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# Report on Potential Challenges and Impacts of Advanced Nuclear-Maritime Applications in the U.S.

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

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## Disclaimer

# Revision Log

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# Executive Summary

This report is the third deliverable[1,2] of a series of reports set forth by the Department of Energy (DOE), led by the American Bureau of Shipping (ABS), for the research award, "Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies." The report highlights the challenges that are facing both the nuclear and maritime industry as technology seeks to integrate.

This report is based on the expertise of the American Bureau of Shipping, the National Reactor Innovation Center, and all supporting parties. The previous report tackled the possible configurations for commercial nuclear-maritime systems. This report seeks to highlight the challenges that are likely to come from on a more pointed level. The expected challenges come in many forms and the solutions for these will require dedicated efforts from all parties involved. For the reactor side of the interface there are considerations of the technological and maritime readiness of existing and emerging technologies. From the maritime side, there is much work to be done in fleshing out the logistics that come from the introduction of the new technology and its impacts to the existing operation landscape. Finally, there are timelines that need to be considered and narrowed so that planning can occur on a myriad of topics like shipbuilding, regulatory preparation, etc.

Future research should focus on the detailed planning that is required in order for a more streamlined transition in the use of nuclear energy in the maritime sector. This planning would focus more closely on the aspects that affect the safe use of the technology on a maritime aspect. Concepts like operational handling training by personnel, comprehensive radioactive waste management procedures, and novel introductions into machinery maintenance could be highlighted in follow up documentation. Expanding on more narrow topics like this would allow industry to follow a blueprint set forth by experts and not only encourage the technology use further, but refine downstream certification and compliance efforts. Additionally, continuing research into the economic challenges stemming from the nuclear technology and the required workforce will allow for better decision making from existing vessel owners looking to convert to an alternative energy.

These, and many other challenges are needing to be addressed, and reports of these types are allowing for solutions to be addressed ahead of the first vessel cutting steel. Continuing work of this kind is crucial to the realization of new technologies at sea. This work also supports the recently issued nuclear Executive Orders (EOs). Specifically, EO 14299, "Deploying Advanced Nuclear Reactor Technologies for National Security", and EO 14300, "Ordering the Reform of the Nuclear Regulatory Commission," by ensuring the rapid development, deployment, and use of advanced nuclear technologies; and increasing the deployment of new nuclear reactor technologies, such as Generation III+ and IV reactors, modular reactors, and microreactors to support America leading the commercialization of affordable and abundant nuclear energy.

1 The first report in the series was titled "Road Map for the Development of Commercial Maritime Applications of Advanced Nuclear Technology"
2 The first report in the series was titled "Configurations of Commercial Advanced Nuclear-Maritime Applications"

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# Acknowledgment

This publication was prepared by a group of contributing authors, including: Sanjay Mukhi[2], Abdalla Abou-Jaoude[3], Levi M. Larsen[3], David H. Johnson[1], River Bennett, Jorge Arvelo[4], Wesley Price[4], Court Freund[4], Jorge Segovia[1], Mayir Mamtimin[1], Dillon Yi[1] and Dallas McCary[3] for graphics and figures.

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2 National Reactor Innovation Center (NRIC)
3 Idaho National Laboratory
4 MPR Associates

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# Table of Contents

## Table of Figures



## Table of Tables

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# Acronyms

ABS ... American Bureau of Shipping
BWR ... Boiling Water Reactor
CFR ... Code of Federal Regulations (U.S.)
DOE ... Department of Energy (US)
DOME ... Demonstration of Microreactor Experiments (INL Facility)
ECC ... Emergency Control Center
ECI ... Export Controlled Information
FHR ... Fluoride High-temperature Reactors
FNPP ... Floating Nuclear Power Plant
GHG ... Greenhouse Gas
HALEU ... High-Assay Low-Enriched Uranium
HPR ... Heat-Pipe Reactor
HTGR ... High-Temperature Gas Reactor
HTSE ... High-Temperature Steam Electrolysis
IMO ... International Maritime Organization
INL ... Idaho National Laboratory
ITAR ... International Traffic in Arms Regulations
LFR ... Lead Fast Reactor
LOTUS ... Laboratory for Operations and Testing in the United States (INL Facility)
LWR ... Light Water Reactor
MEPC ... Marine Environment Protection Committee
MSR ... Molten Salt Reactor
NEICA ... Nuclear Energy Innovation Capabilities Act
NNS ... Newport News Shipbuilding
NQA ... Nuclear Quality Assurance
NRC ... Nuclear Regulatory Commission (U.S.)
NRIC ... National Reactor Innovation Center
PWR ... Pressurized Water Reactor
SFR ... Sodium Fast Reactor
TRISO ... Tri-structural Isotropic Fuel

# INTRODUCTION

# 1 INTRODUCTION

This report is the third deliverable of a series of reports under the work scope established by the Department of Energy (DOE) research award, "Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies."

This report is directed at those interested in the development of possible nuclear reactor technologies for marine and offshore applications. Advanced reactors may be of interest for next-generation marine and offshore solutions but they may also face a range of technical and regulatory challenges.

This DOE research award focuses on realizing the benefits and addressing the challenges in the maritime domain so that new reactor technologies can be deployed rapidly to transform marine and offshore industries and create market disruption that will provide unique competitive advantages for U.S. companies that design, build, operate, and support maritime assets.

This work supports the recently issued nuclear Executive Orders EO 14299 and EO 14300, by ensuring the rapid development, deployment, and use of advanced nuclear technologies; and increasing the deployment of new nuclear reactor technologies, such as Generation III+ and IV reactors, modular reactors, and microreactors to support America leading the commercialization of affordable and abundant nuclear energy.

## 1.1 Goals and Objectives of this Report

The objective of this research award is to connect the maritime industry with the nuclear industry and encourage the development of demonstration and commercial projects using advanced nuclear technologies. This report may be used as an important tool for the U.S. National Reactor Innovation Center (NRIC) to encourage demonstration projects with industry and a useful resource for a range of regulatory bodies and other stakeholders.

This report provides a broad review of:

1. Issues and barriers to adopting nuclear technology in the commercial marine industry.
2. Available advanced reactor technologies that may be most applicable for commercial maritime applications.
3. Potential marine and offshore applications for this technology.
4. Potential impacts of the technology on the U.S. marine and offshore industries.
5. Expected timelines for demonstration projects and industry adoption of such technology.

This report focuses on applications and operations in the United States (U.S.); however, the subject is internationally relevant.

## 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 deployment of advanced nuclear technology concepts, including support for commercial maritime applications.

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

## 1.3 Background

The International Maritime Organization (IMO) has been establishing measures and goals to address emissions from shipping since 2010. They first focused on improving energy efficiency and limiting harmful emissions from ships, including harmful pollutants such as sulfur oxides and greenhouse gases (GHGs). While there are methods and technologies to reduce or capture emissions before entering the atmosphere, the reliance on hydrocarbon-based marine fuels endures. Global maritime shipping currently accounts for approximately 3% of collective human emissions [1].

During the IMO's Marine Environment Protection Committee (MEPC) 80$^{th}$ session in July 2023, the 2023 IMO Strategy on Reduction of Greenhouse Gas Emissions from Ships [Resolution MEPC.377(80)] was approved. The 2023 IMO GHG strategy increases the level of ambition of decarbonization goals when compared to the initial IMO strategy published in 2018 [2]. The revised and strengthened GHG strategy includes the following goals [3]:

- To reduce $CO_2$ emissions per transport work as an average across international shipping by at least 40% by 2030 compared to 2008 levels.
- To increase the uptake of zero or near-zero GHG emission technologies, such that these fuels or energy sources represent at least 5%, striving for 10% of the energy used by international shipping by 2030.
- To peak GHG emissions from international shipping as soon as possible and to reach net-zero GHG emissions by or around 2050.
- These emission goals encompass the projected expansion of maritime trade (currently accounting for over 90% of global trade) over the next few decades. Nuclear power may offer a unique solution to these targets to provide long-lasting, emissions-free solutions for vessels and offshore units.

The development of advanced nuclear reactor technologies for marine and offshore applications directly contributes to national security by ensuring a affordable, reliable, and secure energy supply for critical commercial maritime operations and offshore energy infrastructure. By expanding nuclear propulsion and power generation to commercial vessels and offshore platforms, the United States can significantly reduce its reliance on hydrocarbon fuels, enhancing energy independence and providing robust, long-duration power solutions. Furthermore, by leading in the development and deployment of these advanced technologies, the nation can secure a competitive advantage in the global maritime industry, fostering economic growth and technological leadership that supports national strength.

## 1.4 Summary of Adoption Barriers

For a demonstration program to succeed, it must demonstrate technical, regulatory, and economic feasibility with public support. Each area of feasibility is typically addressed by diverse teams of stakeholders.

Table 1 lists primary adoption barriers to new nuclear technologies with detailed potential items categorized into technical, regulatory, or economic feasibility issues. The solutions to the listed barriers may require coordinating stakeholders from various technological, regulatory, or economic industries. Understanding the representative potential barriers can allow first movers to better position themselves to succeed without any hidden or unexpected issues causing undue delay or expensive corrections during development.

To the extent possible, subsequent reports within this DOE research award will make recommendations to address these expected barriers.

*Table 1. Representative issues and potential barriers to nuclear-maritime adoption.*

| Key Barrier | Technical Issues | Regulatory Issues | Economic Issues |
|---|---|---|---|
| **Security, Non-Proliferation, Safeguards, and Export Control Barriers** | • 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.<br>• Direct attack or sabotage may lead to short- or long-term unit issues and to future designs or applications. | • Potential reactor license delays to address additional risks in unique security situations.<br>• 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.<br>• Potentially restrictive to operational areas or destinations. | • Designing for proliferation issues requires incorporating an entire regime of safeguards considerations that are not required for other propulsion or power generation technologies.<br>• Direct attack or sabotage may have critical economic repercussions for the industry beyond just the vessel or marine unit.<br>• Security arrangements and personnel may increase costs. |
| **Nuclear Licensing Barriers** | • Licensing or equipment certification may require re-design, additional testing, or demonstration efforts.<br>• Nuclear licensing may require certain engineering standards or codes to be used as well as the qualification of specific new technologies. | • Licensing process may not be expedited, resulting in extended delays.<br>• Licensing effort may be challenging for new or unique technology or applications without sufficient operating experience.<br>• If nuclear licensing process is carried out improperly, the result may be severe consequences to liability, safety, and security. | • Licensing or certification effort may be costly for new technology or applications and may require re-design or additional testing (additional costs). |
| **Demonstration and Testing Barriers** | • Design may use new, innovative materials and systems not tested or approved.<br>• Specific maritime nuclear testing equipment and platforms may need to be developed.<br>• Potentially, validation may be needed if material requires code case for standardization.<br>• Potential for serious environmental damage should there be a technological failure.<br>• Engineering solutions are to address risk reduction measures at all phases and for all components. | • Technological failure may cause political and regulatory complications.<br>• New material may require code case for standardization. | • Negative economic outcomes are possible if technological failure were to occur.<br>• New or unique engineering designs may involve developing new codes or standards, increasing the overall costs of the application. |

| Key Barrier | Technical Issues | Regulatory Issues | Economic Issues |
|---|---|---|---|
| **Business Case Barriers** | • High upfront (CAPEX) costs.<br>• Unknown value for "n" at which the $n^{th}$ manufactured reactor unit achieves economies of scale.<br>• Technological development potentially restricted if engineering solutions do not show as economically feasible.<br>• Engineering solutions should consider designing for costs and using materials or parts that are economically suitable.<br>• Supply chain may not be available. | • Questions about multinational ownership of reactor units.<br>• Policy or regulations may affect business cases and market landscapes regionally and globally.<br>• Sustainable energy pricing schemes/policy may not incorporate nuclear power for maritime applications. | • Personnel costs may not be well understood for new environment.<br>• Cost estimates and assumptions may underestimate actual costs of developing and implementing new technology.<br>• Failure to understand or estimate economic factors appropriately may impact owners/investors. |
| **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.<br>• Nuclear waste handling and transport may involve potentially severe environmental and technical consequences.<br>• Nuclear waste handling, transport, and vessel recycling may have technical complexities and high risks to the environment. | • Unclear which U.S. state or region would be responsible for waste management.<br>• Increasingly complicated for international scenarios.<br>• Nuclear waste handling, transport, and vessel recycling may have unknown liability, policy, and regulatory consequences.<br>• Potentially restrictive to implement or approve if no arrangement for transport or long-term waste disposal is available. | • Unclear how decommissioning fees would be collected and managed.<br>• Nuclear waste handling and transport may involve potentially severe economic consequences.<br>• Nuclear waste handling and transport have considerable economic outcomes.<br>• 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 under development.<br>• Supply chain for other advanced materials and plant components may not be developed or available.<br>• Potential for limited fuel, material, and part developers in growing and competitive market. | • Availability of advanced fuel types.<br>• Regulations related to trade may restrict supply chains and material or parts availability. | • HALEU and fuel fabrication costs.<br>• The supply chain for advanced materials may be expensive.<br>• Potentially upfront and lifecycle costs may be prohibitively expensive. |
| **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. |

| Key Barrier | Technical Issues | Regulatory Issues | Economic Issues |
|---|---|---|---|
| **Support Infrastructure** | • Unclear if commercial shipbuilders are capable of handling nuclear material.<br>• Shipyards and ports may not be approved for nuclear material by state regulatory bodies.<br>• Technical quality of product may be adversely impacted.<br>• Appropriately trained and certified crews and operators may not be available to meet rising demand for advanced nuclear-maritime applicactions. | • Gaps in nuclear or maritime regulations may cause issues when technology interfaces with infrastructure and land-based support efforts. | • Potential obstacles to capital and operational costs.<br>• Crew and personnel may not be trained; potential rising costs of personnel. |
| **Public Policy/Public Acceptance Barriers** | • 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. |

# ADVANCED NUCLEAR REACTOR TYPES AND TECHNOLOGIES

# 2 ADVANCED NUCLEAR REACTOR TYPES AND TECHNOLOGIES

## 2.1 Conventional Pressurized Water Reactors for Marine Use

The *USS Nautilus* was the world's first nuclear-powered submarine. It was put to sea in January 1954. The vessel used a pressurized water reactor (PWR) in which a uranium-fueled core was surrounded by a constant flow of light water ($H_2O$) that acted as both the neutron moderator and primary coolant. The pressurized core prevented the water from boiling, which allows the water coolant to transfer more heat. Loss of coolant has been the primary cause of major nuclear reactor incidents in the past where the core is not able to shed heat, which may lead to a meltdown [4].

As the U.S. Government began to consider nuclear power technology as a peaceful tool to supply civilian electrical power on land, the PWR technology was proposed as a candidate for the first power plant. On December 2, 1957, Shippingport Atomic Power Station went critical using a repurposed PWR, becoming the first commercial nuclear power plant in the U.S. This ultimately set the stage for the deployment of light water reactors in the 20th century as the primary civilian nuclear power technology in the U.S. [5].

## 2.2 Commercial Nuclear Reactors at Sea

There have been a handful of non-military applications to harness nuclear technology at sea, including:

- United States: The NS *Savannah*, a cargo and passenger vessel operating from 1962–1972, fitted with 74 MWth power.
- Germany: The *Otto Hahn,* a cargo vessel operating from 1968–1979 with 38 MWth power.
- Japan: The *Mutsu,* the general cargo vessel, which faced public objections that prohibited the carriage of cargo (1972–1996), was installed with 35 MWth power.
- Russia: The nuclear icebreaker fleet began with the *Lenin*, launched in 1957, and grew to a fleet of seven modern vessels owned and operated by the state agency Rosatom. These vessels support ice operations and navigational services in the Arctic. The 1988-built icebreaker cargo vessel *Sevmorput* is installed with 135 MWth to assist with ice operations in the Arctic.

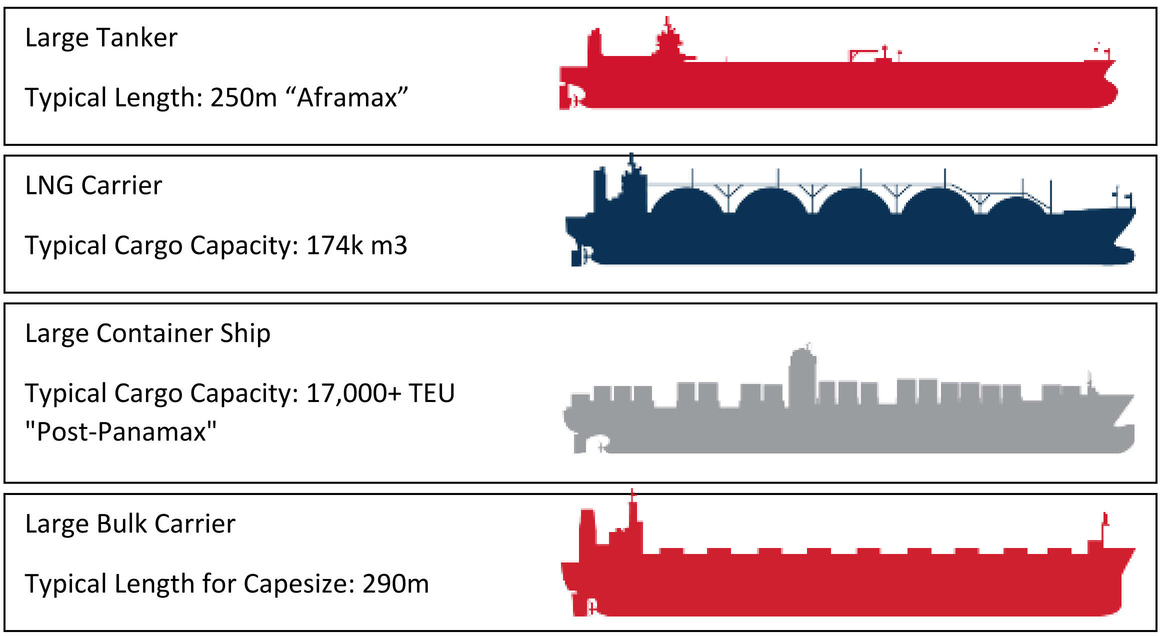


*Figure 1. Typical ship sizes and power arrangements.*

Typical modern maritime applications require a range of installed power for propulsion, cargo operations, or other industrial processing purposes, depending on the ship type and operational profile. A summary of typical ship sizes and power arrangements is shown in Figure 1 for context.

Floating nuclear power plants (FNPPs) may be fitted with less specific powering arrangements, where the existing Russian FNPP *Akademic Lomonosov* is fitted with a total power of 70 MWe (or 300 MWth), while a recent gas-powered floating power plant design Seafloat can range from 150–450 MWe, depending on configuration [6]. Russia has ordered new FNPPs to be fitted with a capacity of at least 100 MWe each.

An important distinction that sets commercial advanced reactors apart from today's existing conventional reactors is size. Commercial reactors today supply between hundreds of megawatts to gigawatts of power to the grids where they operate. Reactor designs are often grouped in terms of size and type. Advanced reactor sizing is typically subdivided into three classes, outlined in Figure 2 [7].

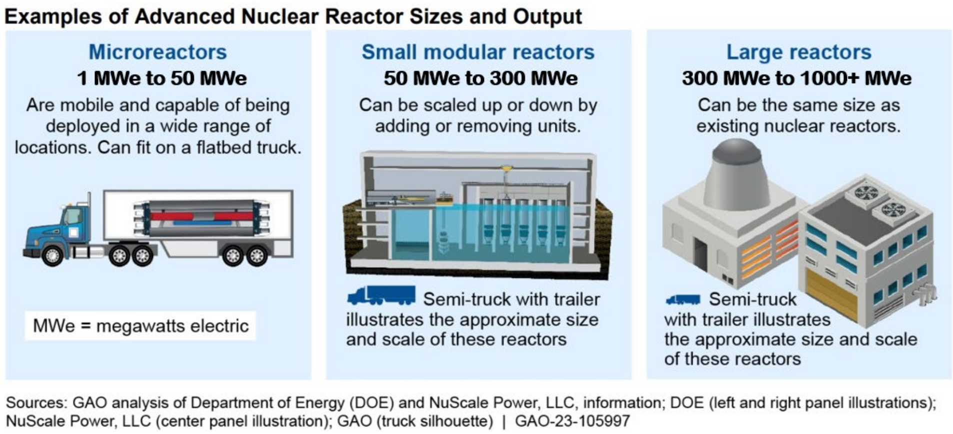


*Figure 2. Advanced reactor sizes [7].*

Within these various classes, proponents are pursuing diverse types of advanced nuclear technologies. While several groupings of the advanced reactor types have been proposed (see Generation IV international Forum 2018 Outlook [8]), for the purposes of this assessment, seven specific categories are considered, as shown in Figure 3.

## 2.3 Advanced Water-Cooled Reactors

Water-cooled reactors are the most widely used reactors today in terms of commercial availability, and many companies are developing new reactors based on this configuration. For oceangoing vessels, seawater is a readily available heat sink. A non-naval advanced water-cooled reactor design may be applicable to commercial maritime applications for both propulsion and non-propulsion applications.

Light Water Reactors (LWRs) are typically fueled with uranium oxide clad with zirconium. Water serves as both the coolant and a neutron moderator. There are two sub-variants: PWRs and boiling water reactors (BWR). LWRs form most of the existing commercial reactors currently in operation. PWRs operate at pressures of roughly 150 atmospheres (15.2 MPa) [9]. As a result, PWRs require containment, piping, and joints that can withstand extremely high pressures. A useful overview of LWR technology is available in the Idaho National Laboratory (INL) Reactor Fundamentals Handbook [10].

For example, Figure 4 shows a scaled-down version of an “integral PWR,” which is based on a single-unit pressure vessel that also houses the core, primary coolant, and steam generator. This smaller system also uses natural circulation to move its primary coolant, which eliminates the need for pumps in the reactor coolant system. This also allows for scalability where a single facility can house multiple reactors. In addition to terrestrial applications, these types of small power modules may be appropriate for installation on FNPPs, which would demonstrate an important application for water-cooled reactors in the maritime domain [11].

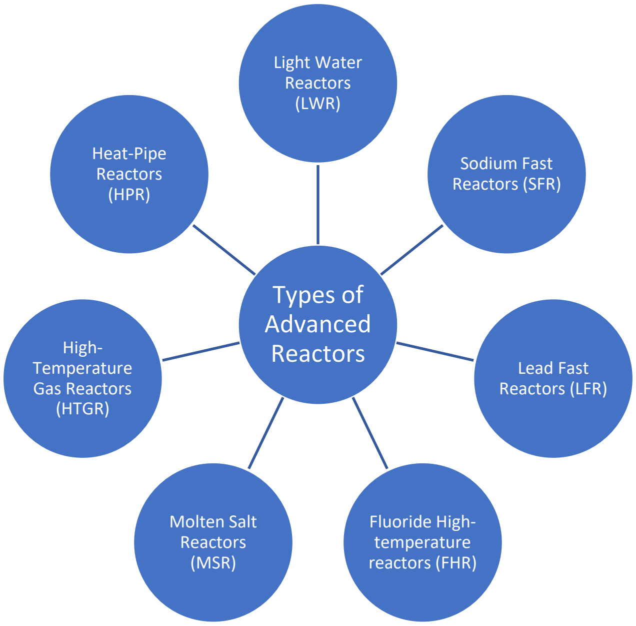


*Figure 3. Types of advanced reactors.*

*Figure 4. Rendering of NuScale's Power Module being transported[7].*

There are also some notable LWR designs today that can be further studied These include, but are not limited to:

- GE-Hitachi's BWRX-300
- Westinghouse's AO300
- Holtec's SMR-300.

## 2.4 Non-Water-Cooled Advanced Reactor Technology

While water-cooled reactors dominate today's market and represent an important segment of the pool of advanced reactor technologies under development, there are multiple other categories of reactors that can provide enhanced performance in different ways.

### 2.4.1 Liquid-Metal-Cooled and Molten-Salt Reactors (MSRs)

Liquid-metal-cooled reactors and molten-salt reactors (MSRs) use molten salts or liquid metals (such as molten fluoride salt, liquid sodium, or molten lead) in place of water to remove heat from the reactor core. Using these materials as coolants provides many benefits, including operation at higher temperature leading to enhanced thermal efficiency, lower operating pressures, and configurations that allow for operations in either thermal or fast neutron spectrums.

Molten salts and liquid metals, as shown in Figure 5, do not expand as much as water when heated, and their boiling points are also much higher. This allows for higher operating temperatures that improve the thermodynamic efficiency of producing electricity. This is also significant as it allows the reactor and its secondary systems to operate at relatively normal pressures. Eliminating high pressures from the system can reduce construction complexity and result in relatively compact configurations, which makes them attractive for use on commercial vessels. However, challenges related to corrosion, liquid metal contamination, and chemical activity need to be better understood and overcome.

<u>Sodium Fast Reactors</u> (SFRs) are cooled by sodium (or sodium-potassium alloy) and have no moderator (hence the neutrons remain "fast"). This enables potential breeding of fissile material in the core and could lead to advantages in terms of fuel consumption. Typical fuels considered are metallic or oxide-based (although carbides and nitrides have been proposed). Several demonstration projects have been deployed in the United States, France, the United Kingdom, China, and Russia in the past (with upcoming demonstration in India [12]). It should be noted that the risks associated with the exothermic reaction between sodium metal and water must be well understood and addressed to allow SFRs to be suitable for maritime applications, especially in the rare possibilities of sodium exposure to large volumes of water during flooding or sinking scenarios. Additional information on Sodium Fast Reactors can be found in the text *Fast Spectrum Reactors* [13]. ARC Clean Technology's ARC-100 and TerraPower/GE-Hitachi's Natrium can be considered for further interest.

<u>Lead Fast Reactors</u> (LFRs) are similar to SFRs but use lead (or lead-bismuth) as a coolant instead of sodium. These reactors also operate in the fast neutron spectrum and can typically use similar fuels as SFRs. These coolants are chemically inert, but they also have a higher melting point than sodium. Additional information on LFRs can also be found in *Fast Spectrum Reactors* [13].

<u>Molten Salt Reactors</u> (MSRs) employ molten salt in the core. In this report, MSRs refer to designs where the nuclear fuel is itself dissolved in the salt. This reactor type with liquid fuel is unconventional but was demonstrated in the 1950s and 1960s via two experiments in the U.S. [14, 15]. Several variants of MSRs are being pursued, but they can be subdivided into two main sub-categories: fast spectrum variants (typically with chloride-based salts) and thermal spectrum variants (typically with fluoride-based salts and graphite moderators). Other information on molten salt reactors is available in Dolans' *Molten Salt Reactors and Thorium Energy* [16].

<u>Fluoride High-Temperature Reactors</u> (FHRs) are a category of MSRs that rely on tri-structural isotropic (TRISO) solid fuel with graphite moderators. FHRs use molten salt (typically a mixture of lithium fluoride and beryllium fluoride, known as FLiBe) as the coolant. This enables lower pressure operations but can bring added challenges (e.g., corrosion). While several of the technologies employed in FHRs have been proven in previous reactors, the specific combination used in this reactor type has never been deployed. More information on FHR concepts is available in Qualls et al.'s 2016 report [17]. Some notable examples include:

- TerraPower's Molten Chloride Fast Reactor
- Abilene Christian University's Molten Salt Research Reactor
- Terrestrial Energy's Integral Molten Salt Reactor
- Moltex's Stable Salt Reactor.

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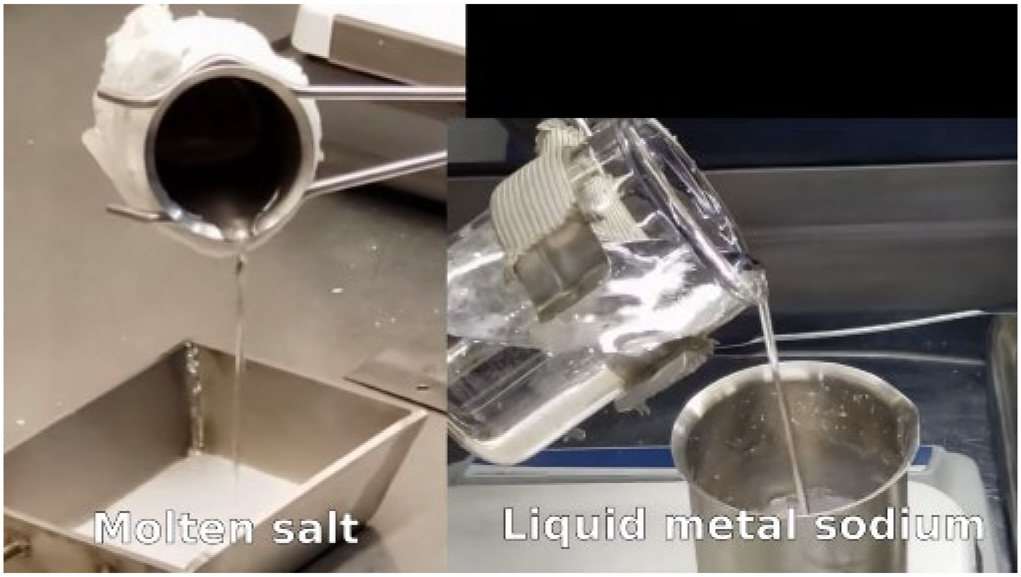


*Figure 5. Molten salt and liquid metal sodium being poured [35].*

### 2.4.2 High-Temperature Gas Reactors

High-Temperature Gas Reactors (HTGR) are usually inert gas-cooled (i.e., helium or $CO_2$) and run in the fast spectrum or thermal spectrum with the use of a moderator like graphite at various pressure levels. Modern versions of these gas reactors use TRISO fuel, similarly to FHRs [18], and can operate at relatively high temperatures, providing new opportunities to not only produce electricity more efficiently (roughly 10–25% higher than existing PWRs [19]), but also contribute to industrial processes such as the production of synthetic fuels, fertilizer production, and water desalination. More background information on this type of reactor is available in the text *Modular High-Temperature Gas-Cooled Reactor Power Plant* [18].

### 2.4.3 Microreactors

Microreactors represent a category of advanced reactor technologies scaled down in power output to between roughly 1 to 0.1% of the size of today's operating nuclear power plants with various benefits as shown in Figure 6. Due to their small physical size, these reactors are designed to be easily transportable and capable of supporting new market segments, including off-grid communities, mining operations, and dedicated industrial partners. Developers envision them to be factory-fabricated to reduce on-site construction issues, and self-adjusting to limit the amount of operator oversight required. Also, due to the reduced size, while many designs use conventional circulating coolants, other innovative heat transfer mechanisms are under development, including heat pipes. Common across the bulk of microreactor designs is the reduction or elimination of water-based waste heat rejection required for normal operation. This can significantly simplify the design and allow the reactor to operate virtually anywhere on the planet.

Proponents are also pursuing heat-pipe reactors (HPR) in the microreactor class. These reactors are in the form of solid fuel blocks with heat pipes passing through to passively dissipate nuclear heat to a heat exchanger. As a result, these systems contain no moving parts in the primary nuclear system and consequently are expected to be simpler and more reliable to operate. While several small HPR demonstrations have occurred in the past, no commercial demonstrations have taken place. Additional information on a proposed unique fast spectrum HPR design is available in Sterbentz et al. [20].

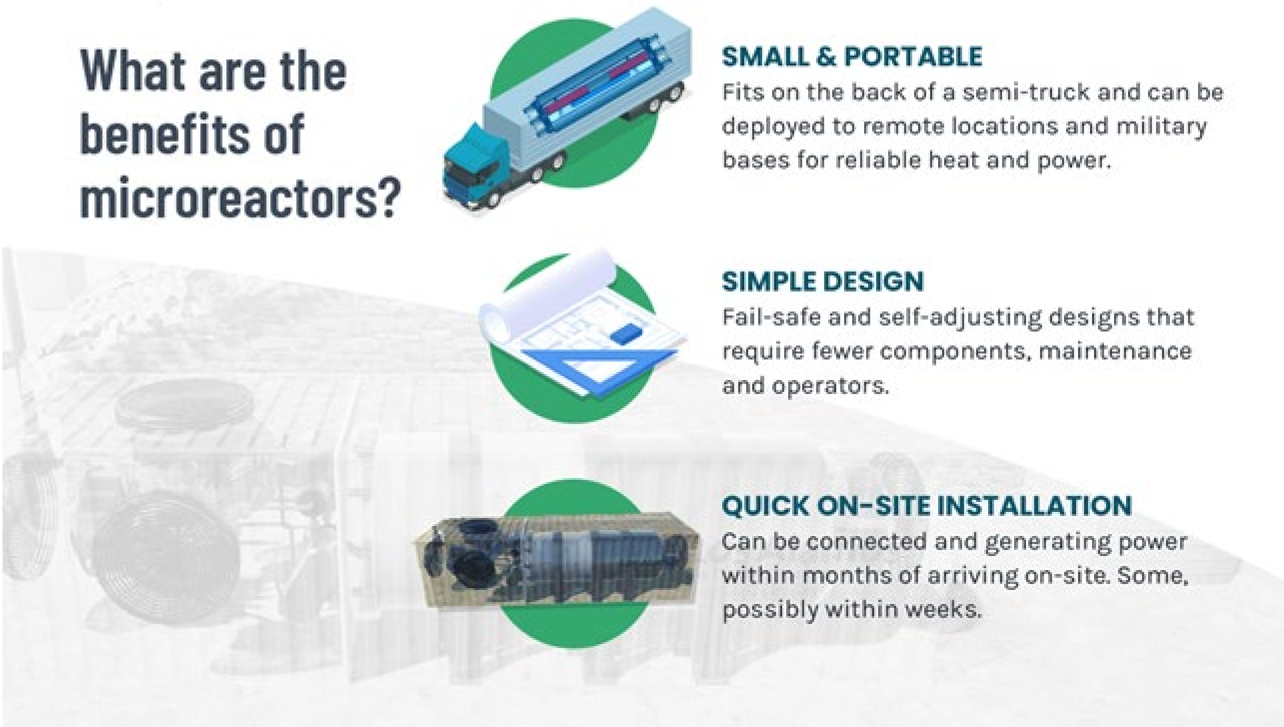


*Figure 6. DOE outline of microreactor benefits [36].*

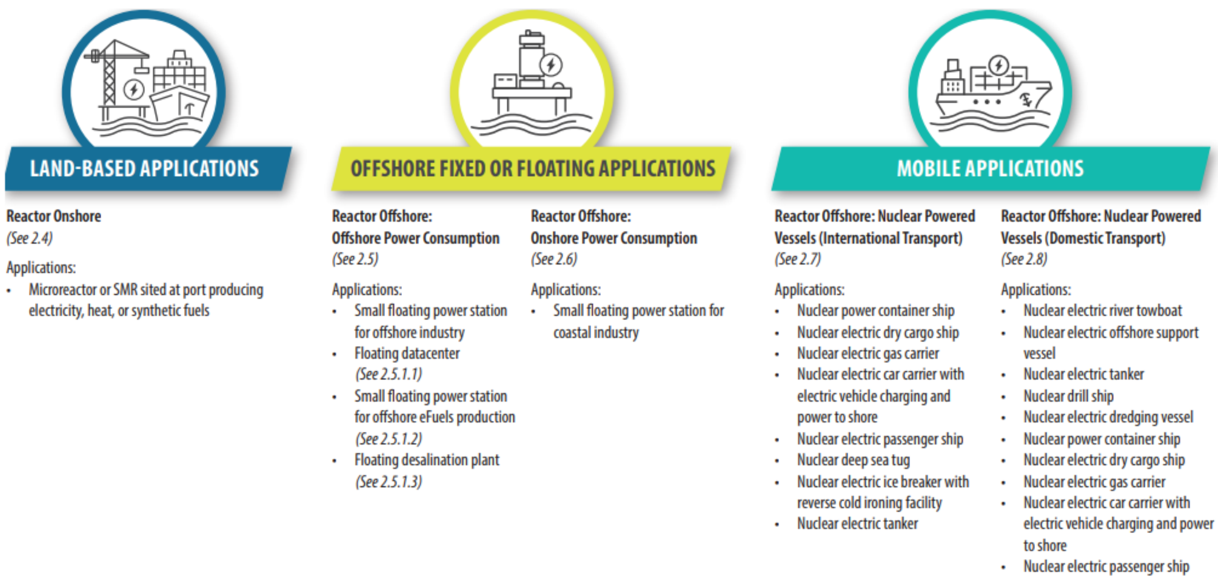


*Figure 7. Potential advanced nuclear-maritime applications.*

# POTENTIAL MARINE AND OFFSHORE APPLICATIONS

# 3 POTENTIAL MARINE AND OFFSHORE APPLICATIONS

## 3.1 Nuclear-Maritime Configuration Considerations

The suitability of each reactor size category for maritime applications can differ. Table 2 provides an overview of tradeoffs and the suitability of reactor sizes against the maritime applications shown in Figure 7.

*Table 2. Technological favorability ranking for each reactor size and class. Magenta corresponds to a low favorability, yellow to medium, and blue to high.*

| Reactor Size | Fixed Land/Coastal | Fixed Offshore Only | Fixed Offshore w/Onshore Grid Coupling | Mobile Local | Mobile International |
|---|---|---|---|---|---|
| Large (> 300 MWe) | Already exists, no size limits | Potential Size constraints | Potential Size constraints | Too large | Too large |
| SMR (< 300 MWe) | Under development | Balance between output and size | Balance between output and size | Already exists for naval/government applications[4] | Already exists for naval/government applications |
| Micro (< 50 MWe) | Limited output as single unit, potential to scale | Limited output as single unit, potential to scale | Limited output as single unit, potential to scale | Wider application | Wider application |

Within these various size classes, diverse types of reactor technologies are being pursued. While several groupings of the advanced reactor types have been proposed (see Generation IV International Forum [8]), for the purposes of this assessment, we see that it is useful to consider seven specific categories of reactors, as shown in Figure 3.

Based on the reactor specifications, it is possible to evaluate the general technological suitability of each reactor type for maritime applications, shown in Table 3 and discussed below.

*Table 3. Technological favorability ranking of each reactor type. Magenta corresponds to a low favorability, yellow to medium, and blue to high.*

| Reactor Type | Fixed Land/Coastal | Fixed Offshore Only | Fixed Offshore w/Onshore gGid Coupling | Mobile Local | Mobile International |
|---|---|---|---|---|---|
| Light Water Reactor (LWR) | Already exists on land | Low temperature limits efficiencies for synthetic fuel production | Will need heat augmentation | Already exists for naval/government applications | Already exists for naval/government applications |
| Sodium Fast Reactor (SFR) | Demonstrated; Under development | Potential risk of sodium-water exposure | Potential risk of sodium-water exposure | Potential risk of sodium-water exposure | Potential risk of sodium-water exposure |
| Lead Fast Reactor (LFR) | Least mature technology in the West | High-temperature, Lead (Pb) shielding | High-temperature, Lead (Pb) shielding | Least pursued technology | Least pursued technology |
| High-Temperature Gas Reactor (HTGR) | Demonstrated; Under development | High temperature improves efficiencies for synthetic fuel production | High temperature improves efficiencies for synthetic fuel production | High efficiency but high pressure and low power density | High efficiency but high pressure and low power density |
| Fluoride High-Temperature Reactor (FHR) | Under development | High temperatures and thermal delivery | High temperatures and thermal delivery | High temperature and low pressure | High temperature and low pressure |
| Molten Salt Reactor (MSR) | Demonstrated; Under development | High temperature and thermal delivery | High temperature and thermal delivery | High temperature and low pressure | High temperature and low pressure |
| Heat-Pipe Reactor (HPR) | Demonstrated, Under development | Limited output as single unit, potential to scale | Limited output as single unit, potential to scale | High temperature and low pressure | High temperature and low pressure |

[4] For the purpose of Tables 2, 3, and 4, while used for naval or government applications, there are likely other challenges when applying this existing naval technology to commercial applications. For example, military or government security restrictions to information and clearances as well as commercial restrictions regarding the use of high-enriched uranium (HEU), where proliferation risks are much more prevalent. Here, it is indicated as suitable only to show the concept has been proven historically under the right conditions of ownership. The suitability of commercial (non-Naval/Government) advanced LWRs may pose more challenging aspects from a technological readiness and experience level.

- Fixed land/coastal applications: The only technology receiving a low ranking for this category are LFRs as they are of low maturity with no official deployment plans in the U.S. for terrestrial application at the time of writing.
- Non-self-propelled offshore applications: High-temperature reactors are ranked more favorably for this category (namely HTGRs, MSRs, and FHRs). HPRs received a lower ranking as they are primarily conceptualized in the form of microreactors, which may not be suitable for the scale of production required for this maritime category. LWRs are ranked less favorably as their outlet temperatures are the lowest (leading to lower thermodynamic efficiencies), meaning they would require heat augmentation for industrial applications. While SFRs operate at higher temperatures, the potential risk associated with large-scale sodium-water interactions in the flooded or sinking conditions make them potentially less desirable candidates for maritime use cases. Last, LFRs are ranked lower for the same reasons as outlined for fixed land or coastal applications.
- Self-propelled, local, and international applications: Here, LWRs are ranked favorably since there is already substantial precedent for this technology combination (nuclear submarines, nuclear carriers, and nuclear icebreakers). FHRs and MSRs are also ranked highly as they provide the combination of high temperatures and low pressures that can result in more compact configurations. Similarly, the HPR's size may be suitable for mobile applications. HTGRs are ranked slightly lower due to the need for high-pressure operations (without the existing precedence as in LWR). LFRs are again ranked slightly lower as there are limited ongoing demonstration efforts for this technology. Last, SFRs are ranked as less suitable for this category for the same reason as outlined for non-self-propelled offshore applications.

Combining the previous two tables provides a good basis to discuss the mix of reactor classes and types against their suitability for various maritime applications. Promising configurations for the marine applications are highlighted in Table 3 in blue

Fixed applications are best served by SMR technologies (namely water, gas, or salt-cooled reactor variants). Self-propelled applications are best served by microreactor technology (heat-pipe or gas reactors). Their smaller size might enable wider applicability across vessel types. However, self-propelled concepts could also be good candidates for SMR-scale technology (namely water and salt-based reactors).

*Table 4. Combining the technological favorability of reactor type and class. Magenta corresponds to a low favorability, yellow to medium, and blue to high.*

| | | ***Fixed Land/Coast*** | ***Fixed Offshore Only*** | ***Fixed Offshore w/Onshore Grid Coupling*** | ***Mobile Local*** | ***Mobile International*** |
|---|---|---|---|---|---|---|
| **Large** | **LWR** | Already exists as a commercial application | Potential size constraints; limited efficiency for synth fuel production | Potential size constraints; heat augmentation required | Too large | Too large |
| | **MSR** | Demonstrated; Under development | Higher thermal efficiency; fuel cycle constraints | Higher thermal efficiency; fuel cycle constraints | Too large | Too large |
| **Small Modular Reactors (SMR)** | **LWR** | Demonstrated; Under development | Under development | Demonstrated, Under development | Already exists for naval/government applications | Already exists for naval/government applications |
| | **SFR** | Demonstrated; Under development | Sodium-water interactions | Sodium-water interactions | Sodium-water interactions | Sodium-water interactions |
| | **MSR/FHR** | Demonstrated; Under development | Higher thermal efficiency | Higher thermal efficiency | High temperature and low pressure | High temperature and low pressure |
| | **HTGR** | Demonstrated; Under development | Highest temperature applications | Highest temperature applications | Higher thermal efficiency but high pressure | Higher thermal efficiency but high pressure |
| **Microreactors** | **HTGR** | Demonstrated, but mismatch between power required and reactor power output could lead to economic inefficiencies | | | Wider application | Wider application |
| | **HPR** | | | | Wider application and low pressure | Wider application and low pressure |

## 3.2 Nuclear-Maritime Configurations

Table 5 provides a comparative overview of the technoeconomic tradeoffs between two types of applications (fixed versus self-propelled). This section dives deeper into specific configurations within each application type and discusses technoeconomic tradeoffs.

*Table 5. Technoeconomic tradeoffs between fixed and mobile nuclear-maritime applications.*

| | Advantages | Disadvantages |
|---|---|---|
| **Offshore and Non-self-Propelled Applications** | Allows for limited changes required to shipping infrastructure. | Potential inefficiencies in power conversion with certain reactor types. |
| **Self-propelled Applications** | Price per unit of energy likely to be lower. Technology already demonstrated for naval applications. | Difficult or prohibitive to retrofit existing ships (requires new ship designs). |

### 3.2.1 Fixed Nuclear Configurations for Synthetic fuel Production

The fixed nuclear configurations, including land-based and offshore non-self-propelled applications, would primarily produce electricity and heat for grid connections or industrial processes. One application that supports marine innovation is synthetic fuel production. There are several configurations to consider for synthetic fuel production, but one option assumes that hydrogen is generated via high-temperature steam electrolysis (HTSE), which has been extensively evaluated for nuclear applications [21].

For an industrial application such as synthetic fuel production, three more considerations may be important to evaluate:

1. Arranged as producing electricity only or electricity with heat from the reactor, see Figure 8.
2. Arranged with or without heat augmentation (increasing the temperature of the heat supply by other means [e.g., electric heating]), see Figure 9.
3. Arranged with or without coupling to the grid (enables diversion of power to electricity markets when prices are exceedingly high), see Figure 10

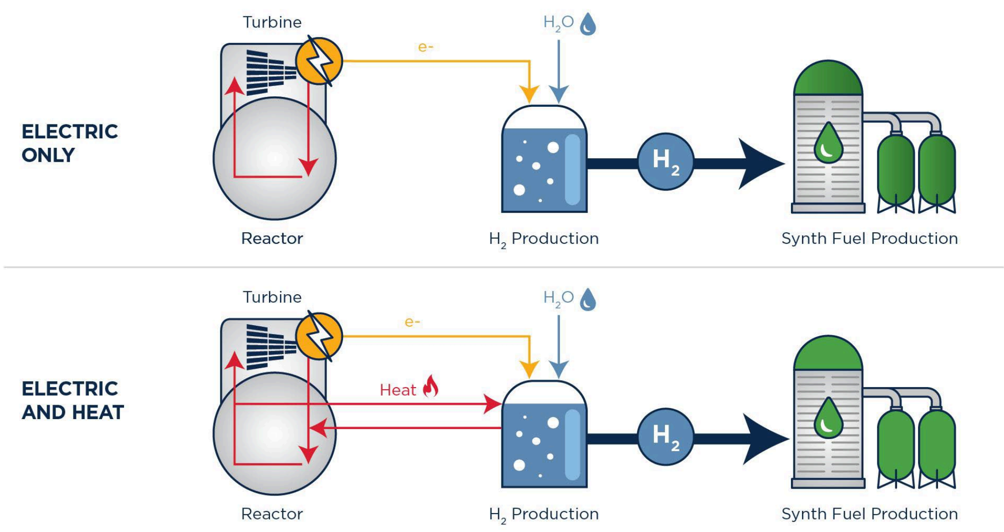


*Figure 8. Option 1. Configurations with or without heat input for synthetic fuel production.*

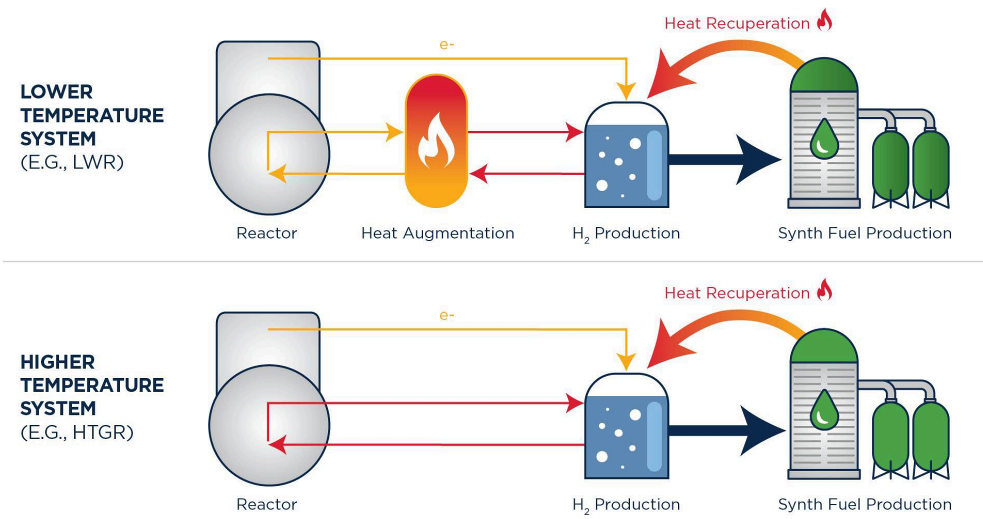


*Figure 9. Option 2. Configurations with or without heat augmentation for synthetic fuel production.*

In Figure 8, on the one hand, leveraging some heat in addition to electricity for the electrolyzer can greatly improve the efficiency of the overall system (since it would minimize conversion losses from heat to electricity and back to heat). On the other hand, the CAPEX and regulatory burden associated with coupling the thermal output of reactors could be substantial. Coupling thermal feeds from reactors to auxiliary systems may be a relatively complex task. However, several studies already point to the potential benefit of leveraging small amounts of heat from LWRs as feed to HTSE plants [22, 23, 24, 25, 26].

The second option is primarily driven by reactor technology considerations. Most reactors are unable to directly provide heat at the required temperatures for the HTSE stacks and will require heat augmentation. The only likely notable exception are HTGRs, which can have the highest outlet temperatures from their reactors. However, this is expected to have additional costs due to the need for refractory (high-entropy) alloys for several reactor materials.

Last, considerations for the third option involve the costs incurred from storing hydrogen or thermal energy versus the revenue that may be obtained from electricity market arbitrage. The first sub-options consist of diverting electricity from the HTSE plant when electricity prices are high (e.g., variable renewables are not providing sufficient energy). This would involve some level of hydrogen storage (and some oversizing of the HTSE plant) that would be fed to continuously produce synthetic fuel without disruption. Several studies have already investigated the economic tradeoffs with HTSE coupled with hydrogen storage to enable grid arbitrage [24, 25]. The second sub-option consists of storing thermal heat from the reactor directly and either directing that stored heat to the HTSE plant or uprating the turbine power when electricity prices are high.

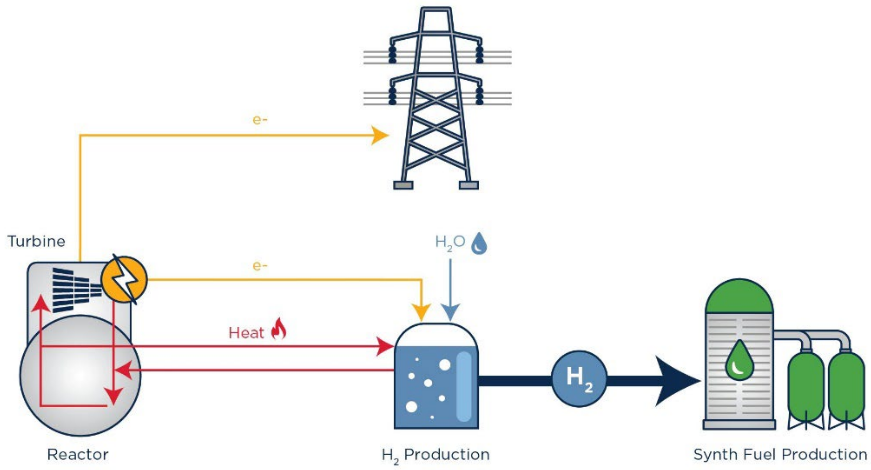


*Figure 10. Option 3. Configurations with or without electricity sale to the grid.*

Deciding on a more economically competitive configuration will likely require a detailed market analysis and is likely to be case specific, driven by impacts such as geography, local electricity markets, reactor costs, etc. Table 6 provides a useful overview of the various technoeconomic considerations and their associated advantages/disadvantages for fixed nuclear synthetic fuel production.

*Table 6. Overview of technoeconomic tradeoff considerations for fixed nuclear synthetic fuel production for maritime applications.*

| Consideration | Advantages | Disadvantages |
|---|---|---|
| Electricity Only | Simpler connection to plant | Lower efficiencies |
| Heat & Electricity | Higher thermal efficiencies, more flexible operations | Regulatory and CAPEX burden |
| | | |
| Lower Temp Reactor | Wider applicability | Need heat augmentation |
| Higher Temp Reactor | Targeting higher temp applications | Expensive alloys in reactor (more challenging to manufacture) |
| | | |
| No Grid Coupling | No additional storage costs | One revenue stream |
| With Grid Arbitrage | Added revenues from feeding electricity back to markets | Heat or hydrogen storage costs |

## 3.2.2 Self-Propelled Nuclear Configurations

Self-propelled nuclear-maritime arrangements will also have configuration options to consider and evaluate. These include:

1. Converting nuclear heat to electricity to drive propellers or leveraging the heat directly, as shown in Figure 11
2. Coupling a single reactor to a propeller, several reactors to a single propeller, or several reactors to several propellers, as shown in Figure 12.

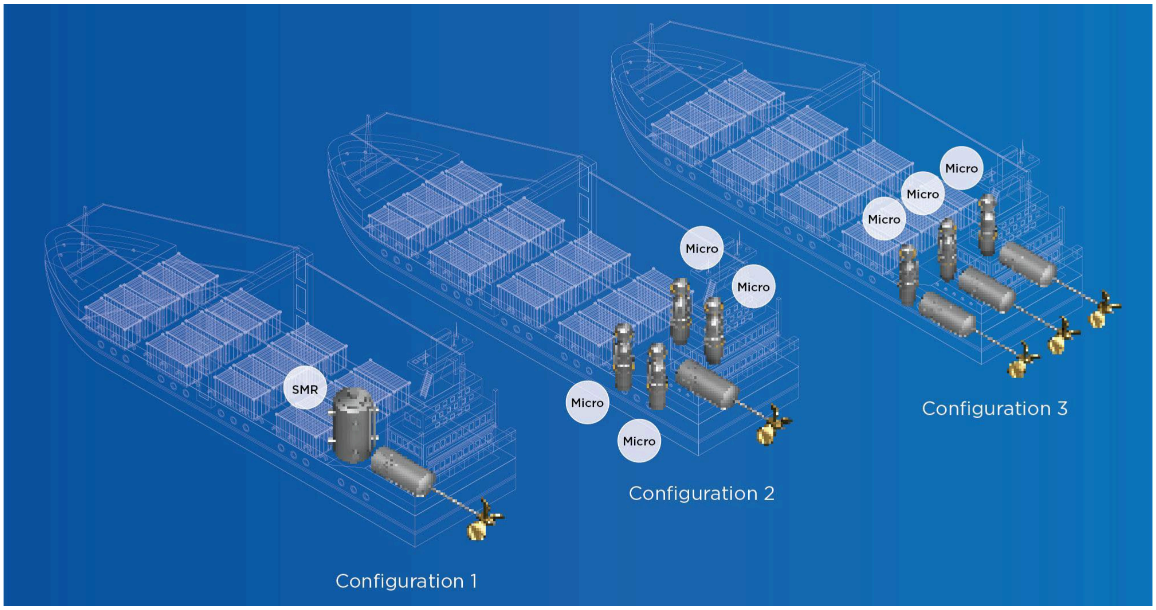


*Figure 11. Possible configurations for reactor-propeller coupling in mobile nuclear maritime applications.*

The first option involves a straightforward technoeconomic tradeoff. On the one hand, an electrically driven system should prove more responsive to variable power requirements for acceleration or deceleration and rapid hazard response. Electricity will be needed to power the ship regardless; the configuration would therefore essentially consist of leveraging a larger turbine generator system. Additionally, most terrestrial systems are envisioned to have some level of electrical generation coupling so they could be "ported" directly for mobile maritime applications. On the other hand, directly leveraging the heat to power the propeller would improve thermodynamic efficiency and allow for a smaller reactor power output for the same propulsion power. This system would be more tightly coupled with reactor dynamics and would still require some auxiliary electrical power production (to support operations and hotel loads). This is more closely akin to the existing configuration with fossil-fuel-powered engines. In general, equipment to generate and store electricity will both decrease overall plant efficiency and increase costs. Direct conversion from nuclear-thermal to mechanical energy is expected to be more economical.

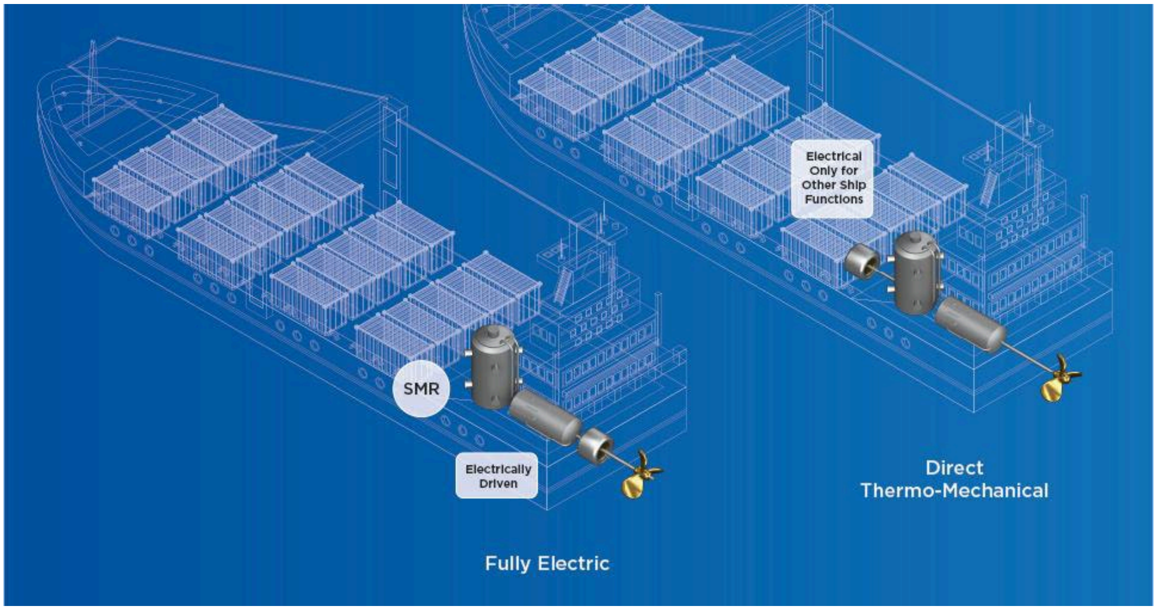


*Figure 12. Option 1. Electrical versus thermomechanical propulsion.*

The configurations for the second option consider the number of reactors to propellers in the ship (whether directly or electrically coupled). In the first configuration, a single reactor is directly coupled to the propeller. This enables economies of scale but may limit applicability to larger ships and can be challenging from a reliability perspective (reactor downtime equates to propeller downtime). The two other configurations consider arranging several smaller reactors, which would drive mass production of these reactors and could expand applicability to smaller vessels. Coupling several reactors to a single propeller would provide economies of scale for the propeller but might limit reliability. While a single reactor's downtime would not translate to downtime for the propeller, the system would still rely on a single propeller. It is worth highlighting that while multi-propeller systems may not always be common in the commercial shipping industry, it is worth considering this option for additional reliability (and design flexibility based on size requirements).

*Table 7. Overview of technoeconomic tradeoff considerations for mobile nuclear-driven maritime propulsion.*

| | Advantages | Disadvantages |
|---|---|---|
| **Fully Electric** | Decoupled from nuclear system, simplified responsiveness | Efficiency losses and expected to be more costly |
| **Direct Thermomechanical** | More thermodynamically efficient, smaller reactor for same power | Potential overlap with sensitive or proprietary nuclear technology and may lead to awareness of civil economic sensibilities |
| | | |
| **One Reactor - One Propeller** | Economies of scale | Cannot target smaller ships |
| **Several Reactors - One Propeller** | Scale for propeller, mass production of reactors | Limited redundancy |
| **Several Reactors - Several Propellers** | Best reliability | No pooling of infrastructure, may lead to more complex maintenance |

## 3.3 Nuclear-Maritime Technoeconomic Recommendations

The previous sections provided contextual technoeconomic considerations on nuclear for maritime systems. Several tradeoffs between technology types, sizes, and configurations were discussed qualitatively. Detailed recommendations will likely require more in-depth quantitative analyses; however, several observations can already be made about the future potential for leveraging nuclear technology for maritime applications.

In the case of fixed offshore systems, nuclear-based synthetic fuel generation is gaining traction for various other industrial applications. Offshore nuclear applications might provide an ideal configuration to provide both electricity generation and industrial heat for synthetic fuel production, resulting in multiple streams of revenue, and still generate a pathway for securing energy independence in the maritime industry. For these applications, SMRs are closer to ideal (compared to microreactors) due to their larger scale. Promising technology includes LWRs (due to their maturity) and HTGRs (due to their ability to avoid/minimize heat augmentation).

In the case of self-propelled vessel arrangements, microreactor concepts appear more applicable due to greater versatility and suitability to a broader range of vessel classes. Promising technologies include HTGR and HPR microreactors. Deploying more than one of these per vessel can improve reliability but minimize costs by pooling common infrastructure (e.g., several microreactors with one single control room, propeller).

MSRs may be suitable for various marine applications with more testing and increased technological maturity.

# POTENTIAL IMPACTS ON U.S. MARINE AND OFFSHORE INDUSTRIES

# 4 POTENTIAL IMPACTS ON U.S. MARINE AND OFFSHORE INDUSTRIES

## 4.1 Pathways to Energy Independence

According to the U.S. Maritime Administration (MARAD), the U.S. domestic combined fleet is composed of over 36,000 units with a total cargo capacity of 82 million tons. Approximately 6,000 of these vessels are either self-propelled or designed to power barge clusters on waterways.

Advancement of waterborne vessels may spur significant change within the U.S. marine and offshore industries. Economically, energy independence will require substantial investment to adopt new technologies and infrastructures. This can be costly but also offers opportunities for industries involved in developing and deploying innovative maritime technologies. Moreover, as innovative energy becomes more widely adopted, capital and operating costs may decrease in the long term.

The push toward energy dominance necessitates advancements in energy storage, energy efficiency, and the development of new energy infrastructure within the maritime setting. The adoption of these technologies could also enhance operational efficiency, safety, and reliability.

In many markets, the cost of technological stagnation may outweigh the costs of retrofitting or building new vessels with next generation technologies. The ABS publication *Setting the Course to Low Carbon Shipping: Zero Carbon Outlook* [27] explains typical policy or market mechanisms used to limit emissions, summarized in Figure 13.

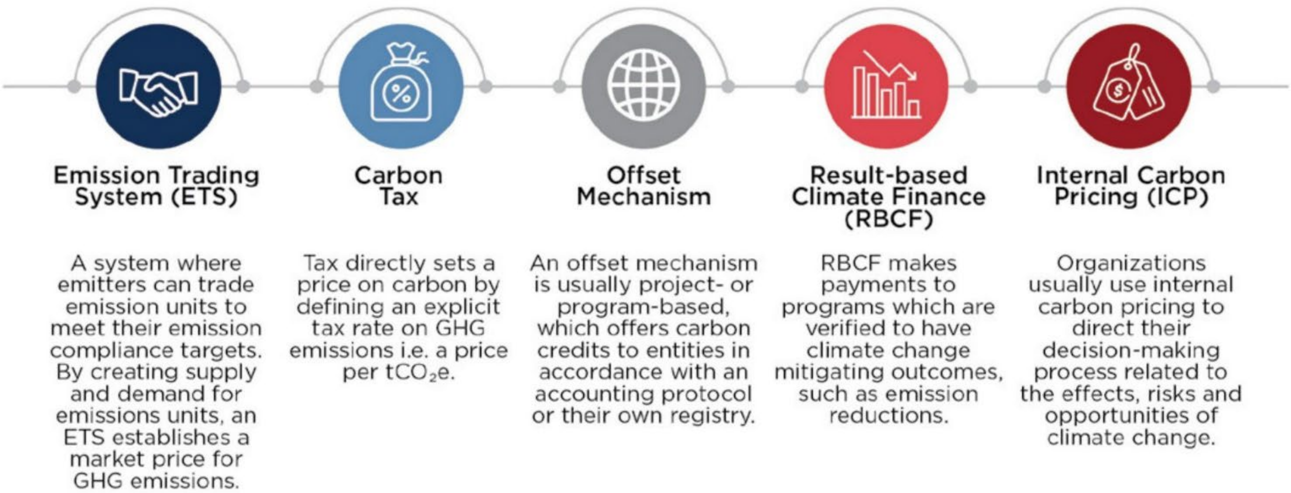


*Figure 13. The main types of energy pricing [28].*

From a regulatory perspective, energy security will require the re-examination of existing regulations, and investigations into how new compliance should be introduced and navigated. Integrated energy standards will be implemented, and companies will need to demonstrate adherence to these requirements. This may result in increased administrative costs and legal liability for non-compliance. However, it can also incentivize industry-wide best practices and provide a level playing field for businesses. In this way, regulation may serve as a precursor to increased economic and human capital investment.

In the U.S., regional economic energy schemes exist for state-based initiatives, focused on the energy sectors. In the future, energy markets and pricing mechanisms may expand regionally as well as incorporate more industries such as maritime.

While energy independence poses considerable challenges to U.S. marine and offshore industries, it also opens a wide range of opportunities for economic growth, technological innovation, and environmental stewardship. National funding programs for research and implementation of energy secure solutions are receiving more attention with the continued emphasis on innovative technologies. As the next generation technology matures, businesses that adapt and incorporate new findings will be the ones to thrive in the emerging economy.

## 4.2 U.S. Shipbuilding

Should the U.S. maritime industry undergo changes to reach the potential 2050 nuclear power demands, several significant impacts should be considered, including market competition, workforce, economic impacts, maintenance regimes, nuclear incident handling, radioactive waste management, export controls, and nuclear quality assurance.

Considering current vendors in the U.S. maritime industry, Newport News Shipbuilding (NNS), Northrop Grumman, and Electric Boat each have a unique set of capabilities. These companies have experience in constructing nuclear vessels, mainly for military applications, which could position them favorably for the potential transition to commercial applications. However, their capacity to ramp up production to meet commercial demand remains untested and would require significant investments in infrastructure and workforce training.

The current gaps in the nuclear shipbuilding industry revolve around production capacity, trained workforce, safety measures, and regulatory approval. To meet the increased demand for nuclear-powered vessels, investment and engagement with regulatory bodies would be needed to address the potential changing landscape and challenges described below. The transition to nuclear power in the U.S. maritime industry presents significant challenges but also offers considerable economic and environmental benefits. Careful planning, collaboration, and investment will be critical to successfully achieving energy resilience.

### 4.2.1 Competition

Meeting the potential 2050 demand of nuclear-marine applications could increase competition at U.S. shipbuilding companies. In general, any commercial shipyard in the U.S. that participates in the construction, maintenance, or operation of a nuclear vessel will likely fall under U.S. Nuclear Regulatory Commission (NRC) jurisdiction 10 CFR Part 73: Physical Protection of Plants and Materials [29].

Commercial nuclear shipbuilding may be able to learn or even leverage from shipbuilders specialized in constructing navy nuclear-powered vessels. This would stimulate competition in innovation and efficiency as companies would be vying to secure contracts for new designs of nuclear-powered commercial vessels. It is likely that cost-effective methods such as streamlined production lines and enhanced technology would be adopted to offer competitive pricing. The increased demand and competition could also entice other companies into the market, further driving down costs through the dynamics of supply and demand. In the long run, this could potentially lead to a decrease in the overall cost of nuclear-powered ships, benefiting the maritime sector economically and environmentally.

### 4.2.2 Workforce

The effort will require an increase in a skilled nuclear workforce. This is going to be needed for every phase of nuclear operation from design to decommissioning. Currently, such professionals are concentrated in sectors such as power generation and defense, but the demand for their skills within the maritime industry would grow as commercial shipping companies pivot to adopt nuclear solutions. Upskilling and adaptation will be needed in order to highlight and advance existing maritime skills to accommodate the shift to nuclear integration and operation. This shift will necessitate a vast range of nuclear-specific competencies, such as nuclear reactor operation, maintenance, safety, and managing nuclear waste disposal. Additionally, the construction and maintenance of nuclear-powered ships will require nuclear engineers, technicians, and safety specialists. Furthermore, given the specific regulations and safety protocols associated with nuclear energy, there will be a need for legal and regulatory professionals with nuclear expertise. This shift would also stimulate changes in education and training programs, with an increase in nuclear engineering and related certifications or licenses. Certification programs would also need to be expanded to cover the new designs and technologies associated with maritime applications of nuclear power. These certifications would be crucial to maintaining the integrity and safety of the nuclear-maritime industry.

Therefore, the move towards nuclear energy in the maritime sector will influence the job market, creating new opportunities and raising demand for nuclear-skilled labor.

### 4.2.3 Economic Impact

The transition to nuclear power could have profound economic implications for the U.S. shipbuilding industry. On the one hand, this transition could spur a surge in demand for new nuclear-powered ships, stimulating economic activity and potentially creating a boom in shipbuilding. The development and construction of nuclear-powered vessels are capital intensive, and this could lead to significant investment in shipbuilding infrastructure and technologies. On the other hand, this transition could introduce substantial costs related to refitting existing shipyards, training or recruiting nuclear-qualified workforce, and adhering to rigorous safety and environmental regulations associated with nuclear power. The U.S. shipbuilding and maritime shipping industries might face a significant increase in operational costs, which could put financial pressure on smaller shipbuilders and potentially lead to industry consolidation. Additionally, the potential liability risks associated with nuclear incidents could necessitate expensive insurance policies. The net economic impact will depend on a balance between the stimulated demand and the increased costs and risks associated with the nuclear transition.

### 4.2.4 Maintenance

Maintenance requirements for advanced reactor designs and primary system(s) may differ from conventional plant maintenance regimes, depending on the reactor design; however, supporting secondary systems (e.g., steam, electric plant) may require more rigorous upkeep than the shipping industry is likely used to. Similarly, refueling may be required depending on the reactor design, which is likely to be far more complex than regular maintenance activities. Alternatively, reactor cores may be replaced rather than refueled, the process for which may involve other complexities. Nuclear-powered ships generally may require additional routine maintenance due to the stringent safety standards of the reactor systems and the associated machinery. Regular inspections, reactor refueling, replacement of key components, and enhanced system checks are some of the activities that could contribute to higher maintenance costs for nuclear vessels. This specialized maintenance may also require skilled personnel with additional training and certifications, likely to be more expensive to employ than traditional ship maintenance workers. Moreover, the necessary infrastructure for advanced maintenance is also likely to be costly to develop, from specialized shipyard facilities to disposal mechanisms for radioactive waste. In turn, these costs would likely drive up the overall costs of building and operating nuclear-powered ships. This could impact the market dynamics of the shipbuilding industry and potentially put smaller players at a disadvantage, leading to consolidation in the industry. However, these costs should be weighed against the potential savings in fuel costs and benefits in the long term.

### 4.2.5 Nuclear Incident Handling

Meeting the nuclear-marine applications potential 2050 demand would place new demands on the U.S. nuclear incident handling program. This program is typically a combination of agencies that respond accordingly. For example, in the U.S. Navy, the shipyards and ports have an Emergency Control Center (ECC) staffed when a significant event happens. The U.S. DOE, Environmental Protection Agency (EPA), DOE/National Nuclear Security Administration (NNSA), NRC, U.S. Coast Guard, and others as necessary can or will become involved [30, 31]. This program is currently designed primarily to respond to incidents at stationary nuclear power plants and other nuclear facilities where incident response missions are the responsibility of the DOE or the NNSA. The introduction of a fleet of remote, mobile nuclear applications would present new challenges for a response group. For example, an incident occurring anywhere in the world could require the program to have quick response and mobility capabilities in a variety of locations and circumstances. This could necessitate an expansion of resources, including trained personnel, specialized equipment, and coordination protocols. Procedures would likely need to be updated or developed to handle maritime-specific scenarios, such as a commercial nuclear incident at sea or in a port, involving potential complications like the containment of radioactive material in a marine environment or evacuation procedures for large vessels. In addition, cooperation with international partners would become increasingly important, given that an incident may impact multiple countries' waters. Hence, transitioning to nuclear power in the maritime sector would require a considerable scale up of existing nuclear incident handling programs.

### 4.2.6 Radioactive Waste Management

The addition of nuclear power for maritime commercial applications would also introduce radioactive waste management challenges for the U.S. maritime industry. The construction and operation of nuclear-powered vessels generates radioactive waste. Such waste must be safely managed to protect human health and the environment. This could require the shipbuilding industry to invest heavily in new technologies and infrastructure for waste containment and disposal, as well as in training and compliance to handle waste according to strict regulations. Such investments could add substantial costs to shipbuilding operations. Furthermore, the logistics of transporting and disposing of radioactive waste could present additional challenges, particularly given the long-term hazards associated with some types of nuclear waste. These difficulties could be exacerbated by public and political resistance to nuclear waste transport and disposal, especially within or near populated areas. Meanwhile, the need to manage spent nuclear fuel could give rise to new opportunities for businesses specializing in these services. Nonetheless, effectively dealing with radioactive waste would be a critical concern for the shipbuilding industry in a nuclear-powered maritime future.

### 4.2.7 Export Controlled Information

Adopting nuclear energy in the U.S. maritime sector would have implications for Export Controlled Information (ECI) and International Traffic in Arms Regulations (ITAR) considerations related to documentation classification and access controls. As nuclear technology and associated information fall under the defined category of sensitive and strategic technologies, their export is closely regulated under both ECI and ITAR. As more vessels are powered by nuclear technology, there would be an increase in the volume of sensitive documentation that would need to be classified and controlled. Secure information handling, storage, and dissemination processes are used to protect controlled information from inadvertently falling into the wrong hands. The access to such information is strictly controlled and limited only to authorized personnel. Moreover, any transfer of this information, even within multinational corporations or to international partners, would be tightly regulated. Such transfers would likely require licenses or other forms of official permission. In effect, the move to nuclear power in the maritime sector would necessitate an expansion of information security measures and export controls to prevent unauthorized access or dissemination of sensitive nuclear-related information.

### 4.2.8 Nuclear Quality Assurance

The transition to nuclear power would necessitate an expansion of Nuclear Quality Assurance (NQA) resources for the U.S. shipbuilding industry, which will be required by the NRC [32], presumably as shipyards will perform construction activities associated with a nuclear power plant. To ensure the safe and effective use of nuclear technology, a robust NQA system is critical. This involves a rigorous process of inspections, audits, and reviews to verify that all aspects of nuclear power usage, from design and manufacture to installation, operation and maintenance, meet the necessary safety and performance standards. Finally, the transition would require the development of industry-wide best practices, providing guidelines for safe and efficient operations. This would involve the collaboration of industry leaders, regulatory bodies, and perhaps international organizations to establish recognized standards that ensure the safety, security, and reliability of the nuclear-powered maritime industry. 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 and 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 (DE)/digital twins (DT)/software quality: Use of DE/DT for quality assurance/quality control (QA/QC) management and modernizing software quality assurance (SQA) requirements.

# EXPECTED TIMELINES FOR DEMONSTRATION AND ADOPTION

# 5 EXPECTED TIMELINES FOR DEMONSTRATION AND ADOPTION

## 5.1 Project Phasing for New Nuclear

The need for energy independence in maritime and other industries is urgent and partially driven by policies such as those published by the IMO.

Several advanced reactor vendors have announced goals to successfully commercialize advanced nuclear technology through early deployments and build the foundation for large-scale deployment from before 2030 and into the mid-2030s.

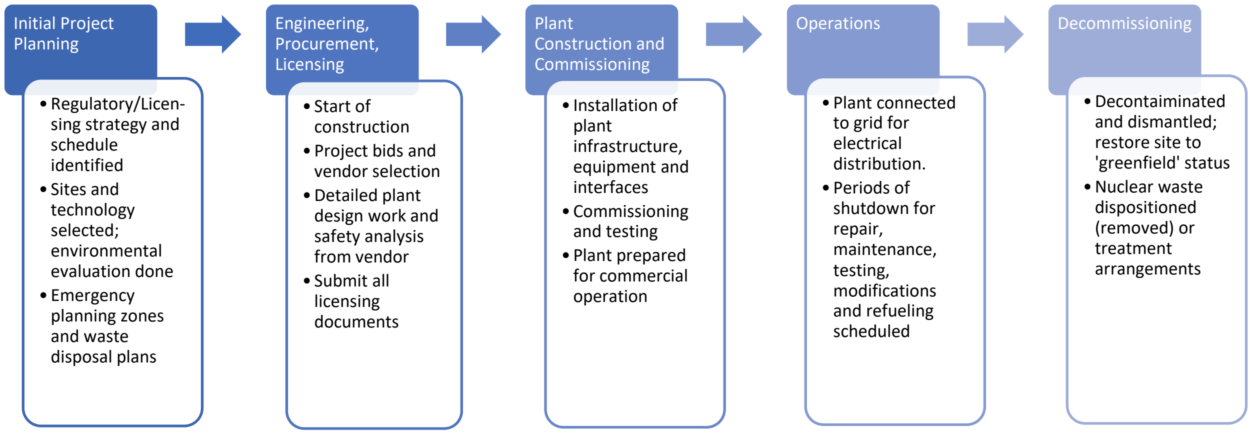


*Figure 14. Typical life cycle phases of nuclear plant projects.*

If advanced nuclear reactors are to play a significant role in meeting these early energy independence goals, they must be constructed much more efficiently than so far demonstrated by conventional U.S. nuclear plants. This effort may be iterative with the regulator rather than done in a single engagement. The typical life cycle phases of a nuclear plant project are summarized in Figure 14. It should be noted that the following are examples, rather than specific requirements, and there may be other requirements that should be considered in the approval process.

The World Association of Nuclear Operators (WANO) *Roadmap to Operational Readiness Guide* provides a typical timeline for the deployment of a nuclear power plant project, shown in Figure 15 [33]. This timeline applies to conventional light water reactors and covers the time from the start of the engineering, procurement, and licensing phase through the start of commercial operations. The current standard timeline for the deployment of a conventional nuclear power station is in the 10–12-year range. We note that large nuclear power plant projects in the U.S. have suffered significant cost and schedule overruns due to civil work issues such as equipment design complications, vendor performance issues, availability of specialized labor resources, and general underestimations of the difficulty of completing installation work in the plant environment. For example, in the case of the V.C. Summer plant in South Carolina, overruns resulted in the complete cancellation of Units 2 and 3 after an expenditure of approximately $9 billion [7]. Advanced reactor projects will need to take deliberate efforts to avoid similar challenges as the workforce and manufacturing base develops to meet the demand for new nuclear deployment.

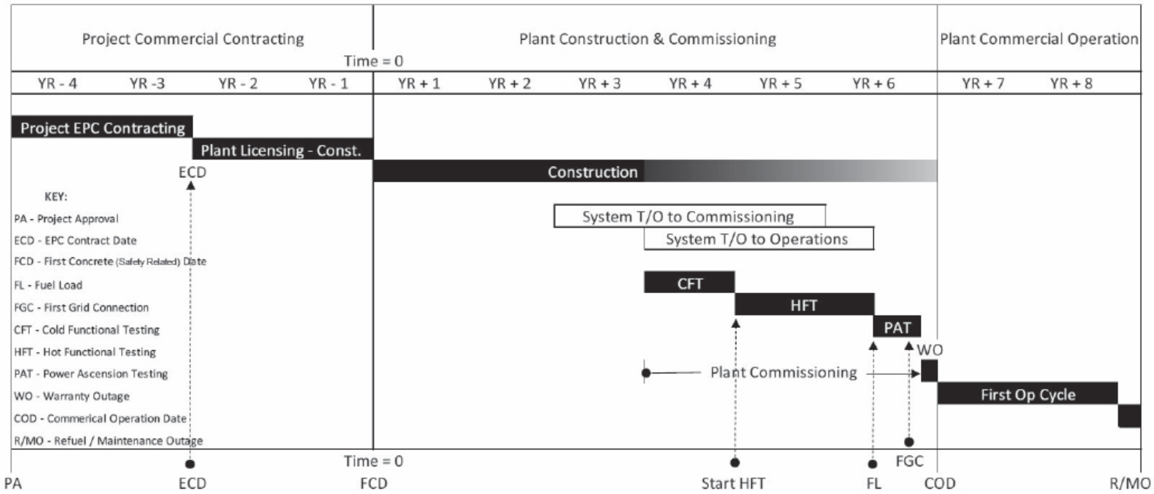


*Figure 15. Standard sequence of activities for nuclear power plant development projects [7] [33].*

Applying nuclear reactor technology to the commercial maritime industry poses its own unique considerations that may challenge or adjust the standard timeline discussed above.

Other significant challenges with the prompt deployment of advanced nuclear reactors lie in the regulatory space. Current regulations in the U.S. were developed for light water reactors. As discussed in the 2023 Electric Power Research Institute (EPRI) report "Advanced Reactor Roadmap, Phase 1: North America" [34], the historical schedule for complete NRC license approvals ranges from four to eight years, accompanied by historical costs between $28–42 million. Some estimates suggest that the NRC could have as many as 60 applications in the licensing process at one time by 2030 [35]. The roadmap further discusses the Vogtle Unit Sites 3 and 4; these are the largest energy sites, of this type, in the United States. While accomplishments, these sites incurred a lot of costs that would not be typical the future installations. These include:

- Incomplete design
- Immature supply chain
- Untrained workforce.

Since the design has been completed, the supply chain has been established, and the project managed to train over 30 thousand workers. As a result, this project could be considered a worst-case scenario for a new site utilizing AP1000s, the reactor used for these units, but not as an expected anchor points. Any future technoeconomic analysis would need to consider these caveats as well as cost reductions coming from a completed design with an established supply chain, an experienced workforce and training system to draw from, and investment credits stemming from the Inflation Reduction Act [35].

While some progress has been made, significant work remains to update and streamline the regulatory framework for advanced reactors. This includes incorporating industry feedback and finalizing 10 CFR 53, "Risk-Informed, Technology Inclusive Regulatory Framework for Commercial Nuclear Plants" by July 2025. Additional considerations with remote and mobile operations in the maritime environment could further complicate and extend regulatory review timelines.

Advanced nuclear reactor developers are aware of the historical delays and cost overruns that have plagued recent U.S. nuclear projects and are evaluating methods to improve cost projections and delivery timelines. For example, smaller scale and simpler designs of some advanced reactors opens the opportunity for a highly standardized manufacturing process, where multiple units can be built efficiently in a single factory (i.e., a product-based deployment model). The EPRI Report outlines several critical industry-wide initiatives and support actions necessary for the successful, large-scale deployment of advanced reactors [34]. While the EPRI Reports addresses some initiatives to strengthen the industrial base for advanced reactors, maritime applications will require services from nuclear-capable shipyards, which has not yet been addressed.

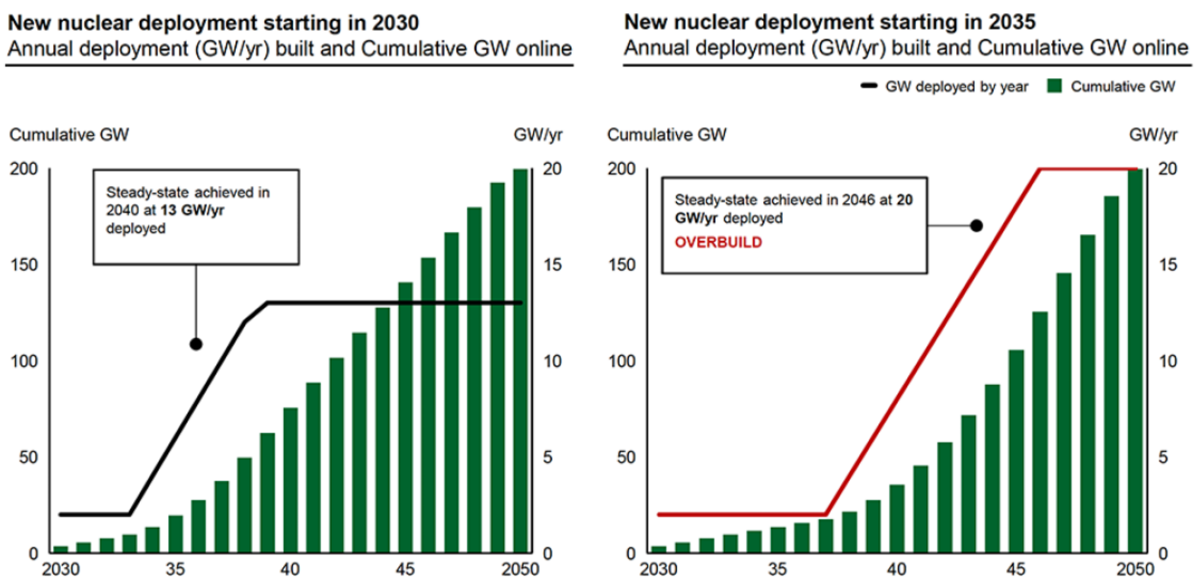


*Figure 16. Land-based new nuclear deployment in the U.S. [35]*

As discussed previously, the earliest deployments of advanced land-based nuclear reactors are expected to occur in the early 2030s. If these early deployments succeed, we believe it is reasonable to assume production ramp-up of advanced nuclear reactors could occur in the mid-to-late 2030s. Given the current projected timelines for land-based reactors and considering the additional design and regulatory challenges that the maritime environment imposes, it is unlikely that nuclear power will contribute significantly in the short term. If a commercial maritime entity "down selected" an advanced nuclear reactor technology in the near term (i.e., a reactor design that is already under development), it is reasonable to assume that some maritime nuclear demonstrations, vessels, or offshore installation could be under construction by the early 2030s. Following the early adopters and demonstrations, the maritime industry could target a similar production ramp up as land-based advanced reactors (i.e., adoption on a wider scale by the late 2030s or early 2040s). We note that these timelines for maritime applications of advanced nuclear reactors are interpreted from land-based projects of similar scope.

The DOE 2023 "Pathway to Advanced Nuclear Commercial Liftoff" report [35] discusses commercialization strategies for land-based advanced reactors and suggests that achieving energy independence in the U.S. would require at least 200 GW of new nuclear capacity. The report also suggests that waiting until the mid-2030s to deploy new nuclear assets could lead to significant supply chain overbuild. Figure 16shows that if deployment starts by 2030, ramping annual deployment to 13 GW/year by 2040 would provide 200 GW by 2050. A five-year delay in scaling the industrial base would require 20+ GW/year deployment to achieve the same result. While not directly applicable to maritime energy independence goals, Figure 14 illustrates the idea that even a moderate delay in production ramp up beyond 2030 will likely result in a longer period to achieve energy independence.

## 5.2 Reactor Demonstrations

In September 2018, the bipartisan Nuclear Energy Innovation Capabilities Act (NEICA) was signed into law, authorizing the creation of the NRIC program. In addition to coordinating resources related to advanced nuclear technologies throughout the national laboratory system, NRIC is also preparing physical test beds to facilitate reactor demonstration programs in a controlled environment. The first test bed is the Demonstration of Microreactor Experiments (DOME) facility located at the INL Materials and Fuels Complex. The DOME facility will support microreactors operating at less than 20 MWth using the TRISO fuel system with high-assay low-enriched uranium (HALEU). The NRIC program is also developing the Laboratory for Operations and Testing in the United States (LOTUS) test bed.

The microreactor vendors that plan to test at the NRIC testbed will operate under approval from the DOE (i.e., they will not pursue NRC licenses prior to their first demonstration). The NRIC test bed program will allow demonstrators to collect critical data, validate analysis methodologies, and apply lessons learned to accelerate the licensing process after the initial demonstration.

NRIC has published timetables for reactor demonstrations, including preparing the DOME and LOTUS Facilities for reactor demonstrations in 2026 and 2028, respectively. The DOME facility is to have the capacity and systems in place to process one reactor demonstration approximately every 12 to 18 months. This would involve installation of the reactor within DOME, performing the reactor test campaign, reactor shutdown and cooldown, and removing the reactor from DOME to support the next demonstrator. Additionally, the NRIC test beds are intended to support multiple reactor designers as they aim to commercialize their designs by the early 2030s. This indicates limited availability will exist for new or additional tests beyond the current scheduled plan.

To date, many of the demonstrators that have expressed interest in using the NRIC test beds are envisioning land-based applications. Demonstrations for marine applications of advanced nuclear reactors are expected to require additional test bed equipment, such as platforms to simulate severe conditions from wave-accelerated motions. There are currently no existing plans to integrate such systems into the NRIC testbeds. NRIC will be conducting a gap analysis across the national laboratory enterprise to catalog existing capabilities that can be leveraged for maritime demonstrations and identify areas where additional resources will be needed. Maritime vendors may be required to develop partnerships or interface agreements with reactor vendors that are already scheduled for operations in the test beds to perform any near-term maritime demonstrations. The development of a separate test bed would likely require a capital project (DOE Order 413.3B), which can require significant time to complete.

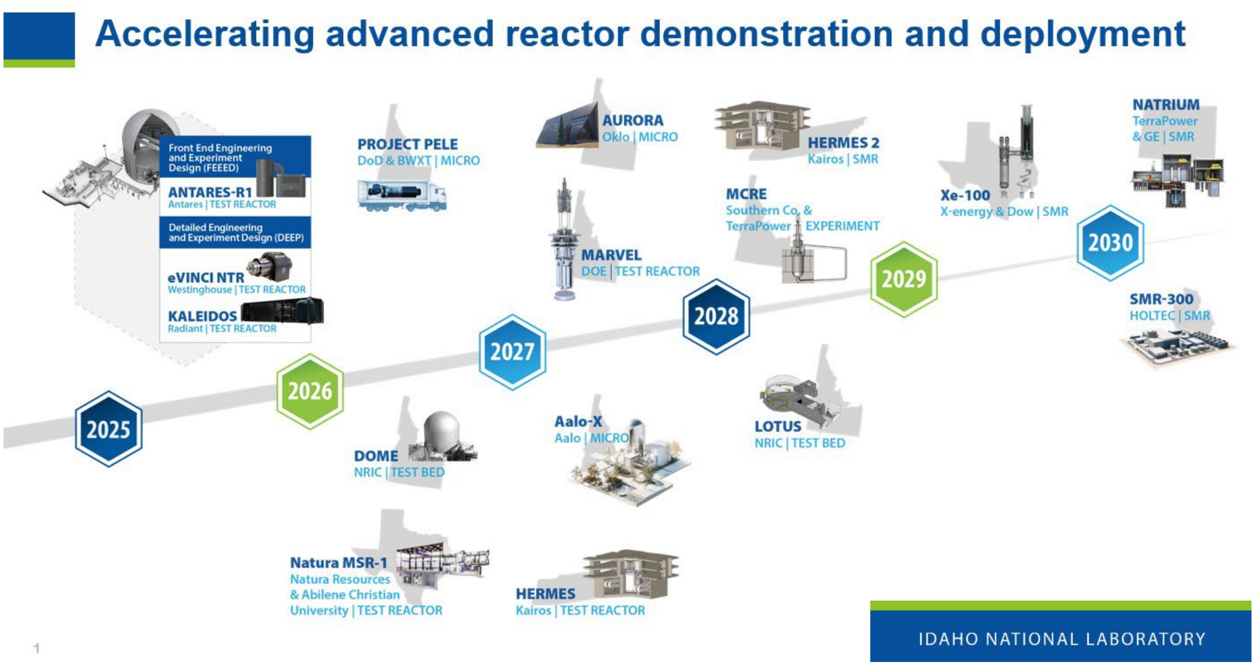


*Figure 17. Advanced reactor demonstration timeline (Source: INL/NRIC)*

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# 6 REFERENCES


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