safety viability criteria, potentially accelerating the development of the technology. The Advanced Reactor Demonstration Program (ARDP) is an example of DOE funding opportunity that was goal-based and focused on concept development, risk-reduction, and demonstrations. As such, as maritime nuclear projects mature, it may be advantageous to establish a similar funding program to ARDP for maritime nuclear applications."

Funding for the creation or modernization of engineering codes and standards to accommodate new technologies may facilitate the design process of early demonstrations as well as potentially lower the costs. NRIC is leading an effort to address reactor developer feedback regarding issues related to codes and standards. The primary areas of consideration include:

- Addressing cultural issues: education, training, guidance development, revision of codes & standards, improved communication across the design process; education of code committees on the state of advanced nuclear.
- Grading and risk-informed approaches: develop guidance on minimizing safety-related structures, systems, and components (SSCs) using grading and risk-informed methods.
- Civil/construction requirements: Develop reliability/statistics-based methods, generate test data to right-size requirements where possible, learn from non-nuclear construction and adopt peer review, modernize requirements for new manufacturing technologies.
- Supply chain expansion: Use of ISO-9001 with additional controls, use of non-nuclear codes and standards where possible.
- Digital engineering/digital twins/software quality: Use of DE/DT for QA/QC management and modernizing SQA requirements.

Additionally, funding allocated to decrease costs associated with licensing and the development of demonstration projects may also accelerate their success. When demonstration are projects considered as FOAK advanced licensed reactors, the ADVANCE Act in (Section 202) includes prizes for the first movers this is a policy that acts more as a economic incentive for successful demonstration.

Beyond funding for demonstration projects, to address any possible economic effects of a technology failure, unit owners are required to have appropriate insurance and financing in place to potentially fund costs associated with post-failure cleanup, remediation, and compensation. Increased insurance demands may in turn require supplemental government support to limit potential costs or inapplicability of traditional maritime insurance mechanisms (42).

2.4.5 Public Engagement/PR

A strategy focusing on leveraging education and outreach seeking capital investments into developing nuclear-maritime technologies or demonstrations can also support early development projects. The education of targeted or influential investment or capital firms, along with regular information sharing about realistic technology functionality or conceptual arrangements, can encourage private funding in support of new technologies.

2.5 Establishing a Business Case

Challenges related to establishing business cases for both demonstration projects and commercializing advanced nuclear products in the maritime industry will be particularly significant in determining financial viability, the extent of its applicability, as well as how aggressively its development may be pursued. If nuclear-maritime applications have financial disadvantages against alternative or other zero-carbon energy sources, and the potential advantages of the technology fail to compensate, their application may become limited.

Because of the nature of demonstration activities is to gather information and learn, it will have a different business case from a purely commercial project using purely proven practices. If a demonstration is to include elements of economic viability as part of the expected outcomes, the business case will need to be generous in separating viability in principle from sufficient investment needed to learn and address gaps needed to take the technology forward. This requires investors who have an appropriate level of risk tolerance and a broader risk sharing framework amongst the demonstration project stakeholders to assure that the demonstration can be successfully completed. For a marine application demonstration project, a coastal power plant demonstration will not only have a similar risk structure to a land-based project, but also very similar stakeholders. For a more mobile facility where shipping companies may be involved in the owner/operator structure, additional work will need to be done to help the marine stakeholders understand and accept their roles in the demonstration risk sharing.

In addition, demonstration activities for mobile systems are likely going to need to be completed in stages, starting with proof of concept and gradually phasing into fleet operations with an expanding list of destinations. In each case, financial viability will need to be verified to optimize the technology, its use and its competitiveness with other alternative energy sources.

Demonstration activities for business cases will need to anticipate and address potentially unique considerations of nuclear-maritime applications, such as increased or complex insurance arrangements, economics of waste management and decommissioning and arrangements for maintenance activities. As discussed in Section 2.9, vessel scrapping or recycling at the end of the unit's life is standard practice and done in a manner that does not impose major expenses upon the owner. These conventional arrangements will not necessarily be the same when managing the decommissioning of a nuclear-maritime application.

Some of these aspects will have an up-front impact on capital expenditure (CAPEX) and introduce potential complications in the nuclear energy supply chain. Depending on the type of demonstration, there may be additional uncertainties regarding the availability of insurance and third-party insurance/liability coverage exclusions, which are not specifically discussed in this report. The following are some of the identified challenges related to the business case for advanced nuclear technology applications in the maritime industry.

- **High upfront (CAPEX) costs.** (CAPEX) to set up testing and demonstration, as well as manufacture reactors and establish infrastructure for nuclear-maritime applications, are expected to be higher than typical costs for alternative energy sources. The inherent nature of using nuclear fission to generate heat (instead of burning a fuel source) to boil steam requires (1) additional safety systems, structure, and components, (2) increased quality requirements, and (3) increased maintenance, testing, and inspections as a way to ensure radiation safety of the public is

adequately maintained per NRC regulations. These additional measures have a significant cost and are not included and/or imposed in other power generation sources. This may appear as a business risk, and without thorough lifecycle cost analyses to understand the tradeoffs between CAPEX and OPEX, may appear disadvantageous and dissuade investment. Traditional land-based nuclear energy has often been hindered by high upfront costs combined with delays, which could prove a major disadvantage for maritime applications (43).

- **Unknown value for “n” at which the nth manufactured reactor unit achieves economies of scale.** While advanced modular reactors and marine construction methods may provide the benefit of factory fabrication to potentially improve their economies of scale and lower CAPEX costs, there is no certainty for the timeframe in which this may be achieved and what the profitability of initial FOAK reactor deployments may be. If fabricated in the U.S., a manufacturing facility that produces complete reactors also introduces another opportunity for delay in NRC regulatory licensing required for the manufacturing facility itself. It is likely that a demonstration project will operate at a loss. However, one can assume that demonstration activities and first movers could lead to nth-of-a-kind (NOAK) products that can achieve economies of scale quicker.
- **Technological development potentially restricted if engineering solutions do not prove to be economically feasible.** This could dissuade investment and stall further development of nuclear-maritime technology despite the potential advantages.
- **Engineering solutions should consider designing for costs and using materials or parts that are economically suitable.** Issues related to using advanced materials or technology may be complex and expensive. To remain economically competitive, designers typically consider incorporating lifecycle costs in the design early on. However, without considering criteria for safety, any technology designed for economy alone may result in a lower quality, poor performing, or more unreliable products. Such a product will not be authorized for use by regulatory authorities. The complex balance of economy and product safety may add constraints to the design and testing process but could potentially result in a more suitable product.
- **Supply chain may not be available.** Unlike conventional energy sources which have well established supply chains, initial applications of nuclear-maritime technologies are initially at a disadvantage as supply chains need to be stood up or adapted for use. This can impede the timelines for demonstration projects. Additionally, limited availability of nuclear fuel, materials, and components could potentially lead to extended delays or redesign efforts. The lack of an established supply chain may also result in difficulties predicting the price of materials. Finally, supply chains may be susceptible to the volatility of geopolitical events and trade agreements, increasing long-term uncertainties of internationally sourced materials or equipment.
- **Questions around multinational ownership of reactor units.** Multinational ownership and multi-lateral business engagements are typical in the maritime industry. Uncertain business arrangements for multinational ownership of reactors aboard vessels may raise questions and concerns regarding non-proliferation, security, export control, liability and other related concerns. For example, there are restrictions in the U.S. Atomic Energy Act on foreign ownership of reactors, although Congress relaxed some of those restrictions for allies of the U.S. in recent legislation (9).
- **Policy, laws or regulations may affect business cases and market landscapes regionally and globally.** Uncertainties associated with policy, laws, regulations and governance may have the potential to limit investment in nuclear-maritime technology. These effects may be particularly

severe in the event of a lengthy approval and licensing process which may further expose projects to regulatory and financial risks. Additionally, political risks such as potential political opposition to advanced reactor development or deployment in maritime applications may also present a barrier.

- ***Sustainable carbon pricing schemes/policy may not incorporate nuclear power for maritime applications.*** Uncertainties around the economic impacts of carbon pricing schemes or policy for all future technology solutions can pose economic risks to business cases. Nuclear power offers a sustainable zero-carbon energy solution. However, political and public perception concerns may have the potential to limit its inclusion in these policies. If nuclear technologies are not able to take advantage of carbon trading schemes, they may not be incentivized for development.
- ***Uncertain characterization of personnel costs.*** Personnel needs for marine-nuclear applications will require certain highly specialized personnel either onboard or on standby. Demonstration projects and first movers may require additional local staff to compensate for uncertainties, particularly for functions such as monitoring and security. Lessons learned would be used to optimize the costs of staffing versus use of technologies.
- ***Cost estimates and assumptions may underestimate actual costs of developing and implementing new technology.*** Lifecycle cost assessments—including equipment, materials, supply chains and decommissioning arrangements—may be difficult to estimate and predict over the entire life of the facility. This may result in difficulties completing projects and the subsequent need for additional funding or investment. Macroeconomics and market risks and uncertainties may also hinder investments into the technology throughout the development and life of the project, particularly if there is a lack of government funding and support.

These challenges related to establishing a business case will need to be addressed for nuclear energy to become widespread in the maritime industry. Several solutions or approaches are discussed below, which, alone or in combination, may address one or more of the business case and economic viability challenges.

A breakdown of the responses from industry experts is shown in **Error! Reference source not found.** to understand the types of approaches to addressing issues related to business cases. While we again see a high number of recommendations related to addressing business case issues with strategies of robust design (e.g., design for economy, design for manufacturability), and code standardization and regulatory harmonization activities (e.g., to resolve uncertainties in licensing costs and schedules), the primary resolution category to address business case issues is related to funding policy; specifically, funding policy related to the technical aspects of the business case such as supporting new technology development, engineering solutions, and demonstration or testing provisions. It is notable throughout the responses that most categories emphasize technical aspects of the issue rather than regulatory or economic. This may indicate that many issues related to business case development and risk evaluation can be addressed by derisking technical aspects of the nuclear-maritime application.

2.5.1 Funding Policy

Much of this report emphasizes the need for demonstration projects and first movers to increase nuclear technology deployment and achieve decarbonization and energy security goals. Demonstration projects

must be realistic in expressing expected costs and engage the public to share the need of the investment, even if it seems expensive. See other Sections in this report discussing public engagement and PR.

To meet these goals supported by the public, public funding may be necessary to support the upfront CAPEX of initial demonstration projects, particularly the investments which may be required to initiate the production of advanced reactors as well as any infrastructure modifications or licensing arrangements that may be needed at destination ports and shipyards, potentially providing economic benefits as outlined in the Robust Design section.

Beyond infrastructure investments, nuclear-maritime applications should be included in decarbonization policies such that the reactor production and operation can benefit from tax credits, subsidies, or other funding policy benefits to improve the business case, incentivize development of the technology and aid in securing investors, as Congress has done for certain land-based reactors.

2.5.2 Robust Design

To ensure the success of demonstration projects incorporating advanced nuclear technology for maritime applications, business and economic objectives may need to be pursued and addressed within all segments of the design process.

Economic models of advanced modular reactors have demonstrated that decisions taken in the design stage can acutely affect the economic reality when deployed. A 2021 economic analysis completed by J. Buongiorno et al. (44), found that alterations of design criteria such as staffing needs and fueling cycle periods may lead to operational cost variations ranging from \$85/MWh to \$335/MWh, highlighting the importance of incorporating economic viability to design criteria.

The development of accurate models demonstrating the viability of designs may be a necessary first step with the potential to lower risks and secure investments. Completeness and thoroughness in the design may also be particularly useful in diminishing the risks of redesign resulting in increased initial CAPEX. The lifecycle cost of components and fuel being factored into the design criteria at an early stage could potentially benefit the viability of the finished product as well as reduce OPEX and constraints. However, the challenge with nuclear is meeting the stringent safety and security requirements while remaining cost competitive.

During initial development of demonstration projects, early coordination with potential vendors of difficult-to-source materials or components could benefit the timely completion of the project and potentially assist in lowering the risks from a potential lack of established supply chains. For the benefit of investors, vendors, and other stakeholders, proper communication of risks and mitigation strategies may assist in reducing uncertainty.

The fabrication process of advanced reactors as well as the industrial processes associated with their installation or incorporation into specific maritime units or facilities may be key in determining the commercial viability of the technology. The potential for shipyards to manufacture heavy equipment in series as well as the concentration of production with a centralized workforce may be a challenge at the first demonstration but can benefit from potential learning curves and economies of scale.

Additionally, developing the ability of systematic factory fabrication and delivery of advanced reactors may facilitate mass manufacturing, which may result in lower costs for individual units. Incorporating

criteria related to manufacturing, mass-production, and economies of scale to the design of reactors as well as their assembly process may facilitate this approach and improve the commercial viability of the technology (45).

Beyond the design of reactors, it may be beneficial for stakeholders to arrange for maritime units or facilities to potentially incorporate several smaller reactors as opposed to a smaller count of larger reactors. In practice, there may be vessels or maritime units of various sizes incorporating different numbers of reactors of the same model and power output. This may then widen the applicability of specific reactor models and increase the potential of mass production and reduced costs (30).

Other challenges associated with the business case may be addressed by the mobile nature of many maritime applications, which may allow units to more easily adjust their operations if necessary. For example, if the economic viability of a FNPP changes after years of service at one location, the facility may be able to relocate for a more economically feasible service.

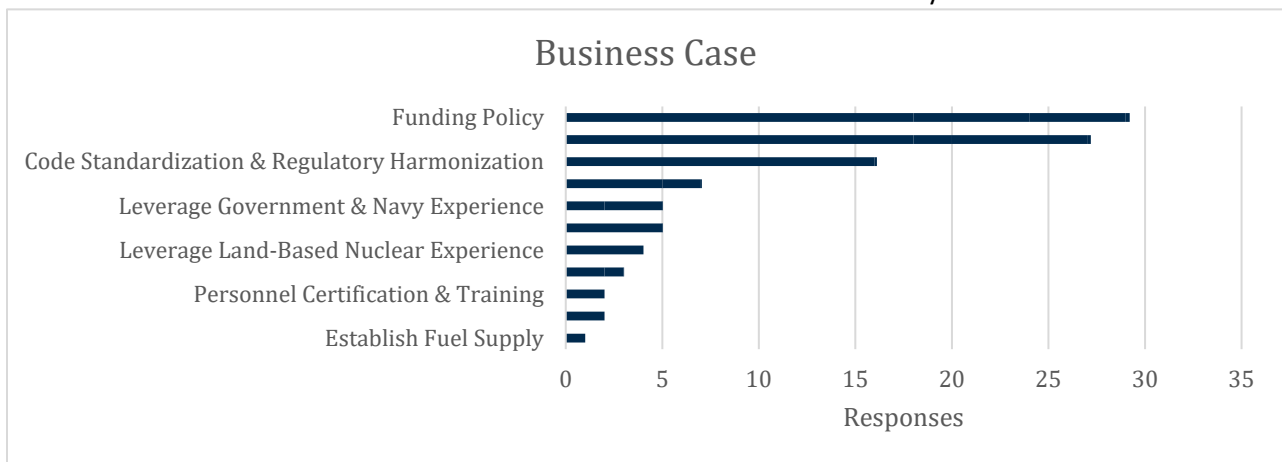


Figure 12: Addressing Challenges Related to the Business Case

For ships, leveraging other potential advantages of nuclear propulsion such as increased speeds, longer fueling cycles, increased cargo capacity, and zero carbon emissions may also be key in establishing viability and competitiveness. Reactor concepts that incorporate long fueling cycles may be independent from fluctuations in fuel prices that routinely affect users of traditional energy sources.

While economic feasibility and establishing a strong business case will be critical, it is important to emphasize that commercial success is not the only applicable success metric. Safety and risk reduction strategies will be useful for the success of initial demonstration projects.

2.5.3 Code Standardization and Regulatory Harmonization

First movers and demonstration projects will likely follow existing regulatory arrangements and licensing



Figure 13: A Full Service Fincantieri Bay Shipbuilding Shipyard Specializing in New Construction, Repair, Conversion and Sustainment of Commercial Vessels (74)

frameworks. However, if the process is complex for novel technologies or alternative arrangements, it may be necessary for applicable laws, regulations and licensing mechanisms to be adjusted before projects can be effectively scaled up and commercialized. Resolving any ambiguities or addressing gaps in design standards or licensing regulations can reduce the financial risks and improve investor and stakeholder confidence. The ADVANCE Act mandates NRC to act on addressing gaps in design standards and regulations. Because of this, early communication with regulators will be of paramount importance for the successful and timely completion of novel projects. This may also support the inclusion of nuclear energy in potential carbon pricing policies.

In the US, the NRC's Advisory Committee on Reactor Safeguards (ACRS) has endorsed a microreactor licensing proposal which would allow for microreactors to be fueled and operationally tested in their factory before being deployed. This potentially signals the movements of licensers to adjust to accommodate the modular manufacturing approach of advanced nuclear reactors, although further development may be needed (39). Additionally, discussions with regulators in the early stages of a project may reveal whether a technology has a higher potential for approval, which may allow these technologies to be more easily pursued. In the U.S., this may include pre-application activities with the NRC, some of which have been defined by the NRC to address the 2019 Nuclear Energy Innovation and Modernization Act (46).

Regulatory delays or regulatory gaps associated with demonstrating new concepts and technologies may potentially be mitigated by limiting the scope of the application, such as operations potentially being

initially limited to the U.S. and its territorial seas. Requirements applicable to nuclear-maritime units will be set by the deployment countries' authorities which may result in lowered risks to units which only operate within their deployment country's territories.

Additional support and backing from Governments may also play a key role in accelerating the implementation of advanced nuclear technology in time to assist with net zero carbon goals. The U.S.-based Clean Air Task Force (CATF) has published potential avenues for this, including potential requirements for Jones Act Vessels to implement zero-carbon-fuels. While amending the Jones Act to incorporate this may prove politically difficult, other mechanisms may be pursued by mandating the use of zero-carbon-fuels and including nuclear power in specific industry sectors. One recommendation from the CATF to promote the deployment of zero-carbon fuel vessels is to 'build zero-carbon fuel vessel requirements (for newbuilds) into leasing conditions for offshore wind.' Similar provisions may be included in future design or operating mandates to encourage the development and use of offshore nuclear power (47).

2.5.4 Robust Testing and Demonstration

The successful demonstration of maritime projects incorporating advanced nuclear technology can help optimize the economics of future product development and deployment. Demonstration efforts should carefully incorporate economic validation strategies to evaluate and address economic risks.

2.5.5 Novel Ownership Arrangement

Innovative ownership schemes implemented to support first movers may play a key role in reducing potential risks for owners of nuclear-maritime facilities. For example, separating the ownership in the form of a leasing scheme, where reactors are leased to vessel or unit operators, is a potential ownership structure that may reduce risks and lower liabilities to vessel owners and investors while potentially lowering the necessary CAPEX. This arrangement is not implemented in the marine industry, and the first project implementations using this strategy will be a key model for others to implement and improve upon.

Ownership requirements are likely to vary depending on the regulating administration. For example, reactors subject to U.S. jurisdiction would currently face, but in the U.S. it may be possible to have reactor and vessel ownership requirements mirror those in place for land-based nuclear facilities, which restrict certain foreign ownership, control, or domination restrictions of nuclear reactors. In general, under the U.S. Atomic Energy Act and the recently issued ADVANCE Act, the NRC cannot issue a reactor license to an entity subject to foreign ownership, control, or domination except under limited circumstances and when the NRC determines that issuance of the license for a reactor is not inimical to the common defense and security or the health and safety of the public. The limited circumstances apply to entities who are owned, controlled, or dominated by the government of a member of the Organisation for Economic Co-operation and Development (plus the Republic of India), corporations incorporated in such countries, or a citizen or national of such countries, unless subject to certain sanctions. Leverage Land-Based Nuclear Experience

Although additional testing and demonstration is needed to show the viability of operating in the marine environment, the successful deployment of advanced reactors on land could accelerate the development of supply chains and improve the availability of materials and components for future maritime

applications. Lessons learned related to the process and approvals of the transportation of fueled reactors over land or water would also support the delivery of reactors to shipyards for marine deployments. Additionally, advanced reactor companies may also gain experience which may assist in the development of new supply chains unique to maritime applications.

2.5.6 Personnel Certification & Training

Uncertainties associated with potential costs of personnel and crew are addressed throughout the design process by incorporating crewing needs into the design criteria and analyzing the potential associated costs early on. It may also be possible for potential OPEX savings associated with longer fueling cycles to partially or completely offset any additional operational costs associated with additional personnel.

2.6 Integration of Nuclear and Maritime systems

The integration of advanced nuclear technology with maritime systems may face several challenges that may not necessarily be present for land-based applications. Nuclear reactors deployed on commercial maritime units or facilities will be required to prove their ability to eliminate or overcome various challenges unique to operating in the maritime environment, which include a high degree of autonomy, resistance to corrosion, resistance to vibrations, and preparedness for maritime system failure scenarios.

Integrating innovative technologies will require extensive testing and demonstrations to verify compatibility with maritime systems and the maritime environment, which may raise the need to develop complex testing platforms, increasing costs and potentially causing delays. Additionally, maritime regulations may have gaps that may limit international applications of advanced nuclear-maritime technologies, such as the IMO Code for Safety of Nuclear Safety Ships (Resolution A.491(XII)), which is limited to conventional types of vessels propelled by nuclear propulsion plants with pressurized light water type reactors.

Further issues related to this challenge are discussed below:

- **Potentially restrictive to adopt and implement new technology, component, part, or material in an unfamiliar industry.** Proving the safety and viability of these technologies may be costly and potentially extend the timeline for demonstrations and widespread adoption.
- **Outdated maritime regulations may be misinterpreted; potential that no alternative mechanism is available for new and innovative technologies.** This may have the potential to delay the deployment of advanced nuclear technology in the maritime industry, particularly regarding international deployments. Additionally, gaps may exist between maritime and nuclear law, such as gaps regarding requirements for the physical protection of nuclear-propelled vessels within the IAEA Convention on the Physical Protection of Nuclear Material (CPPNM) that may generate uncertainties regarding the applicability of specific regulations to advanced reactors in the maritime industry (48).
- **New or unique maritime technology may be expensive or costly to standardize, certify, and regulate.** To integrate nuclear technology with maritime applications, developing and validating new engineering solutions may increase the costs associated with initial deployments. The costs of introducing a new technology to the maritime industry may be prohibitive when combined with potential risks and uncertain viability.

These challenges related to nuclear-maritime integration will need to be overcome for nuclear energy to become widespread in the maritime industry. Several solutions or approaches are discussed below, which, alone or in combination, may address one or more of the listed nuclear and maritime systems integration issues.

A breakdown of the responses from industry experts is shown in Figure 14 to understand the types of approaches to addressing issues related to the integration of nuclear and maritime systems. Responses strongly emphasize regulatory harmonization between nuclear and maritime requirements. Additional emphasis is put on addressing technical aspects of the integration of nuclear-maritime technologies using strategies such as robust design, robust testing arrangements, and public engagement.

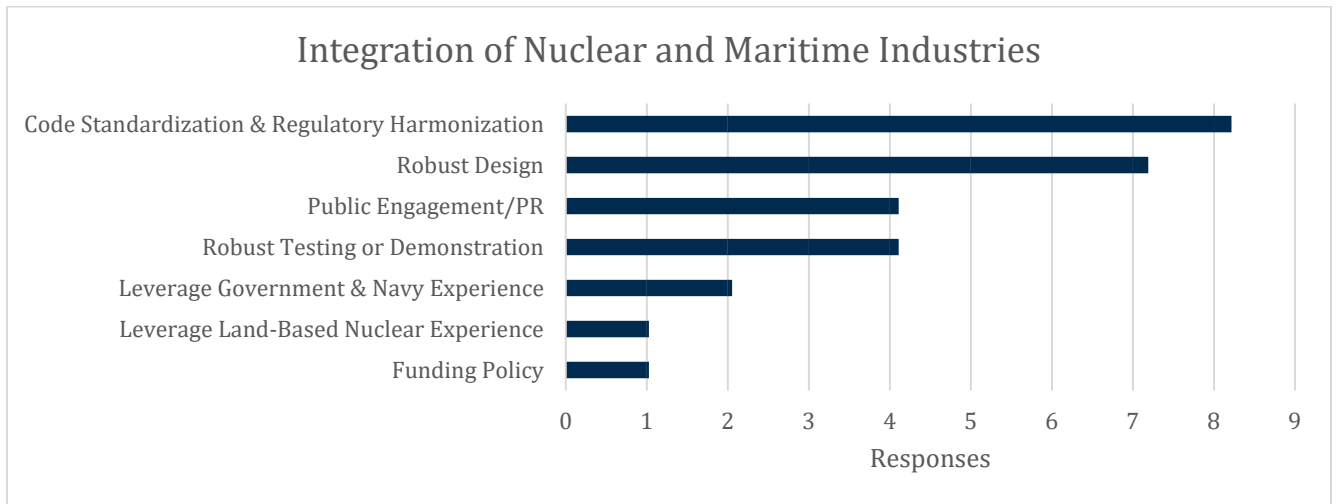


Figure 14: Addressing Challenges Related to the Integration of Nuclear and Maritime Industries

2.6.1 Code Standardization and Regulatory Harmonization

Regulatory harmonization may be necessary for the successful deployment and scale-up of advanced nuclear technologies in the maritime industry. Engagement with regulators and policymakers, classification societies, the IAEA, and the IMO will aid to facilitate this harmonization as well as modernize existing laws or regulations to be technology inclusive. Additionally, collaboration between the IAEA and the IMO ensures the design of regulation of nuclear merchant ships can incorporate the organizations' respective areas of expertise (49).

2.6.2 Robust Design

The continued completion of technical studies as well as collaboration between stakeholders may be beneficial for understanding specific design gaps and criteria, potentially facilitating efforts to eliminate or overcome design challenges.

The ability to modularize nuclear systems and segregate them from any connected adjacent, non-nuclear facility may be an effective approach to minimize the footprint of nuclear systems and the scope of nuclear regulations on the unit as a whole. As recommended in EPRI's 2023 report "Technical Methodology to Demonstrate the Separation of Nuclear Facilities from Adjacent Facilities," first introduced in 2.2.1 for the purpose of security, the separation of nuclear facilities from adjacent facilities can also simplify the interface and the application of both nuclear and maritime standards and regulations (22).

Marine operating conditions will necessitate additional design criteria and constraints for nuclear technologies. On the other hand, nuclear operating conditions may necessitate modified marine design accommodations. For example, designing onboard systems to reduce unit vibration or the implementation of dynamic positioning systems may be beneficial to reduce motions and accommodate nuclear technology onboard (50).

PNTL vessels carrying nuclear materials must be in accordance with the International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium, and High-Level Radioactive Waste on Board Ships (INF Code). Some provisions to meet this Code include the additions of collision strengthened hulls, increased propulsion redundancy, and enhanced buoyancy through increased compartmentalization (51). These design features are fitted to generally increase the vessel's factor of safety and resilience in the case of an incident or rough marine conditions. Other design considerations such as these for the PNTL vessels may be necessary for other commercial nuclear-maritime applications.

2.6.3 Robust Testing and Demonstration

Potential challenges hindering the adoption of advanced nuclear technology in the maritime industry may be further understood and overcome throughout the demonstration process. If demonstration projects are successful, they may then allow for future implementations of the technology to be more easily integrated into nuclear-maritime applications. Additionally, a successful demonstration may accelerate licensing of the technology by regulators, potentially facilitating the modernization and harmonization of existing regulations.

2.6.4 Public Engagement/PR

To overcome potential challenges associated with the adoption of advanced nuclear technologies by the maritime industry, it may be necessary for stakeholders to raise awareness of the potential benefits of nuclear energy as well as the role it may play in achieving industry goals such as net-zero carbon emissions by 2050. It is especially true for early movers and demonstration efforts to engage the public both as educational outreach and to campaign for public support and social license.

Additionally, stakeholder engagement focused on bridging gaps between the nuclear and maritime industries may support and encourage the modernization of laws, regulations and requirements, which may consequently accelerate the adoption of nuclear technology.

2.7 Supply Chain and Fuel Availability

Establishing supply chains as well as ensuring the availability of fuel, materials, and components may pose a challenge towards the implementation and viability of advanced nuclear-maritime projects. The deployment of advanced reactors with unique or novel characteristics may necessitate materials or fuels that may not be easily attainable or which vendors have difficulty sourcing. These difficulties may increase costs and cause delays, while also potentially decreasing the competitiveness compared to alternative energy sources with established supply chains.

Several advanced reactor concepts being considered for maritime applications incorporate fuel forms such as tri-structural isotropic (TRISO), enrichment levels such as high-assay low enriched uranium (HALEU), or new materials such as thorium fuel, some of which may be difficult to source due to a lack of established or viable vendors (52). Other concepts such as molten salt fuel may require implementing

corrosion resistant components and materials for which vendors and supply chains are not yet established. This presents the primary challenge associated with establishing supply chains and fuel availability for nuclear-maritime applications. Other issues related to this challenge are listed below:

- ***HALEU and advanced fuel forms (such as TRISO) supply chain still under development or not yet developed.*** This supply of enriched HALEU fuel—enriched to concentrations of up to 20% U-235, shown in Figure 15—is currently limited due to a lack of enrichment infrastructure, as well as the standard regulatory and proliferation concerns surrounding the production, handling, and transport of nuclear fuel (53).

The availability of other advanced fuel forms such as TRISO fuel particles or pellets, or the use of fertile thorium as fuel may also face difficulties due to the complexities associated with their fabrication and the current lack of vendors in comparison to traditional nuclear fuels (54)

Potential costs and delays associated with establishing a new supply chain for fuel may increase risks to investors as well as result in potential disadvantages compared to alternative energy sources with established fuel supply chains.

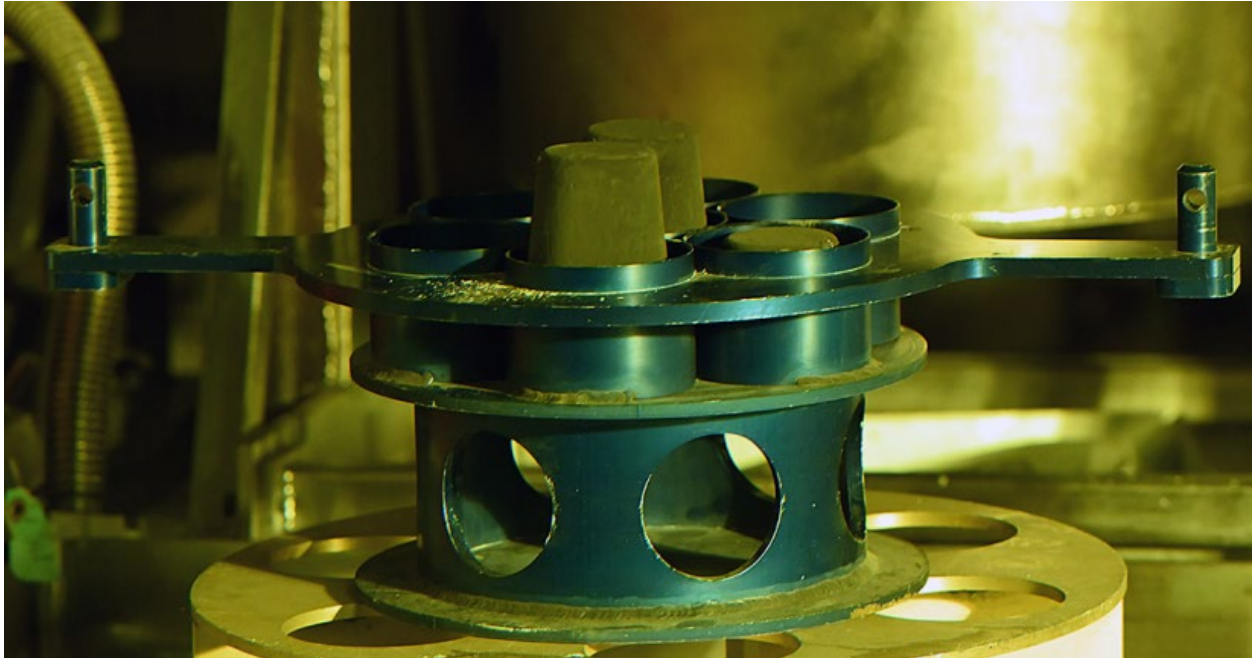


Figure 15: HALEU reguli fabricated from down-blended high-enriched uranium recovered from legacy EBR-II fuel at Idaho National Laboratory (52)

- ***Supply chain for other advanced materials may not be developed or available.*** Advanced nuclear technologies may have novel components and materials without an established or reliable supply chain for large scale applications. The potential for increased costs or delays associated with establishing new equipment or material supply chains may affect the financial viability of advanced nuclear-maritime projects. This may be especially true when considering the remote locations of operation for some nuclear-maritime use cases.
- ***Potential for limited fuel, material, and part developers in a growing and competitive market.*** This may result in additional difficulties for some developers to establish reliable networks of material and equipment supply chains, as well as potentially increase the costs

of materials and components. Insufficient availability of fuel or material may produce delays throughout the entire industry that may hinder a product’s competitiveness against traditional sources of energy with more robust supply chains in place.

- **Laws and Regulations related to trade may restrict supply chains and material or parts availability.** Export and trade controls between nations may impose additional challenges to advanced reactor technologies. These constraints may limit access to certain nuclear materials or components, potentially resulting in additional design constraints or increased costs.
- **HALEU and fuel fabrication costs.** Despite the potential for longer fueling cycles, high fueling costs may affect the financial viability of nuclear-maritime applications as well as potentially result in higher up-front costs.
- **The supply chain for advanced materials may be expensive.** Costs associated with this may be prohibitive for developing advanced reactor technologies.
- **Potential upfront and lifecycle costs may be prohibitively expensive.** This may potentially result in a loss of future investment and hinder the development of the technology.

These challenges related to supply chains will need to be addressed for nuclear energy to become widespread to sufficiently support deployment in the maritime industry. Several solutions or approaches are discussed below, which, alone or in combination, may address one or more of the listed supply chain and fuel availability issues.

A breakdown of the responses from industry experts is shown in Figure 16 to understand the types of approaches for addressing issues related to supply chain and fuel availability. Recommendations primarily address technology and regulatory aspects related to establishing supply chains and fuel availability. Other categories that received attention in the survey suggest that the availability of parts and fuel should be considered or addressed during the design stages to address specific economic risks that may exist if the supply chain is not developed.

Similar to nuclear waste transport and decommissioning challenges, it is expected that maritime applications would not experience such acute issues or challenges related to supply chains if advanced nuclear reactors are first deployed on land and lead to the early development of these supply chains.

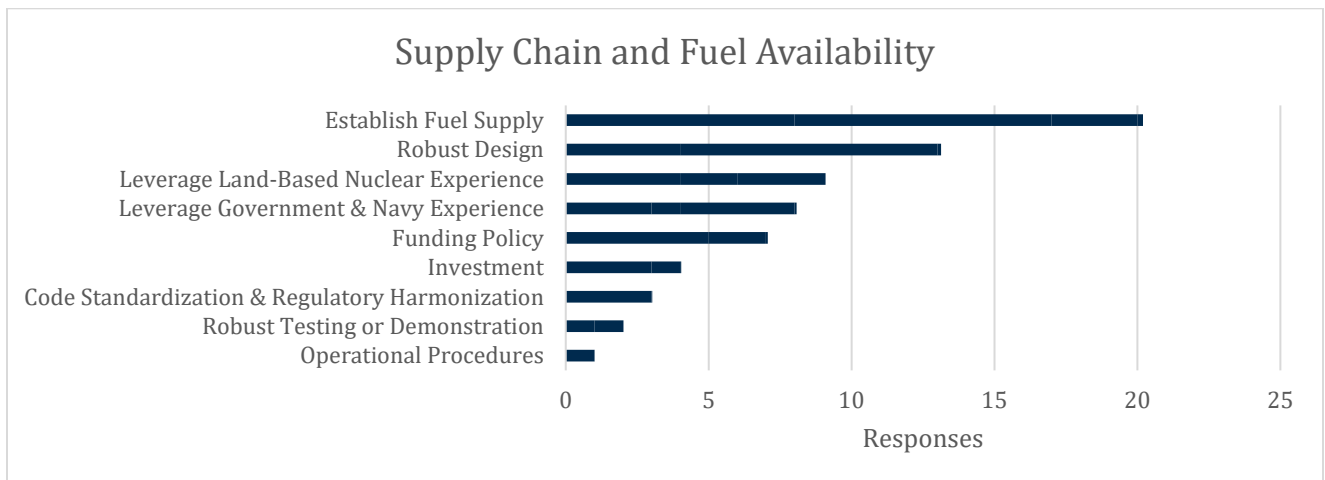


Figure 16: Addressing Challenges Related to Supply Chain and Fuel Availability

2.7.1 Establishing Fuel Supply

The creation of a diversified supply chain for fuels that is resilient in the face of geopolitical and market conditions may be substantive for the successful deployment of advanced reactor technologies, including the first movers to adopt nuclear technology for maritime applications.

It is possible that once demand for specific fuels is well defined, a supply chain may be more easily established with coordination and communication between designers and vendors. Additionally, mechanisms such as the formation of fuel buyer groups may assist in ensuring a sufficient and long-term supply of fuel is produced to meet industry needs.

2.7.2 Robust Design

It may be necessary to incorporate supply chain criteria during the design stages to minimize risks as well as potential costs and delays later. A potential path for this may be to consider light-water cooled advanced reactor concepts as they may leverage existing commercial nuclear energy industry supply chains (55).

Additional early steps towards establishing a robust supply chain have been proposed, such as identifying necessary materials and coordination between stakeholders to share and utilize a single supply chain for separate demonstration projects and potentially across international markets (6). Normally, having a diverse supply chain strategy eliminates risk, and is recommended to address many supply chain challenges. However, for specialized supply chains such as those supplying materials and parts to nuclear manufacturers, a diverse supply chain strategy may not be available until nuclear energy technology is scaled up in mass production.

Sharing a single supply chain as opposed to each project requiring its own may better distribute the costs and challenges associated with establishing a robust supply of fuel and components. A potential opportunity to enable this may be for reactor and facility concepts to incorporate open architecture into their modules where possible, which may allow supply chains of materials and components to be more easily shared between projects. This activity increases market demand, and naturally supports the development of supply chains.

The early identification of necessary materials and components may also facilitate the timely establishment of the relevant supply chains or reveal potential problems early on to allow for necessary re-designs or substitutions.

The risks associated with reliance on a single supplier for fuel or other components may also need to be considered and analyzed, as although there may be cost savings, there may be a potential for costs to increase if there is a need to produce replacement parts or other components from specialist vendors.

2.7.3 Leverage Land-Based Nuclear Experience

The successful demonstration of advanced nuclear land-based reactors may facilitate the development of supply chains as well as establish vendors for fuel, materials, and components for subsequent availability for use in maritime applications.

Additionally, difficulties in sourcing specific components and fuels may also be resolved following land-based demonstrations that may assist in implementing design criteria for projects that follow.

2.7.4 Funding Policy

Government funding to set up supply chains for fuels and materials may provide advantages to accelerate the deployment of advanced nuclear technology. Support from government funding policies or arrangements may reduce the costs of initial demonstrations as well as potentially reduce uncertainties regarding material costs and schedules. Additionally, non-military government-funded demonstrations of advanced nuclear technology may have the potential to generate the initial volume of demand to establish availability of fuel and components for future projects.

2.7.5 Investment

It may be necessary for advanced nuclear reactor stakeholders to leverage or investigate investments for supply chains that facilitate the implementation of the technology. Early supply chain investments can also potentially lower risks to investors later.

Additionally, owners and investors in the marine industry may need to demonstrate commitment to net-zero goals as well as the willingness to adopt nuclear technology. Incorporating decarbonization goals into the strategy of the nuclear-maritime application can facilitate investments into the necessary supply chains as well as increase confidence in the development and viability of maritime reactor concepts.

In 2024, the DOE announced an effort coordinated with international partners to mobilize \$4.2 billion in government spending to expand global uranium enrichment and processing capacity to improve the resilience of the uranium supply chain. This arrangement supports the potential development of HALEU availability for advanced reactor demonstration projects (56).

The DOE, over the past 15 years, has also invested approximately \$400 million to \$500 million in the development, study and qualification of TRISO, which is still undergoing research (55).

2.7.6 Code Standardization and Regulatory Harmonization

If changes to laws, policies, or regulations governing the availability of nuclear fuels are needed, it is recommended to provide sufficient time to work with decision-makers, engage the public in any official changes, and contact policy makers and regulators as early as possible to assist the process.

Additionally, government support for advanced reactor technologies in commercial applications may initiate interest in international frameworks and allow for a more diversified and resilient supply chain for nuclear fuels while also potentially increasing fuel availability.

The NRC and its Canadian counterpart, the CNSC, published a report in 2019 providing a common understanding of what evidence TRISO manufacturers would need to provide in order to prove acceptability (57). Further work in this area may facilitate establishing a fuel supply as well as other supply chains through the development of standards, clarification of requirements, and international cooperation.

2.7.7 Robust Testing and Demonstration

To address supply chain challenges effectively, demonstration projects are essential. These projects can validate the feasibility, reliability, and performance of new materials and fuel forms in real-world maritime environments, providing critical data to support their broader adoption. Demonstration projects will help to identify and mitigate supply chain bottlenecks, establish partnerships with reliable vendors, develop

and implement new sourcing strategies, and validate the operational viability of advanced fuels and materials under maritime conditions.

2.8 Support Infrastructure

The support infrastructure required to implement advanced nuclear technology in the maritime industry may impose specific challenges that may affect the viability of the technology as well as potentially increase the costs of its development and deployment. Many of these challenges may be unique, as maritime units have specific infrastructure needs within ports and shipyards, and nuclear technology necessitates specific requirements such as additional safety concerns and specialized material handling.

These challenges may be particularly severe if the costs associated with licensing or upgrading ports and facilities for handling nuclear materials are prohibitive. Additionally, the construction of new infrastructure may be necessary on land to support nuclear-maritime applications. For example, infrastructure, supporting supply chains, and marine facilities for the construction, commissioning, maintenance and decommissioning of reactors may need to be established before successful deployment of nuclear-maritime technologies. This activity may also extend deployment timelines and risk losing investments that would support the development of maritime applications of nuclear technology. Specific issues related to supporting infrastructure challenges are discussed below:

- ***No commercial shipbuilder capable of handling uranium based nuclear material in the U.S.*** This issue may also be applicable to international shipyards that have not handled nuclear materials in the past. Without appropriate approvals and specific equipment or processes for safely handling nuclear material, shipyards may face challenges adjusting to different practices and gaining certain regulatory approvals.
Overall, this may be a major challenge towards the adoption of advanced reactor technologies, as it may result in increased costs and timeframes associated with modifications and licensing to shipyards or port facilities required to permit them to handle nuclear material. This may also result in design or operational constraints for reactor designers and will likely require specific reactor installations, maintenance, and decommissioning arrangements at ports.
- ***Shipyards and ports may not be suitable for nuclear material.*** In general, the port environment may pose additional operational risks to the maritime application and presence of a nuclear-maritime application may pose insurmountable risks to the port or shipyard. This issue, if not addressed, may result in the operational profiles of some maritime units to be limited. This could generate design and operational constraints.
- ***Potentially severe consequences to technical quality of product.*** Constraints and risks associated with infrastructure challenges, or the deployment of new specialized facilities may have the potential to impact the quality and viability of deployed marine units. Lack of necessary international infrastructure elements such as ports capable of handling nuclear related material may add constraints to the design, operation, and viability of maritime advanced reactors.
- ***Appropriately trained and certified crews and operators may not be available to meet rising demand for advanced nuclear-maritime applications.*** Both onboard and at port, appropriately trained and certified personnel must be available wherever a maritime reactor deployment plans on calling. This may result in operational risks as well as the potential for increased costs and delays.

- **Gaps in nuclear or maritime regulations may cause issues when technology interfaces with infrastructure and land-based support efforts.** These gaps may create uncertainties that could limit the development of the technology as well as potentially add risks which may dissuade continued investments and funding.
- **Potential severe consequences to capital and operational costs.** Costs associated with the development and operation of support infrastructure for maritime reactors may be higher than estimated, and the financial responsibilities not well understood. These uncertainties may affect the financial viability of the technology. Additionally, potential delays in the development of infrastructure may result in additional losses and potentially negative impacts on the development of the technology. Some of these challenges can be overcome by demonstration projects and first movers.
- **Crew and personnel may not be trained; potential rising costs of personnel.** The necessity for highly qualified and trained personnel may pose a challenge during the early implementation of the technology as onboard, shipyard and port personnel may not have experience with nuclear-related processes, training or qualifications. Units needing to employ and train additional qualified personnel for operations in port may add expenses with the potential of reducing the viability of the technology.

These supporting infrastructure challenges will need to be overcome for nuclear energy to become widespread in the maritime industry. Several solutions or approaches are discussed below, which, alone or in combination, may address one or more of the listed challenges.

A breakdown of the responses from industry experts is shown in Figure 17. Recommendations focused on robust design and code standardization and regulatory harmonization activities specific to equipment and services available in ports and shipyards. Across the categories, many recommendations focused on addressing technical issues rather than regulatory issues.

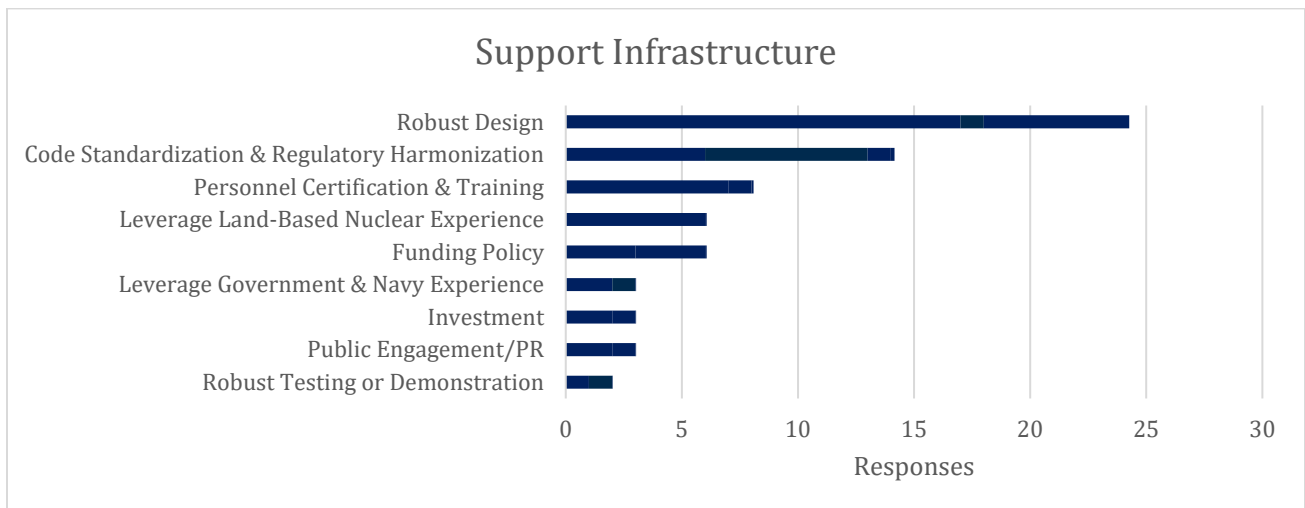


Figure 17: Addressing Challenges Related to Supporting Infrastructure

2.8.1 Robust Design

Robust system design may play a key role in limiting the effects of potential challenges in relation to infrastructure. Implementing a modular construction approach, for example, may reduce constraints

related to infrastructure availability, as reactor installation and commissioning may take place at a more centralized facility before being fully assembled in the field.

Modular reactor concepts may take advantage of specialized assembly facilities, potentially lowering production costs and limiting the level of involvement that a shipyard may have in the assembly of nuclear systems.

Design considerations to reduce infrastructure needs include reducing maintenance requirements, allowing for long fuel cycles and designing reactors like “nuclear batteries” that can be entirely removed and replaced as necessary with no need for refueling onboard. These operational features should be considered during the design phases and may result in reduced needs for nuclear-maritime-specific infrastructure.

It may also be beneficial to leverage advanced nuclear technology to support port infrastructure during operations, such as the ability for a nuclear ship to provide power to shore while in port. This could generate interest from ports and lower the costs for the adjustment of existing infrastructure.

Additionally, it is suggested that FNPPs, permanently located in a single location, may reduce the overall infrastructure needed for construction, servicing, and maintenance on site, potentially proving to be the first step for the introduction of advanced reactors to the maritime industry.

2.8.2 Code Standardization and Regulatory Harmonization

Coordination with regulators may facilitate the creation of specific training program requirements in ports and at shipyards and establish specific infrastructure licensing programs that may be necessary before work on support infrastructure can begin. This may facilitate the introduction of a qualified workforce and potentially remove uncertainty associated with infrastructure needs.

2.8.3 Personnel Certification & Training

Regulatory bodies such as the U.S. NRC authorize qualified personnel to participate in reactor installation, commissioning, and maintenance. Engaging with regulators when establishing new crew certification and training programs would provide clarity and address risks related with implementing new training and certification programs at maritime academies, operating companies, shipyards and ports.

2.8.4 Leverage Land-Based Nuclear Experience

The collaboration or alignment among companies deploying advanced land-based reactors may be interested in sharing infrastructure and supply chain resources to mutually benefit from standardized materials, parts or components.

Activities and infrastructure established to scale up advanced reactor power plants on land may also benefit maritime applications intending to use nuclear technology. Some of these activities include the development of easily transportable modular reactors, establishing accessible manufacturing of specialized materials or parts, standardizing parts to establish parts available off the shelf, and manufacturing processes focused on increasing capacity and output of many reactors of the same type.

2.8.5 Funding Policy

Government funding available for the creation of necessary infrastructure in ports for the implementation of advanced nuclear technology may have the potential to facilitate the deployment of initial demonstrations as well as introduce strategic advantages regarding the domestic application of the technology.

Government funding allocated to the creation of necessary infrastructure may assist in the growth of shipbuilding capabilities, and in some areas such as the U.S., revitalize commercial shipbuilding. These activities generally support local economic growth and job creation.

2.8.6 Public Engagement/PR

A focus on outreach and education aimed towards increasing awareness of advanced nuclear technology as well as its potential role in the maritime industry, specifically at ports and within port communities may encourage more interest in developing nuclear technology solutions and their supporting infrastructure for maritime applications. Local support can grow public opinion and provide the social license to arrange construction and deployment activities for first movers. Additional interest from the public may also attract new talent to the sector while encouraging personnel training and qualification.

Additionally, funding scholarships for programs that combine the maritime and nuclear fields may lead to increased interest and future workforce potential.

2.8.7 Leverage Government and Navy Experience

Collaboration with naval shipyards that have previously built nuclear-powered vessels and submarines, such as the USS Columbia shown in Figure 18 may provide many benefits to accelerate the deployment of nuclear technologies in the civilian market.

Additionally, government support of infrastructure projects may allow for additional collaboration with the Navy, potentially establishing new civilian infrastructure capable of accommodating nuclear-maritime applications.

Experience from naval operators and designers may also increase the availability of qualified operators and provide insight into the specific personnel needs as well as the qualification and training processes that may be necessary for maritime reactor deployments.



Figure 18: USS Columbia (SSBN-826) have been under construction at the General Dynamics Electric Boat facility at Quonset Point (58)

2.8.8 Investment

Investment into the development of infrastructure necessary for the installation, servicing, maintenance, and decommissioning or end-of-life activities of maritime reactors may be necessary to achieve successful deployment. Leveraging the potential benefits and educating the public regarding the needs of the new technology may assist in attracting investment.

It may be particularly effective for initial demonstrations to be government-backed and receive assured funding. Support from governments could support infrastructure development and lower market risks.

2.8.9 Robust Testing and Demonstration

The successful deployment of demonstrations has the potential to induce the necessary demand to create or update infrastructure, as risks and uncertainties associated with the market for new maritime reactors may be diminished.

2.9 Nuclear Waste Transport and Disposal, and Nuclear-Maritime Decommissioning & Vessel Recycling

The required handling of nuclear waste as well as end-of-life procedures specific to nuclear technology have the potential to present challenges to the adoption of nuclear-maritime technologies as a result of the technology's associated costs, design constraints, and uncertainties. This section identifies challenges related to handling nuclear material and end-of life considerations for nuclear-maritime applications and provides suggestions to overcome them.

Nuclear waste handling and disposal may present increased challenges for maritime applications when compared to traditional land-based reactors, as nuclear waste may have to be stored and subsequently discharged from the vessel or unit where it was produced. Novel arrangements for handling, disposal or recycling of spent fuel may also be needed if reactor technologies incorporate innovative fuel

arrangements. These novel arrangements also include low-level and high-level waste disposal. Low level waste disposal demonstration activities will need to be considered to show the public, government and investors how effective waste management and decommissioning will be carried out. For all types of regulated nuclear waste and SNF The starting point will be domestic strategies for decontamination of the nuclear marine facility, management of waste streams and the overall process for dismantling the marine facility at a suitable licensed waste facility. The dismantling facility is likely best organized in a manner like the factory, to conduct its activities in a repetitive fashion and interface with offsite waste disposal or recycling processes. For this type of facility, existing nuclear laws and regulatory requirements can be leveraged, however, certain marine requirements will also need to be addressed.

In the maritime industry, vessels are scrapped once they reach the end of their life or the end of profitable operations. Commercial salvage yards purchase the units to dismantle and recycle or sell the materials. The IMO Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships is set to go into effect in 2025 in the countries which have ratified the convention. The Hong Kong Convention will require ship owners to inventory and report all onboard hazardous material to reduce health risks to salvage workers (59). However, the Hong Kong Convention does not address managing nuclear materials. Any facility expected to manage decontamination and decommissioning (D&D) activities would require a license from the regulatory authority to receive, handle, store, or package nuclear materials. The costs of vessel recycling and scrapping are typically arranged so there are only minor costs to the owners, often considered negligible compared to CAPEX and OPEX. It is unlikely that existing vessel recycling or scrapping facilities would voluntarily apply for nuclear license to manage D&D activities.

The low-, intermediate-, and high-level nuclear waste as well as the nuclear power plant facilities may need to be separately managed ahead of time and incorporated into business plans to allow for decommissioning and safe ship scrapping according to the Hong Kong Convention. Depending on the laws and regulations applicable to a vessel at the time of scrapping, the potential may exist for vessels, or sections of vessels which incorporate nuclear technology, to be required to undergo D&D in their country of origin separately from the vessel salvage and recycling. This additional activity is expected to result in additional lifecycle costs.

Challenges may also arise from regulatory gaps and political hurdles regarding the responsibility for nuclear waste storage and disposal. The international nature of some maritime nuclear applications may result in complexities when assigning responsibilities to nations or provinces responsible for handling and storing waste. Also, the potential costs and risks associated with D&D may negatively impact the competitiveness of nuclear-maritime applications, as nuclear waste issues are generally more complicated than those of alternative energy sources.

The following potential challenges are among those identified in relation to nuclear waste handling and the D&D for advanced nuclear technology applications in the maritime industry:

- ***Maintenance and servicing may require specialized and complex remote handling equipment due to shutdown radiation fields.*** Factors unique to the marine environment may require development of additional equipment in ports, shipyards, or docks specific to handling nuclear material or operating in areas where exposure to radiation may be possible.

- ***Nuclear waste handling and transport may involve potentially severe environmental and technical consequences.*** Failure to properly establish or follow technical arrangements or operational procedures for handling nuclear waste or irradiated material may result in severe consequences. Requirements and regulations for handling nuclear materials must be followed and integrated with the marine operating profile.
- ***Vessel recycling will need to include measures to prevent and mitigate risks to workers, the public and environmental consequences.*** Traditionally, vessels are scrapped and many components are recycled upon their decommissioning. However, shipbreaking and recycling of vessels or maritime units with nuclear reactors may introduce new challenges. The contamination of material as well as other possible risks associated with handling nuclear-maritime units during decommissioning may lead to personnel or public exposure to radioactive material as well as potential disadvantages when compared to alternative energy sources. There may be costs associated with the decommissioning of reactors and the maritime units housing them, as experience shows from naval nuclear decommissioning costs.
- ***Nuclear waste handling, transport, and vessel recycling introduce novelties to liability, policy, and regulatory processes.*** Demonstration activities will need to be carried out to establish decommissioning facilities and their practices as well as responsibly and economically managing waste while safeguarding nuclear substances against diversion for malicious purposes.
- ***Potentially restrictive to implement or approve if no arrangement for transport or long-term waste disposal is available.*** Political and regulatory challenges in the U.S. may create resistance for the adoption of advanced nuclear technology for maritime nuclear applications due to the current lack of interim storage or permanent disposal (or recycling programs) options for used nuclear fuel in the U.S.. Regardless of the nation responsible for managing the permanent disposal of SNF if there is no long-term nuclear waste plan, or any resistance to storing nuclear waste or used fuels, challenges may exist for demonstration efforts or first adopters of nuclear-maritime applications.
- ***Unclear how decommissioning fees would be collected and managed.*** In the U.S., each commercial land-based nuclear reactor signs a Standard Contract with the U.S. Department of Energy (DOE) through which the DOE agrees to eventually take title to and dispose of the used nuclear fuel. In exchange, the nuclear utility pays DOE a set amount of money for the electricity generated by the reactor. If nuclear decommissioning is done in association with maritime decommissioning, there may be uncertainties associated with how the Standard Contract and these used fuel fees may contribute to difficulties assessing the economic viability of nuclear-maritime applications. The costs of D&D are independent of the Standard Contract and will need to be addressed for nuclear maritime applications.
- ***Nuclear waste handling and transport may result in increased costs.*** Risks and liabilities associated with the handling of waste may contribute to a potential lack of available vendors as well as possibly increase costs and regulatory constraints. Severe consequences of this challenge may include the loss of viability of the application against its competitors or the hinderance of its development.

These nuclear waste handling challenges will need to be addressed for nuclear energy to become widespread in the maritime industry. Several solutions or approaches are discussed below that may

address one or more of the listed nuclear waste transport and disposal issues as well as nuclear-maritime decommissioning and vessel recycling.

A breakdown of the responses from industry experts is shown in Figure 19 to understand the strategies to address nuclear waste transport and disposal challenges, as well as nuclear-maritime decommissioning and vessel recycling issues. From the results, much of the guidance relates to robust design, recommending appropriate designs of reactor systems, including the amount of nuclear material used or generated, and the arrangements required for handling. This may also include the design of support facilities and arrangements for transport of nuclear materials as well as the analysis and mitigation of risks associated with all aspects of nuclear material handling and decommissioning according to the defined operational profile.

It is also notable that the responses emphasize that when advanced reactors may be successfully demonstrated and deployed for land-based applications, the infrastructure, arrangements, laws, regulations and waste disposal process may already be established and can be leveraged by nuclear-maritime applications without major adjustment.

Finally, nuclear waste management pathways are primarily driven by regulatory aspects as opposed to other guidance categories, which relays the importance of regulators and policymakers regarding this subject.

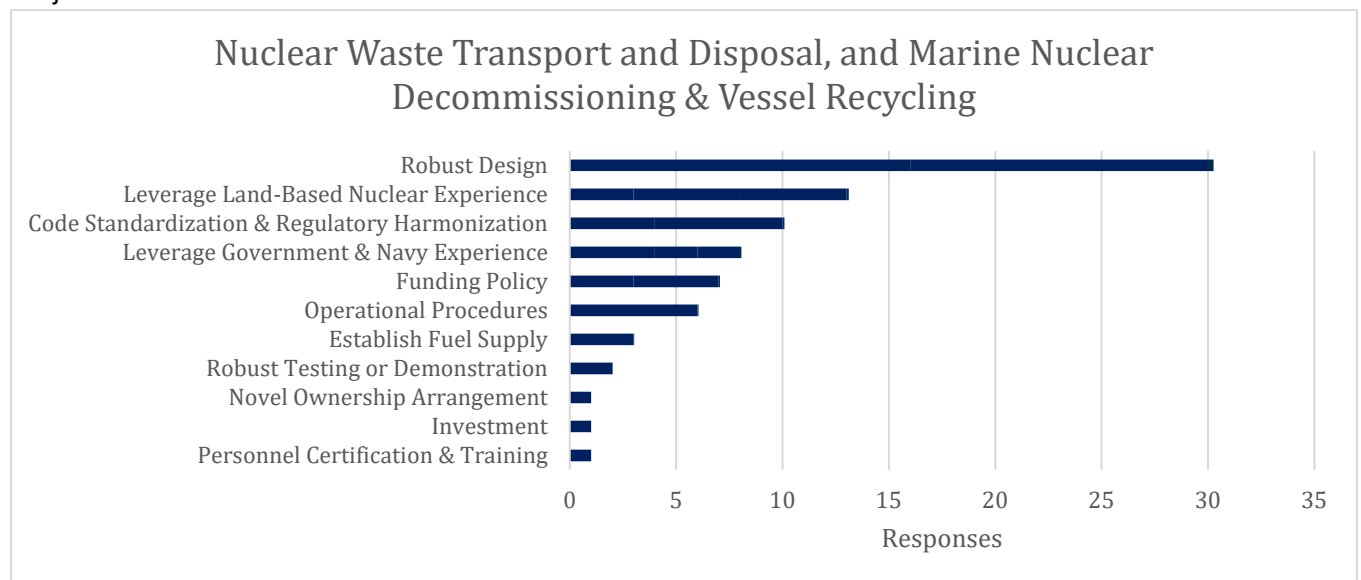


Figure 19: Addressing Challenges Related to Nuclear Waste Transport and Disposal, and Marine Nuclear Decommissioning & Vessel Recycling

2.9.1 Robust Design

As part of a systematic decommissioning by design approach, it is recommended for nuclear-maritime designs to demonstrate the use of modular systems so that, for example, the core and reactor compartment may be removed in-situ, and all waste handling and maintenance work can be completed in specialized land-based facilities. This arrangement may reduce challenges related to handling nuclear waste onboard or at shipyards, however may pose novel challenges for preventing theft and diversion that may need to be addressed. It may also provide more certainty regarding nuclear material and radioactive waste management responsibilities on land.

Other design criteria and analyses that may be beneficial to emphasize are those related to reliability and maintainability of reactors with a focus to reduce the risks associated with on-site waste handling or unplanned maintenance needs. This may be of particular importance in determining the logistical and economic viability of technology deployment projects. Diminishing the amount of waste produced may also facilitate waste handling and limit costs associated with it, which may potentially be accomplished through thermodynamically efficient reactor concepts which operate at high temperatures.

Risks associated with the decommissioning and recycling of units incorporating nuclear reactors may be addressed by incorporating decommissioning plans early in the design stage, potentially through the incorporation of modularity as well as substantial separation of nuclear facilities and adjacent facilities. Modular onboard nuclear facilities separated from adjacent facilities on board may facilitate the decommissioning and dismantling process, so that once onboard nuclear facilities are removed, the rest of the unit may be dismantled similarly to non-nuclear units.

2.9.2 Leverage Land-Based Nuclear Experience

The successful demonstration of advanced nuclear land-based reactors may help create a precedent for handling advanced nuclear reactor materials and radioactive waste, which may be leveraged by the maritime industry. As many of the potential challenges associated with waste handling, disposal, and reactor decommissioning may also be applicable to land-based reactor deployments, it is possible that some of these challenges may be entirely overcome or addressed by the time a maritime deployment takes place.

2.9.3 Code Standardization and Regulatory Harmonization

Engagement between stakeholders and regulators will be beneficial at an early stage to arrange permanent solutions to nuclear materials handling and waste storage. Obtaining political support and public approval may serve to obtain government support in handling and storing nuclear waste.

Each country is responsible for managing its own nuclear material and waste although many have requirements for the implementation of IAEA safeguards for these materials. For commercial nuclear vessels, this means that D&D activities would need to facilitate the return of used nuclear fuels and nuclear waste from where the fuel originated. New arrangements and agreements may need to be established between nuclear and marine stakeholders to complete D&D activities. Alternatively, the possibility of waste reprocessing facilitates the deployment of new nuclear technologies that can use reprocessed fuel or other fissile products as fuel. However the arrangements for closed fuel cycles have not yet been developed in the US.

Although standards, regulations and laws exist to manage nuclear waste, interfacing with maritime stakeholders and regulators may add complexity. To facilitate the safe dismantling of maritime units incorporating nuclear technology, it may be necessary to create standards and regulations for marine stakeholders governing the necessary planning, processes, and considerations. It may be particularly beneficial for stakeholders to engage with the IMO to facilitate the incorporation of nuclear-maritime decommissioning considerations into the Hong Kong International Convention for the safe and environmentally sound recycling of ships fitted with nuclear power plants. Another relevant existing standard is the INF Code which has provisions in place for how irradiated material and nuclear waste is to

be handled on board ships, which may potentially serve as a basis for how nuclear waste is to be handled, stored and discharged from vessels incorporating advanced nuclear technology (60).

2.9.4 Leverage Government and Navy Experience

Government experience from the decommissioning of nuclear-maritime reactors may prove valuable in the development of commercial deployments. In the U.S., experience obtained by the DOE in nuclear reactor decommissioning and nuclear waste handling may be leveraged for plans and guidelines for novel reactor deployments. Additionally, lessons learned from deployments such as the NS *Savannah*, shown in Figure 20, as well as the MH-1A (also known as the *Sturgis*) FNPP deployed in the Panama Canal in the 1970's, shown in Figure 21, may prove relevant and a valuable learning experience. Important things to highlight from these two vessels is their time mothballed before undergoing nuclear decommissioning, with the MH-1A costing over \$34 million to decommission despite being built on the hull of a WWII era cargo ship (61). We can't expect future nuclear-maritime applications to include this reality as an option in their plans for decommissioning (62).



Figure 20: NS Savannah, Baltimore, Maryland, May 19, 2009. N/S Savannah is the world's first nuclear-powered merchant ship (75).



Figure 21: STURGIS operating in the Panama Canal Zone. The Sturgis, a former World War II Liberty Ship, was converted into the first floating nuclear power plant in the 1960s [42].

Additional experience from the U.S. Navy may facilitate the development of commercial D&D procedures to support the introduction of civilian applications. A 2018 report completed by the U.S. Government Accountability Office (GOA) analyzed the costs, options, and logistics of decommissioning the nuclear aircraft carrier *USS Enterprise*, shown in Figure 22, following its deactivation, providing insight into the challenges and opportunities which may potentially be encountered during the end-of-life process for

civilian nuclear vessels. The report states that it would cost between \$750 million and \$1.4 billion for a commercial dismantling of the vessel over the course of 5 years, with an additional 10-year period for defueling, preparation, and environmental planning. The report also analyzed dismantling in a naval shipyard, which was estimated to induce costs ranging from \$1.05 billion and \$1.55 billion. While this high cost may be associated with many factors which may be unique to aircraft carriers or other Navy ships, such as the large number of on-board military facilities and the presence of eight reactors, the expenses for decommissioning nuclear submarines, which are low, were assessed to cost an average of \$26 million, significantly more than non-nuclear powered Navy vessel decommissioning. For comparison, dismantling of non-nuclear Navy ships usually has minimal costs of up to \$6 million (63).



Figure 22: The USS Enterprise (64)

Experience obtained from the USS Enterprise, NS Savannah, other nuclear vessels', and land-based reactor decommissioning efforts may prove helpful in planning for end-of-life logistics during the design stage of commercial vessels incorporating advanced nuclear technology. This experience will be useful for a near-prompt demonstration model that may be needed for public acceptance of nuclear vessels at harbors. It may also be particularly useful in implementing end-of-life and decommissioning considerations into the design criteria, as addressing potential problems during the design stage has been shown to result in decreased costs.

2.9.5 Funding Policy

For projects to receive final approval and reach maturity, funding for nuclear material handling and radiological waste management infrastructure must be available. Funding for these purposes may be sourced through several potential mechanisms, including the upfront payment of decommissioning insurance for all nuclear-maritime units or vessels, setting fees aside during construction and gradually afterward, or through government funding or guarantees. Government funding may be particularly beneficial if decommissioning, or waste disposal costs are prohibitively high.

2.9.6 Operational Procedures

Establishing operational procedures for reactor maintenance and safe handling of nuclear material will allow for the successful approval and implementation of advanced reactor technology.

Additionally, procedures and financial arrangements may need to be established to ensure reactor owners are prepared for severe scenarios that may be possible for nuclear-maritime applications, potentially through vehicles such as the Price-Anderson Act (although it's not clear if this would be applicable to nuclear-maritime applications), which requires reactor operators to contribute to a common insurance fund to cover the potential associated liabilities of a severe incident regardless of who is liable (65).

3 Conclusion

The paper aims to provide guidance for the successful demonstration and eventual deployment of nuclear technologies in maritime environments by highlighting key areas of focus and action.

All input received is summarized in Figure 23 below to provide an overview of expert recommendations for overcoming the challenges identified in this and previous reports. The most widely proposed strategies to address all issues primarily relate to robust design, as well as other related activities mostly undertaken in the initial stages of the technology development phase. The second most widely proposed approach according to expert responses is to address issues by focusing on code standardization or regulatory harmonization across disparate regimes, regions and international frameworks. The third and fourth most important approaches identified were robust testing or demonstration and funding policy activities. These are key strategies that can address technical, regulatory and economic challenges.

The responses from industry subject matter experts provide some insights on details of the challenges or issues, as well as considerations and potential strategies to address them. Details within the recommendations provide hints as to how strategies to address issues should be prioritized as well as an indication of the most severe issues that ought to be addressed first.

In the near-term, robust design strategies should include stakeholder engagement and delivering tangible results from demonstration and testing activities.

Primary challenges to address or pursue **in the mid-term** relate to leveraging experience or operational successes from land-based reactors and Naval nuclear deployments. Lessons learned and supply chains may be leveraged for nuclear-maritime applications after land-based nuclear successes. Mid-term strategies should also focus on making fuel more readily available and expanding supply chains for materials, equipment and components. Operational procedures should be developed for the use of these nuclear-maritime applications that resolve safety, security, and non-proliferation concerns as well as other regulatory requirements throughout the life of the product.

Lower priority strategies, while still needing to be addressed, may not need to be resolved or addressed immediately. These activities may include, for example, assessments and implementations of digital solution regimes and arrangements related to novel ownership and liability agreements.

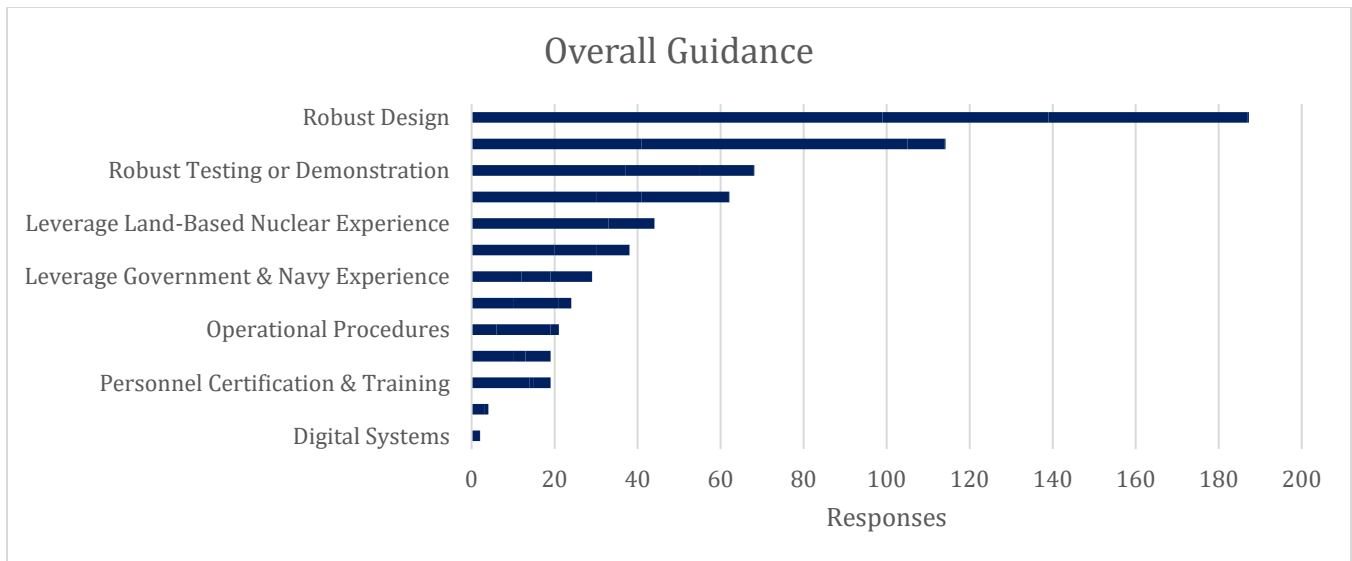


Figure 23: Overall Guidance for Addressing All Challenges

3.1 Actionable Recommendations for Effective Demonstration:

To facilitate the successful and safe deployment of advanced nuclear technology in the maritime industry, there are several steps to be taken as early as possible.

Recommended Action 1. Facilitate early and continued engagement between regulators, industry stakeholders, governments, the public, the scientific community, and potential future vendors and customers. Implement research project initiatives with strong project management practices, including milestone tracking, budget controls, and external independent reviews. These practices help manage risks and ensure that projects stay on track and within budget. For example, The DOE's Advanced Reactor Demonstration Program (ARDP) successfully uses these methods to manage multi-year awards and ensure effective oversight and performance of demonstration projects.

Undertake research projects to produce tangible results that lead to demonstrations and deployments of the technology. Safety, in terms of the potential effects that the technology or its failure may have, must be a priority for all involved stakeholders, who must ensure that all hazards are well understood and that all unacceptable risks are eliminated.

Engage and collaborate with groups doing groundwork to further the technological integration of nuclear energy in the maritime industry. Groups like these include, but are not limited to, The Marine Nuclear Application Group (MNAG) The World Nuclear Transport Institute (WNTI), and the Nuclear Energy Maritime Organization (NEMO). Working with groups like these helps introduces new stakeholders to existing projects, brings new projects that accelerate adoption pathways, and facilitate progress overall.

Thorough design, testing and demonstration of all materials, components, and systems will be necessary to understand and mitigate their associated risks, leading to reliable technology in which the public can have confidence. Early activities should include assessments of the technical, regulatory, and economic issues associated with maritime-nuclear technology. Robust design, testing or demonstration regimes, and the design considerations need to consider the

full lifecycle and operations of the nuclear-maritime application, including manufacturing, construction, operations, and D&D.

Recommended Action 2. Release information and research results to the public to both share technical findings and lessons learned as well as to engage the public and grow interest in the subject. Public engagement should include the use of local and regional social media, public forums, informational sessions, and open dialogues to address concerns and provide credible information. Leverage public communication channels such as social media or relevant news sites. Emphasize to the public the potential role that nuclear technology may play in meeting energy transition goals as well as the advantages it may hold compared to alternative energy sources.

Needed for engagement, transparent communications will be of particular importance in increasing confidence in the technology, the industry, and its regulators, while also potentially accelerating the licensing process.

Recommended Action 3. Focus on Standardization and Regulatory Harmonization. Establishing a strong understanding of how to navigate the regulatory and licensing frameworks will be essential in the first stages of development.

Based on early demonstration and testing activities, concurrently develop standardized codes and harmonized regulations to streamline the approval and deployment process of nuclear technologies. This can reduce challenges and facilitate smoother transitions from demonstration to commercialization. For example, Industry-wide efforts to create unified licensing frameworks for Floating Nuclear Power Plants (FNPPs) can reduce the complexity and time required for regulatory approvals.

Recommended Action 4. Leverage Funding policies and investment early on. Monitor and take advantage of economic opportunities to incorporate into demonstration, testing, or FOAK activities. Engage with policymakers and investors to transparently express the need and benefit of early and continued economic support.

Funding and investment are critical to pursue and establish resources for continued development and operations of the product. Appropriate funding policy and sufficient investment regimes can also support public outreach and engagement strategies.

3.2 Guidance for Nuclear Stakeholders

Nuclear stakeholders include nuclear reactor system designers, owners, fabricators, vendors/suppliers, certifiers, nuclear material transporters, disposal facilities and operators. These parties are responsible for the following actions when engaging with early testing and demonstration efforts as well as FOAK deployment projects:

Recommended Action 5. Provide resources to engage in research and demonstration design activities to produce nuclear reactor technologies that meet the maritime operational requirements, design criteria and constraints as defined by the maritime stakeholders. Design advanced nuclear technology for safety, security, safeguards, cost, reliability, supply chain viability, fuel availability, and other factors as appropriate.

Recommended Action 6. Engage with NRIC for Safety Design Basis. Reach out to the National Reactor Innovation Center (NRIC) to understand how the safety design basis for your reactor may

change in a maritime environment. This engagement can provide specific insights and guidelines tailored to maritime applications.

- Recommended Action 7. Convene Industry Summits. Organize and participate in industry summits with the Nuclear Regulatory Commission (NRC) and other relevant bodies to propose a licensing framework for Floating Nuclear Power Plants (FNPPs). This collaborative effort can help streamline the licensing process and address regulatory challenges collectively.
- Recommended Action 8. Develop Collaborative Projects. Consortia with other industry players to develop joint projects that can demonstrate the feasibility and safety of maritime nuclear reactors. These projects could include developing licensing schemes such that ownership of the vessel and nuclear systems are separated. Such collaborations can leverage shared resources and expertise, reducing individual risk and cost.
- Recommended Action 9. Address Supply Chain Challenges. Conduct a detailed supply chain analysis to identify potential bottlenecks and develop strategies to ensure the availability of critical components and materials. Engage with suppliers early to secure long-term partnerships and develop contingency plans for supply chain disruptions.
- Recommended Action 10. Public and Investor Engagement. Launch targeted public and investor engagement campaigns to communicate the benefits and safety of advanced nuclear technologies in maritime applications. Providing transparent and credible information can help build public trust and attract investment.
- Recommended Action 11. Early Regulatory Engagement. Initiate early discussions with regulators to understand the specific requirements and expectations for maritime nuclear applications. This proactive approach can help identify potential regulatory hurdles and address them before they become critical issues.

3.3 Guidance for Maritime Stakeholders

Maritime stakeholders include owners, operators, charterers, insurers, classification societies, designers, builders, ports, shipyards, marine jurisdictional authorities, investors, maritime vendors/suppliers and associated institutions. These parties are responsible for supporting the actions of nuclear stakeholders as well as the following actions when engaging with early testing and demonstration efforts as well as FOAK deployment projects:

- Recommended Action 12. Provide operational requirements, design criteria and constraints of maritime applications that are proposed to be fitted with advanced nuclear technologies.
- Recommended Action 13. Analyze the potential risks of nuclear technology, and subsequently apply risk mitigation or elimination strategies to develop designs that meet the acceptable level of risks.
- Recommended Action 14. Share economic information and operational data for project teams, as applicable, to develop effective business cases for demonstration and FOAK deployment.
- Recommended Action 15. Communicate the demand for nuclear energy to the nuclear industry and the public. Maritime stakeholders must make their intentions clear about the adoption of zero-carbon technologies or nuclear technology specifically, to demonstrate the demand for the technology and better incentivize its technical and regulatory development. For example, engage with Classification Societies to demonstrate the importance of the development of new Classification rules for nuclear-maritime applications.

3.4 Guidance for Regulators or Policymakers

Depending on the scope of the potential government, political, or policy environment, opportunities exist to provide resources to increase the capabilities of nuclear regulators to more effectively carry out their tasks, leading to support the adoption of advanced nuclear technology in new and novel applications. However, these laws, regulations and processes are in place to ensure the safety and reliability of the technology as well as assure the public's trust and confidence in guaranteeing their safety. Balance in terms of regulatory requirements is important, as overregulation may prevent the development and implementation of technology, while a lack of necessary laws or regulations may compromise safety and reliability. These criteria must be considered during the regulation of new and novel technologies, or the introduction of new rules aimed at eliminating regulatory gaps. Based on survey results, it is recommended that the regulators and policymakers, often for or with governments, takes the following actions:

- Recommended Action 16. Fund FOAK Demonstrations. The U.S. government should select several promising use cases and continue to provide funding for FOAK advanced nuclear technology demonstrations and future development of the technology for maritime applications. This approach aims to build public and financier support, demonstrating the viability and safety of the technology while moving down the cost curve.
- Recommended Action 17. Collaboratively engage with commercial entities. Survey results indicate a need for interaction with the Nuclear Regulatory Commission (NRC) and other regulatory bodies. Policymakers should encourage and facilitate collaboration between these regulatory entities and commercial stakeholders to ensure that necessary regulatory frameworks and processes are in place.
- Recommended Action 18. Implement actions to support the amendment of laws and regulations where there are gaps. Regulators and policymakers should analyze and amend existing laws and regulations to support the economic viability and adoption of new technologies. This includes investigating alternative options or adjustments to the NRC's approach to licensing maritime nuclear applications to reduce licensing costs. For example, amend the Jones Act to require new vessels to utilize zero-carbon fuels and examine whether existing laws and regulations are adequate for addressing third-party nuclear liability for maritime nuclear applications
- Recommended Action 19. Introduce Funding for Nuclear-Maritime Decarbonization. Policymakers should introduce funding mechanisms that support the development and adoption of nuclear energy and other decarbonization strategies within the maritime industry.
- Recommended Action 20. Ensure Adequate Funding for Regulatory Bodies. Regulators need adequate funding for staff and resources to support all industry activities effectively. Mitigating licensing delays can enhance the adoption of the technology.
- Recommended Action 21. Support Infrastructure and Operational Standards. Amend flag requirements for specific vessel applications to mandate the use of and integrate maritime nuclear energy within potential carbon tax or carbon credit schemes.

3.5 Recommendations for Future Work

Future research focused on defining challenges not specifically discussed in this document, and identifying strategies which may be beneficial in overcoming them, may be important in order to enable future technology demonstrations. The construction, preparation, and use of demonstration activities are



Figure 24: The Russian Floating Nuclear Power Station Being Transported from Murmansk (78).

necessary to validate the applicability of reactor concepts for the maritime environment. First movers and demonstration projects may also help identify, assess and address additional challenges not covered in this document. Some examples of challenges which may be important to consider but were not specifically addressed as part of this document may include:

- Recommended Future Work 1. Research the risks associated with insurance and 3rd party insurance/liability coverage exclusions.
- Recommended Future Work 2. Research market competition between land-based demonstrations and maritime-based demonstrations for funding as well as demonstration bandwidth.
- Recommended Future Work 3. Research risks associated with managing and sharing proprietary information during the development and testing stages of the technology.
- Recommended Future Work 4. Develop a comprehensive matrix of technology maturity levels for different reactor types and assess suitability for specific maritime applications. The scope of this project initiated this work to investigate the suitability of different reactors for general maritime applications, but a closer look will be needed when investigating specific maritime applications and deployment locations. To a limited degree this should include some consideration into ongoing fusion technology. This work will be important to market feasibility and increase investment.

Focus on potential concepts for early deployments that may eliminate potential challenges in the future to more complex applications. For example, deployments similar in scope to Russia's deployment of a FNPP, shown in Figure 24, (66) may prove to be an ideal first step as many international or complex regulatory challenges identified in this report related to transportation or nuclear propulsion may not apply to a local, stationary deployment.

- Recommended Future Work 5. Future studies to develop a U.S. road map for the deployment of FNPPs and nuclear powered ships to promote the adoption of the technology in time to reach national 2050 net zero goals.
- Recommended Future Work 6. Future studies collaborating with U.S. government agencies and shipyards should identify areas of opportunity for non-military nuclear-maritime application development and create a plan to develop a FOAK government-owned nuclear-maritime unit.

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Appendix 1: Industry Survey for Guidance on Addressing Challenges

The table below shows the technical, regulatory, and economic issues related to the respective key challenges. This table was used to present a list of expected challenges to elicit input from industry experts discussing methods to resolve or address each challenge.

Key Challenge	Technical Issues	Regulatory Issues	Economic Issues
Security, Non-Proliferation, Safeguards, and Export Control Challenges	Designers must consider security and proliferation risks at every stage and level of component. Risk of unauthorized access to sensitive information or nuclear material with the potential to support the development of a country's naval program and nuclear weapons program.	Potential reactor license delays to address additional risks in unique security situation.	Designing for proliferation issues requires incorporating an entire regime of safeguards considerations that are not required for other propulsion or power generation technologies.
	Direct attack or sabotage may involve potentially severe technical consequences to the unit and to future designs or applications.	International Traffic in Arms Regulations (ITAR), trade controls, or other restrictions may block nuclear ships, marine units, or marine nuclear materials from entering foreign ports.	Direct attack or sabotage may have severe economic repercussions on the industry beyond just the vessel or marine unit.
		Potentially restrictive to operational areas or destinations.	Security arrangements and personnel may increase costs.
Nuclear Licensing Challenges	Licensing or equipment certification may require re-design or additional testing or demonstration efforts.	Licensing process may not be expedited, resulting in severe delays.	Licensing or certification effort may be costly for new technology or applications, and may require re-design or additional testing (additional costs).
	Nuclear licensing may require certain engineering standards or codes to be used as well as the qualification of specific new technologies.	Licensing effort may be challenging for new or unique technology or applications without sufficient operating experience.	
		If nuclear licensing process is carried out improperly, the result may be severe consequences to liability, safety, and security.	
Demonstration and Testing Challenges	Design may use new, innovative materials and systems not tested or approved.	Technology failure may involve potentially severe political and regulatory consequences.	Technology failure may involve potentially severe economic consequences.
	Specific maritime nuclear testing equipment and platforms may need to be developed.		
	Potentially restrictive or causing delays if material requires code case for standardization.	New material may require code case for standardization.	New or unique engineering designs may involve developing new codes or standards,

Key Challenge	Technical Issues	Regulatory Issues	Economic Issues
	Technology failure may involve potentially severe environmental consequences.		increasing the overall costs of the application.
Business Case	High upfront (CAPEX) costs	Questions around multinational ownership of reactor units.	Personnel costs may not be well understood for new environment.
	Unknown value for “n” at which the n th manufactured reactor unit achieves economies of scale.	Policy or regulations may affect business cases and market landscapes regionally and globally.	Cost estimates and assumptions may underestimate actual costs of developing and implementing new technology.
	Technological development potentially restricted if engineering solutions do not show as economically feasible.	Sustainable carbon pricing schemes/policy may not incorporate nuclear power for maritime applications.	Failure to understand or estimate economic factors appropriately may involve severe consequences to owners/investors.
	Engineering solutions should consider designing for costs and using materials or parts that are economically suitable.		
	Supply chain may not be available.		
Nuclear Waste Transport and Disposal, and Marine Nuclear Decommissioning & Vessel Recycling	Maintenance and servicing may require specialized and complex remote handling equipment due to shutdown radiation fields.	Unclear which U.S. state or region would be responsible for waste management. Increasingly complicated for international scenarios.	Unclear how decommissioning fees would be collected and managed.
	Nuclear waste handling and transport may involve potentially severe environmental and technical consequences.	Nuclear waste handling, transport, and vessel recycling may involve potentially severe liability, policy, and regulatory consequences.	Nuclear waste handling and transport may involve potentially severe economic consequences.
	Vessel recycling may involve potentially severe technical and environmental consequences.	Potentially restrictive to implement or approve if no arrangement for transport or long-term waste disposal is available.	Arrangements for transport or disposal may be prohibitively costly to implement.
Supply Chain and Fuel Availability	HALEU and advanced fuel forms (such as TRISO) supply chain not yet developed.	HALEU availability.	HALEU and fuel fabrication costs.
	Supply chain for other advanced materials and plant components may not be developed or available.	Regulations related to trade may restrict supply chains and material or parts availability.	The supply chain for advanced materials may be expensive.
	Potential for limited fuel, material, and part developers in growing and competitive market.		Potentially upfront and lifecycle costs may be prohibitively expensive.

Key Challenge	Technical Issues	Regulatory Issues	Economic Issues
Integration of Nuclear and Maritime Industries	Potentially restrictive to adopt and implement new technology, component, part, or material in an unfamiliar industry.	Outdated marine regulations may be misinterpreted; potential that no alternative design mechanism is available for new and innovative technology.	New or unique marine technology may be expensive or costly to standardize, certify, and regulate.
Support Infrastructure	No commercial shipbuilder capable of handling nuclear material in the U.S.	Gaps in nuclear or maritime regulations may cause issues when technology interfaces with infrastructure and land-based support efforts.	Potential severe consequences to capital and operational costs.
	Shipyards and ports may not be suitable for nuclear material.		
	Potentially severe consequences to technical quality of product.		Crew and personnel may not be trained; potential rising costs of personnel.
	Appropriately trained and certified crews and operators may not be available to meet rising demand for advanced nuclear-maritime applications.		
Public Policy/Public Acceptance Challenges	Negative public perception may reduce number of dedicated engineers and technicians interested in supporting the development of the technology.	Negative public perception may result in restrictive transport or trade policy or regulations regionally or globally.	Negative public perception may limit investment opportunities.
	Engineering solutions are to address risk reduction measures at all phases and for all components.		