Navigating nuclear energy in maritime

Initial considerations for nuclear ships and offshore

Contents

Chapter 1:

Introduction and background

1.1 Introduction

Nuclear industries are preparing for increased technology deployment in advance of the next major stage of energy transition. Maritime industries demand compliant, reliable energy sources or sustainable fuel to maintain effective shipping and offshore industries.

This document gives information and guidance for the engineering and product development of nuclear power solutions for commercial shipping or offshore industries. It aims to help project teams navigate regulatory, legal, and economic challenges. The first adoption of nuclear technology for a commercial maritime project can offer precedents for more projects to scale-up and pave the way to the development of a harmonised international framework as nuclear takes its place in the energy transition of the commercial shipping and offshore industries.

Large-scale nuclear power plant projects often see cost and schedule creep attributed to one-of-a-kind projects, sometimes called ‘large infrastructure projects.’ A blending of marine, offshore, and nuclear practices, integrated with the nuclear regulatory environment, can lead to manufactured systems that are immediately deployable and “pre-licensed” to be readily integrated. When deployed at a smaller scale, such as for maritime, the design and integration effort can be reduced with production in numbers, component design or type approval, and pre-licenses for smaller deployable nuclear products, including small modular reactors (SMRs).

The International Atomic Energy Agency’s (IAEA) safety principles have been developed and matured for civil, land-based gigawatt-scale power plant production. However, the current maritime law and International Maritime Organization (IMO) regulations, codes and standards do not adequately address certain aspects of nuclear technology. There are jurisdictional and enforcement ambiguities around safety, security, and liability. As of October 2025, neither global maritime regulators nor nuclear regulators have declared their views or guidance on commercial or privately owned nuclear applications in the commercial shipping and offshore industries.

The trans-geographic mobility of commercial ships and the offshore industries adds to the regulatory complexity. The lack of harmonised international frameworks and trans-geographic boundary enforcement strategies will pose challenges for the deployment, operation and decommissioning of nuclear power solutions. Therefore, it is imperative to establish a pathway for licensing the nuclear unit, enforcing standards (nuclear safety, security, and safeguards, or “3S”), coordinating trans-geographic emergency response functions and establishing liability agreements to ensure that nuclear power solutions can be deployed with the universally accepted standards of safety, security, and environmental performance.

1.2 Objectives

This document aims to guide the deployment of nuclear power in maritime applications. In this context, 'maritime' includes commercial shipping, offshore production facilities or other floating uses of nuclear energy, unless indicated otherwise.

The intended audiences are project teams looking to advance their development of nuclear technology for commercial maritime applications. At this point, a project team may have already selected a nuclear reactor or identified key operating criteria and constraints. Project teams may comprise a range of stakeholders such as designers, engineers, owners, operators, insurers, financiers, project administrators, regulators, and others involved in a maritime nuclear programme.

1.3 Scope

Chapter 2 gives background information on the multifaceted aspects of nuclear technology for commercial maritime use, including regulatory frameworks.

Chapter 3 outlines technology integration, safety, security, operations, insurance and finance requirements.

Chapter 4 offers a Roadmap to adoption strategies, including considerations for project planning and areas of investigation. The Roadmap presents key questions that project teams must address when pursuing nuclear applications for maritime use.

This document is not a technical design guideline or a basis for commercial plans. It describes the current and near-future domain of nuclear technology in maritime, specifically to aid teams in development and delivery. This document does not apply to applications of nuclear technology that are not intended for commercial or civil use.

The Lloyd's Register (LR) *Fuel for Thought: Nuclear* (2024) and *Fuel for Thought: Nuclear for Yachts* (2024) are general interest reports that provide information on nuclear technologies and their suitability for maritime and offshore use.

Each project should be tailored to the unique aspects of the team's goals, stakeholders, design criteria, and operating constraints. This document does not present a complete list of design standards, rules, engineering codes, regulators, or stakeholders, or make recommendations regarding deploying nuclear technology for maritime.

Instruments from international organisations such as the IMO or the IAEA are adopted, interpreted, and enforced by individual states. For example, signatories of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) may enact and enforce the treaty in different ways, and project teams must be aware of the national statute or legislation where the NPT is adopted into law. Local maritime law that enacts the IMO regulations among the IMO member states should be similarly identified.

Any proposed nuclear installations on maritime assets are to meet the applicable rules and regulations for classification and requirements of the nominated flag administration (i.e., the 'flag' under which the ship will sail).

1.4 More information

Project teams are invited to contact LR directly to discuss support available throughout the process to tailor the approach.

LR offers a holistic, integrated approach to safety, compliance, and risk management while remaining flexible to meet the needs of the maritime nuclear sector. This is achieved by the advisory services, compliance services, lifecycle activities and complementary services of the LR Service Portfolio shown in *Figure 1: LR Service Portfolio*.

Service Portfolio

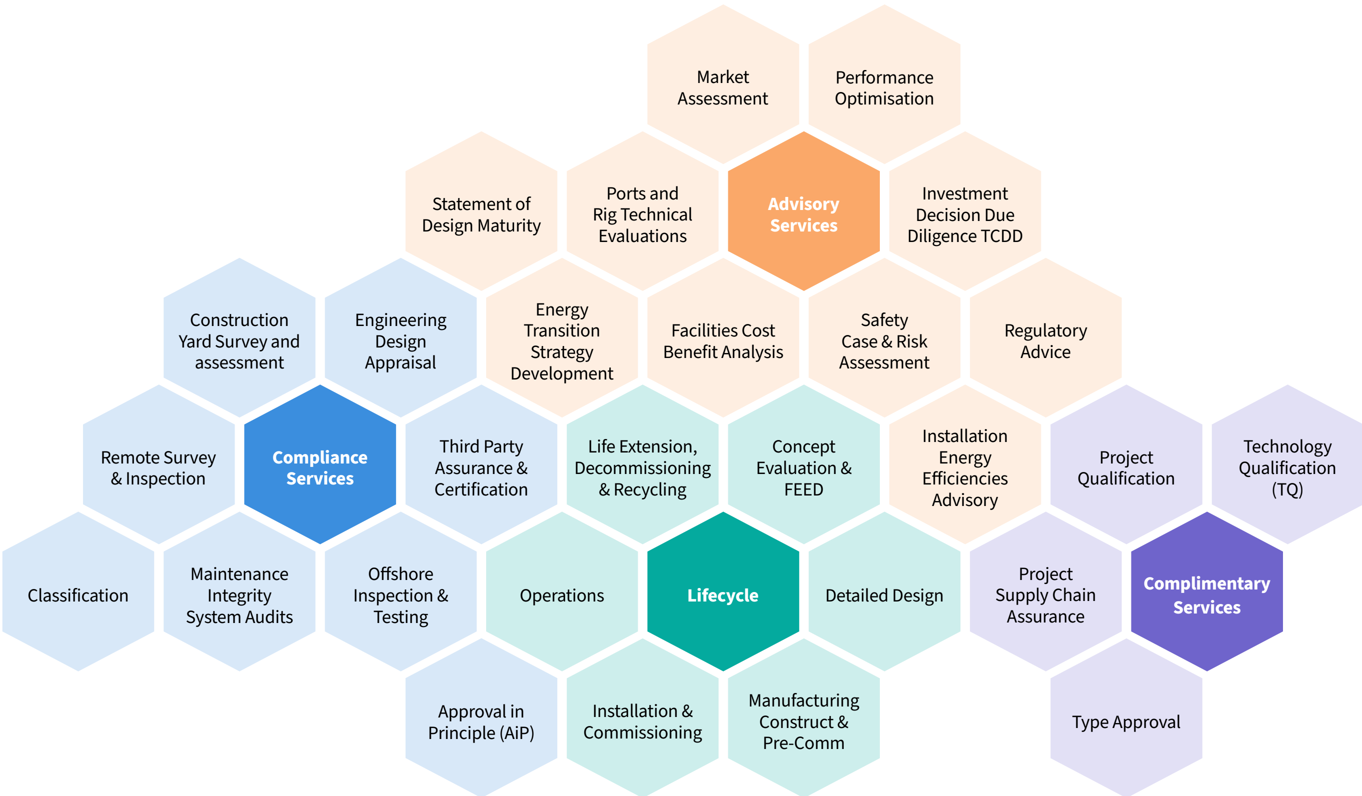


Figure 1: LR Service Portfolio

Using the combined experience of maritime classification and specialised nuclear knowledge with a global presence and established relationships with regulators and industry stakeholders, LR offers independent, third-party verification and certification services, which are crucial for building and maintaining trust and confidence between stakeholders. From concept to decommissioning, LR offers lifecycle support covering the entire project. LR helps developers identify and manage risks early in project development, reducing the potential for delays and costly rework.

LR was founded in 1760 as the world's first marine classification society. Today, LR remains a leading provider of classification and compliance services to the marine and offshore industries and is a trusted partner for asset and operational optimisation, with over 3,700 employees operating in 75 countries. LR is uniquely placed to provide a full suite of consulting solutions. LR's multidisciplinary experts understand the intricacies of maritime operations and give clients evidence-based, strategic advice on critical issues including digitalisation, energy transition and commercial success.

Using the combined experience of maritime classification and specialised nuclear knowledge with a global presence and established relationships with regulators and industry stakeholders, LR, Global Nuclear Security Partners (GNSP) and NorthStandard have contributed to this document.

GNSP
GLOBAL NUCLEAR SECURITY PARTNERS

Global Nuclear Security Partners (GNSP) is a management consultancy dedicated to nuclear security and threat reduction across the civil and defence nuclear sectors. Operating from offices in the U.K. and Australia, GNSP supports a growing global client base by helping organisations and governments address nuclear power's critical challenges of security and safeguards. GNSP is committed to ensuring the secure development of nuclear power as a cornerstone for achieving carbon emission reduction and energy security targets, working with mature nuclear markets and emerging nuclear programmes to build the capacity and capability needed for success. GNSP contributed to the content related to nuclear security and safeguards.

NorthStandard

NorthStandard is a leading provider of global marine insurance products and services and one of the twelve International Group of P&I Clubs (IG P&I Group). From headquarters in the UK and with offices throughout Europe, Asia and the Americas, NorthStandard offers specialist insurances including P&I, FD&D, War Risks, Strike & Delay, Hull & Machinery and ancillary insurance. NorthStandard is a member of the Nuclear Energy Maritime Organisation (NEMO) and is engaged in supporting the development of the regulatory environment for civil maritime nuclear to ultimately enable its commercial insurability. NorthStandard contributed to the content related to insurance and reinsurance.

SECTION 2:
Terminology, definitions, and acronyms

2.1 Introduction

The onshore nuclear sector is a well-established and highly regulated global industry. Whilst the definitions provided in this document have been derived from existing industry-accepted sources, there may be variance in the terms or definitions among the references. These differences are not discussed, but readers are encouraged to review existing glossaries and definitions provided by recognised sources. Refer to recognised sources for official definitions of nuclear terms, such as the IAEA Nuclear Safety and Security Glossary, the IAEA Safeguards Glossary, the US Nuclear Regulatory Commission (NRC) Online Glossary and the UK Office for Nuclear Regulation (ONR) Security Assessment Principles (SyAPs).

2.2 General terminology and definitions

Spent Nuclear Fuel (SNF)
Fuel that remains in the core after the reactor reaches a point where it can no longer efficiently sustain a nuclear chain reaction. This material is highly radioactive and contains unused fuel material, fission fragments and other heavy elements. A key differentiator between SNF and high-level waste is that SNF can be reprocessed and several advanced reactor developers suggest using this reprocessed SNF as fuel.

Structures, Systems and Components (SSC)
A general term encompassing the elements (items) of a facility or activity that contribute to protection and safety, except human factors.

Nuclear Safety
The achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation risks [1].

Nuclear Waste
Radioactive materials with no further foreseen use. There are different arrangements for storage of the waste, depending on the category of waste:

- **High-level waste (HLW) –** SNF deemed as waste, including the highly radioactive byproducts of the reprocessing process. This waste generates decay heat and requires a long-term storage solution.
- **Intermediate-level waste (ILW) –** Includes nuclear components or products used in the maintenance of nuclear activities such as resins for filtering coolant. ILW is radioactive but generates less heat and radiation than HLW.
- **Low-level waste (LLW) –** Includes contaminated items, such as inspector's coveralls and tools. It has low levels of radioactivity and can often be disposed in near-surface facilities.

Offshore Unit
A unit engaged in offshore operations including drilling, oil production and storage, accommodation and other support functions, including power or synthetic e-fuel production, and which often operates within the territorial waters of a "coastal state."

Operator
In shipping, this is the entity that holds the "document of compliance" to operate the ship. In offshore, this is the installation operator of the offshore unit. The field operator (of the field in which the offshore unit is located) may be a single company or the managing partner of a field operated by a joint venture.

2.3 Terminology and definitions related to nuclear security and safeguards

Design Basis Threat (DBT)
The DBT is a classified document, owned by the nation-state, that details the capabilities of threats (maximum numbers of attackers, weapons systems, equipment and likely tactics, techniques and procedures used) that a national regulator will expect a nuclear security system to counter.

Nuclear Security
While nuclear safety focuses on preventing and mitigating accidents, nuclear security focuses on the prevention, detection, and response to criminal or intentional unauthorised acts involving or directed at nuclear material, other radioactive material, associated facilities or associated activities or operations.

Nuclear Safeguards
Provisions that are designed to prevent the unauthorised misuse of fissionable nuclear material for non-peaceful purposes. Nuclear safeguards are an international legal requirement that signatory states constantly account for nuclear material (for example, reactor fuel or certain waste products) under their control.

Security by Design
Nuclear security is constant throughout the nuclear lifecycle and is particularly important when designing structures, systems or components for nuclear use. Nuclear security must be considered at the beginning of any project, from the concept to completion. The cost of retrofitting nuclear security measures to meet regulatory requirements is greater than including them in the design from the start.

Safeguards by Design
This encompasses the integration of nuclear safeguards considerations into the design process of a nuclear facility. The goal is to improve the implementation of nuclear safeguards by addressing potential efficiency and effectiveness issues early in the design process.

Suitably Qualified and Experienced Person(s) (SQEP)
National regulators require personnel in nuclear engineering, safety and security to be suitably qualified and experienced. These are individuals with the necessary competence to perform duties defined by their role, as demonstrated by their training and relevant experience. The process is an approved part of the regulatory licensing process and is used to demonstrate to the national regulator adherence to the agreed standards and provide assurance that these standards are maintained throughout all lifecycle phases [2].

2.4 Terminology and definitions related to insurance and reinsurance

Insurance Pool
An insurance pool is a way in which an insurer can exchange some of their own risk for a percentage of the total combined loss of all members within the insurance pool. An example is the The International Group of Protection and Indemnity Clubs, who pool their combined losses above a particular level of liability. Another example is nuclear insurance pools whereby multiple insurers collectively underwrite the nuclear liability, which is seen as a low occurrence, but high catastrophe event.

Liability and compensation regime
Global liability and compensation regimes in maritime serve to provide strict liability of the shipowner, direct rights of action for the victim against the shipowner's insurers, compulsory insurance, and in turn allow the shipowner to limit their liability. An example is the *Convention on Limitation of Liability for Maritime Claims 1976* (LLMC Convention). For land-based nuclear reactors there is the IAEA's *1963 Vienna Convention on Civil Liability for Nuclear Damage* with its *1997 Protocol* (Vienna Convention) and the Organisation for Economic Co-operation and Development's *1960 Paris Convention on Third Party Liability in the Field of Nuclear Energy* and its *2004 Protocol* (Paris Convention). The Vienna and Paris conventions are founded upon strict liability, exclusive liability of the operator, compulsory insurance, compensation of victims without discrimination, exclusive jurisdiction and limitation of liability in amount and time. Some of these foundations are similar to the principles in marine global liability and compensation regimes.

Protection and Indemnity (P&I) Insurance
An insurance taken out by shipowners, operators and charterers to provide protection against third party liability claims, such as damage to third party ships or offshore units, damage to fixed or floating objects, loss of or damage to cargo, pollution from the ship or its cargo, loss of life and injury to crew, passengers and third parties and wreck removal.

Reinsurance
This is a contract between an insurer and a reinsurer whereby the insurer will transfer risk to the reinsurer as added protection for themselves. There can be layers of reinsurance.

2.5 Acronyms

3S
Safety, Security and Safeguards

ALARA
As Low as Reasonably Achievable

ALARP
As Low as Reasonably Practicable

CPS
Cyber Protection System

DBT
Design Basis Threat

D&D
Decontamination & Decommissioning

FSA
Formal Safety Assessment (IMO)

GNSP
Global Nuclear Security Partners

IACS
International Association of Classification Societies

IAEA
International Atomic Energy Agency

IMO
International Maritime Organization

ISO
International Organization for Standardization

LR
Lloyd's Register

NGO
Non-Governmental Organisation

NNR
National Nuclear Regulator

NPT
Treaty on the Non-Proliferation of Nuclear Weapons (NPT) (IAEA INFCIRC/140)

QA
Quality Assurance

RBC
Risk Based Certification (LR)

RO
Recognised Organisation

SNF
Spent Nuclear Fuel

SMR
Small Modular Reactor

SQEP
Suitably Qualified and Experienced Person(s)

SSC
Structures, Systems and Components

UN
United Nations

Chapter 2:

Regulatory frameworks

SECTION 1:

Maritime regulation

1.1 Overview

The IMO is a body of the United Nations (UN) that is the centre of intergovernmental collaboration and development of international regulations for the shipping industry. Members of the IMO include 176 Member States, over 65 observing intergovernmental organisations (IGOs), and more than 85 consultative non-governmental organisations (NGOs) (July 2025).

> The mission of the International Maritime Organization (IMO) as a United Nations specialised agency is to promote safe, secure, environmentally sound, efficient and sustainable shipping through cooperation. This will be accomplished by adopting the highest practicable standards of maritime safety and security, efficiency of navigation and prevention and control of pollution from ships, as well as through the consideration of the related legal matters and effective implementation of IMO's instruments with a view to their universal and uniform application.

Through efforts of its working groups and member engagements, the IMO has developed principal codes and conventions that may be relevant to the nuclear industry. These include, but are not limited to:

- *International Convention on the Safety of Life at Sea* (SOLAS), 1974, as amended. Particular attention should be directed towards Chapter VIII – Nuclear Ships
- *IMO Code of Safety for Nuclear Merchant Ships* (Resolution A.491(XII))
- *International Convention for the Prevention of Pollution from Ships*, 1973, as modified by the Protocol of 1978 relating thereto and by the Protocol of 1997 (MARPOL)
- *International Convention on Standards of Training, Certification and Watchkeeping for Seafarers* (STCW) as amended, including the 1995 and Manila Amendments
- *International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships* (INF Code)
- *International Maritime Dangerous Goods Code* (IMDG Code)
- *Convention on the International Regulations for Preventing Collisions at Sea*, 1972 (COLREGS)
- *International Convention on Load Lines*, 1966, as Amended by the Protocol of 1988 (ICLL)

- *International Safety Management Code* (ISM Code)
- *International Ship and Port Facility Security Code* (ISPS Code)

Other Codes and Conventions that provide international governance of the oceans.

- *United Nations Convention on the Law of the Sea* (UNCLOS)
- United Nations International Labour Organization (ILO) Conventions, Recommendations, Codes of Practice and Guidelines

Member states become parties to IMO Conventions and their associated Codes or use the supporting guidelines, interpretations or other instruments. This simplifies the regulatory efforts of owners and operators to show compliance across multiple maritime jurisdictions, rather than being required to comply with separate regulatory mandates at every destination port. The IMO regulatory approach underpins the effective global transport of goods. The rules are focused on safety and environmental protection, but as an overall package, they facilitate trade.

Flag states or flag administrations are the national maritime bodies responsible for ships or offshore units registered with a government and acting for or on that government's behalf. The IMO refers simply to the *Administration,* which means the state government whose flag the ship is entitled to fly.

Port states and coastal states are the national maritime bodies of the jurisdictions where ships are visiting (port states), passing through, or temporarily or permanently installed (coastal states).

1.2 Role of Classification Societies

The role of Classification Societies (Class), such as LR, is that of independent third-party assurance. Classification societies are technically oriented organisations that have a comprehensive and detailed understanding of the shipping and offshore domains at international and local levels. LR classification services include rule development, design appraisal, Risk Based Certification (RBC), technology qualification, type approval, survey of components or systems while under construction and in service, and validation of systems.

Flag states can delegate classification societies to conduct surveys and issue certificates on their behalf using "Recognised Organisation" (RO) arrangements. This provides a global footprint to assure asset compliance with the internationally agreed statutory requirements and the flag administration's interpretations of them.

Statutory requirements are those requirements produced by the IMO and transposed into national/domestic law with any national interpretations. They also include any additional legal requirements a flag administration may have.

Flag administrations enforce compliance with statutory requirements for ships and offshore units registered with them.

To support the harmonised implementation of IMO conventions, codes, guidelines and other publications (collectively known as statutory requirements), the role of ROs to act on behalf of flag administrations is described in the IMO *Code for Recognized Organizations (RO Code)* in MEPC.237(65) and MSC.349(92) [3, 4]. ROs (including classification societies) provide third-party verification and certification regarding the design, construction, and in-service condition of ships and offshore units. However, the authority to oversee the appropriate training and certification of personnel and crew remains with the flag administrations and is not typically covered by ROs.

In addition to the statutory requirements, classification societies establish and require compliance with classification rules for vessels or offshore units that are "Classed." Classification societies' rules complement and support the statutory requirements and may exceed the minimum requirements of IMO conventions. Class Rules are referred to in the

SOLAS and Loadline Conventions as a possible means of compliance for parts of those Conventions. Class Rules apply to specific ship and offshore unit types regardless of their flag registry or operating jurisdiction. To provide lifecycle assurance, Class Rules cover requirements for materials, onboard equipment and systems, machinery, structures and arrangements with specific provisions for certain ships and offshore units. Verification practices and requirements for survey and inspection are also provided in these Rules, which are used to conduct classification inspections or surveys. Classification surveys occur at material and equipment manufacturing facilities, shipyards, and onboard ships or offshore units during and after construction. In this way, Flag Administrations may require their registered ships or offshore units to receive a classification certificate from a recognised classification society.

Some classification societies are members of the International Association of Classification Societies (IACS), which develops minimum technical requirements and provides technical input to external regulatory bodies and standards organisations. This includes the IMO, at which IACS is a consultative NGO. Individual classification societies also support Member States' and other NGOs' delegations at the IMO.

IMO instruments generally apply to ships and mobile offshore units that operate or trade internationally, but may also be cited as applicable by administrations for assets operating in their territorial waters. Offshore installations such as oil and gas industrial platforms or floating wind installations are subject to the regulations and requirements of jurisdictional maritime authorities. For the safety of offshore installations, the responsible maritime authority may require compliance with other internationally recognised organisations that develop engineering and operational standards, such as those produced by the American Petroleum Institute (API), the International Organization for Standardization (ISO), or the American Society of Mechanical Engineers (ASME), for example. Class societies offer rules for offshore units and provide verification to their own rules and certification to other standards.

Some applicable classification rules from LR include but are not limited to the following:

- *LR Rules and Regulations for the Classification of Ships*
- *LR Rules for the Manufacture, Testing and Certification of Materials*
- *LR Rules and Regulations for the Classification of Offshore Units*

SECTION 2:
Nuclear regulation

2.1 Overview

The IAEA originated from President Eisenhower's 1953 "Atoms for Peace" speech to the UN General Assembly, with the IAEA fully established in 1957 as a UN agency reporting to the UN General Assembly and Security Council. IAEA participants include 180 Member States (July 2025), and a number of other organisations depending on the topic. The IAEA works within the power generation industry and scientific fields of nuclear medicine and agriculture to promote the peaceful use of nuclear technology. The IAEA drafts guidance, recommendations, and standards on the acceptable use and operation of nuclear power, however, nuclear safety and security regulations are national responsibilities. The IAEA provides a centre for international nuclear collaboration and advancement.

While technical recommendations and standards are developed within the IAEA that are available for member states to either adopt or interpret, the most important role of the IAEA is to facilitate and enforce international treaties and agreements between member states on the safe handling of nuclear materials. Some relevant efforts coordinated by the IAEA include, but are not limited to the following:

- *Treaty on the Non-Proliferation of Nuclear Weapons* (NPT) (INFCIRC/140) [5]
- *Convention on Nuclear Safety* (INFCIRC/499) [6]
- *Convention on the Physical Protection of Nuclear Material* (CPPNM) (INFCIRC/274 Rev.1) [7]
- *1963 Vienna Convention on Civil Liability for Nuclear Damage* (INFCIRC/500) [8]

Unlike the IMO, the IAEA did not develop an international validation scheme with ROs. While it is common for nuclear technology and materials to be traded internationally, other than nuclear power for naval ships and submarines, operating nuclear power reactors does not extend beyond national jurisdictions. Therefore, regulatory oversight for commercial nuclear uses has fallen to the authority of individual member states and their nuclear regulatory bodies. Furthermore, national nuclear regulators (NNRs) have formed approaches and processes independently from each other for evaluating, reviewing, licensing, and validating the operations of nuclear power plants. This has traditionally been a land-based activity bound within the control of a single nation (for nuclear material accounting, according to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT)).

The IAEA:

- Serves as the global focal point for nuclear cooperation in the United Nations family - independent, intergovernmental, science and technology-based
- Helps Member States in their social and economic goals, planning for and using nuclear science and technology for various peaceful purposes, including the generation of electricity by facilitating the transfer of such technology and knowledge in a sustainable manner
- Develops nuclear safety standards and, based on these standards, promotes the achievement and maintenance of high levels of safety in applications of nuclear energy, as well as the protection of human health and the environment against ionising radiation
- Verifies through its inspection system that Member States comply with their commitments, under the NPT and other non-proliferation agreements, to use nuclear material and facilities only for peaceful purposes

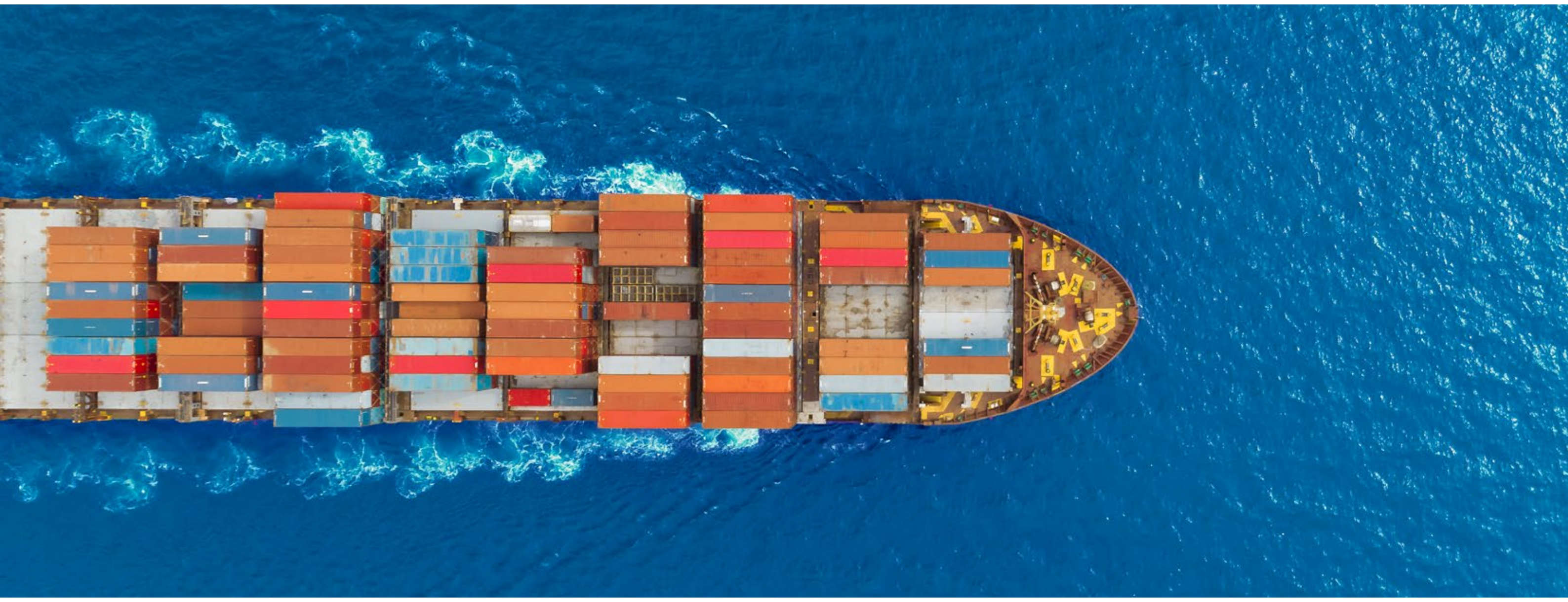
2.2 National regulatory approach

NNRs are responsible for approving and overseeing related safety and security aspects within their jurisdiction. This includes the licensing and regulating of nuclear sites, fuel facilities, spent nuclear fuel (SNF) and radioactive waste management, and the transportation of radioactive materials. NNRs have established mature regulatory requirements and safety standards based on the IAEA guidance, recommendations and standards, national laws, and international recommended practices. NNRs conduct statutory inspections and surveys, including process and management reviews such as assessments on the qualification of duly authorised personnel to verify they possess and meet the required standards and have the necessary knowledge and skills to operate and manage facilities safely. These inspections cover the entire lifecycle of the facility.

In addition to the verification of design, engineering, construction suitability and quality of nuclear power plants, NNRs act as the licensing authority for the safe and secure operation of nuclear power plants, and the management of nuclear material and SNF.

2.3 Nuclear licensing requirements

NNRs are responsible for independently overseeing nuclear energy technologies, this includes technology verification or certification approvals, equipment procurement, environmental assessments and site evaluations, construction, personnel certification in construction and operation, accounting for nuclear fuel and radioactive materials, and the safe management and handling of radioactive materials. The role of NNRs extends over all phases of a reactor's lifecycle, from concept development through decontamination and decommissioning (D&D) and final disposal of SNF and nuclear waste. While different processes, procedures, requirements, and policies may exist between NNRs, all generally have the same mission to oversee the safe use of nuclear technologies within their jurisdiction. They typically require information from developers and nuclear site operators about safety cases, environmental considerations, security, and operational considerations.



SECTION 3:

Prescriptive and goal-based requirements

3.1 Introduction

Many complex and novel projects use a hybrid approach of prescriptive and goal-based requirements, risk assessments, and risk management strategies to develop safety and security measures within the design philosophy, concept of operations, and inspection, maintenance and repair (IMR) activities. Goal-based requirements are applied to the system-of-systems integration and novel components or sub-systems. Prescriptive requirements are often used for specific components and sub-systems. Goal-based approaches provide flexibility at the expense of time and effort to demonstrate compliance; prescriptive requirements provide wider market access to "commercial-off-the-shelf" components and can simplify design and assurance of specific sub-systems. The industry and regulators have expressed a preference for the hybrid approach. Experience with complex offshore projects offers useful precedent for using the hybrid approach.

3.2 Prescriptive approach

Prescriptive requirements, standards, guidelines, or other regulatory mechanisms are developed with a mix of relatively conservative derivations and simplifications using first principles and empirical approaches. Requirements are added as experience grows, for example, technical lessons learned from accident analyses or near-miss investigations. However, one of the difficulties associated with prescriptive requirements is that there may be limited or no information on the context of its origin or goal. This makes proposing an "equivalent" or "alternative" difficult because there may be no clear reference point. To manage these complexities, for example, the IMO produced MSC.1/Circ.1455 *Guidelines for the Approval of Alternatives and Equivalent as Provided for in Various IMO Instruments (2013)*.

3.3 Maritime prescriptive approaches

Since the beginning of shipping and offshore regulation, the safety of passengers, crews, the environment, and cargoes has been a prominent driver for acceptable solutions. Prescriptive approaches offer straightforward rules to help achieve acceptable levels of safety. This provides a level of confidence to financiers, insurers and shippers that the asset meets a minimum standard. Verification and validation from marine inspectors is also included, where quality requirements are prescribed along with industry criteria.

Project teams should refer to flag administration and classification society rules that are prescriptive for many aspects of a design to reduce the design effort and number of design tasks and submittal items. While the prescriptive rules provided by flag administrations and classification societies simplify the design process for conventional vessels, they are often inadequate for new concepts. This limitation applies even when mature and well-understood marine technologies are incorporated into novel designs.

Over time, classification has evolved from prescriptive rules with limited scope to more comprehensive rules for topics such as hull structures and common rules for certain aspects across IACS. Classification is a source of rules as they apply to safety, environment, and asset integrity. Combined with statutory requirements, classification services provide a level of assurance that the design, equipment, and maintenance associated with the equipment meet applicable requirements.

When developing the regulatory assessment, maritime regulations, standards and codes should be identified according to the type of maritime unit and the deployment or operating region(s). Requirements may differ by marine jurisdictions, and alternative design and approval methods may be required where new or novel applications must demonstrate a level of safety equivalent to conventional or prescriptive designs. Most class societies have a method of working through the application of novel systems, such as LR's RBC process, which is aligned with MSC.1/Circ.1455.

3.4 Nuclear prescriptive approaches

Similar to the IMO's historical approach, the IAEA facilitates nuclear industry collaboration to identify internationally acceptable solutions for safety and security. Prescriptive requirements typically develop over time as experience and technology mature, with certain designs or engineering processes. For example, decades of operating experience with pressurised water reactors (PWRs) lent themselves to prescriptive design, construction and operating practices for land-based PWR power plants.

Building on experience regulating and operating nuclear power plants for many decades, IAEA technical working groups have developed various publications dedicated to providing member states with standard approaches for various aspects of nuclear facilities, including the lifecycle of nuclear fuel and plant decommissioning. As industries requested support for advanced water reactor technologies with novel applications or new features, non-prescriptive recommendations and guidance have been produced.

Project teams should refer to the NNR requirements during the regulatory assessment. It is advisable to leverage relevant and applicable prescriptive requirements supporting design simplicity where they meet project scope requirements. However, it is important to remember that prescriptive regulation is often the result of technology maturation and, as such, may be incomplete or non-existent for novel applications.

3.5 Goal-based approach

With the increase of complex systems across a variety of industries, it is increasingly difficult for prescriptive standards to be applied where the risks are not fully articulated. Traditional prescriptive standards developed may no longer be considered sufficient, and reasonably foreseeable risks should be recognised in the design and operation. Novel technologies may eliminate or lower certain risk exposures while adding new or increased risk exposures.

Prescription is still a key part of a goal-based standard, and at the lower tiers, it is essential. Goal-based standards are organised into tiers, gradually becoming more prescriptive. For example, the International Convention for the Safety of Life at Sea (SOLAS), Chapter II-1, Part A-1 – MSC.287(87) identifies:

- **Tier I Goals:** to be met in order to build and operate safe and environmentally friendly ships or offshore units
- **Tier II Functional requirements:** relevant to the functions of structures to be complied with to meet Tier I goals
- **Tier III Verification:** compliance criteria to provide the instruments necessary for demonstrating that the detailed requirements in Tier IV comply with the goals and functional requirements
- **Tier IV Technical procedures and guidelines:** including national and international standards, comprising detailed requirements developed by the IMO, flag administrations, or classification societies, for example
- **Tier V Industry standards:** codes of practice and safety and quality systems for building, operations, maintenance, training, and crewing

In the maritime and nuclear domains, both the IMO and the IAEA have adopted the use of goal-based standards to address novel technologies in increasingly complex systems. The fundamental principle of a goal-based approach is 'equivalent levels of safety.' Alternative or equivalent design and approval is expected to be carried out only for functions, systems or components that either directly or indirectly proposes alternative ways of compliance with prevailing regulations and cover the following elements:

- The top levels of the standards need to have a structured hierarchy, goals and objectives. There are a variety of ways in which a standard can be divided up or structured. This division is key, because it could restrict the scope of the regulation and could unduly influence the focus of the standard. For example, if the high-level goal is 'preventing uncontrolled fires,' some general functions might include 'fire detection,' 'fire containment,' and 'firefighting systems.'
- Standards typically provide at least one detailed prescriptive solution to the upper tiers. Sometimes prescriptive requirements are of limited scope and applicability, but the solution allows easy and cost-effective assessment of straightforward designs with a known operating context.

This approach can allow for design flexibility or innovative solutions. However, adhering to goal-based regulations typically requires more upfront effort to identify specific goals, functions, risks, and solutions. Hazard Identification (HAZID) and Failure Modes and Effects Analysis (FMEA) are examples of risk management techniques at various stages of the risk management cycle. Risks are addressed using a hierarchy of controls, prioritised in order of effectiveness:

- **Elimination –** design such that the hazard is removed entirely (e.g., do not use the equipment that poses the risk).
- **Substitution –** replace high-risk items with lower-risk options.
- **Engineering controls –** physical and automated safety systems (e.g., containment structures).
- **Administrative controls –** procedures and training to manage risks (e.g., qualified operators).
- **Personal Protective Equipment (PPE) –** protect individuals from the risk (e.g., hard hats).

Risk needs to be reduced to defined, acceptable levels. This process is iterative. As certain risks are managed, new ones might be introduced. Insufficient risk management can expose a project to undue technical, cost, and schedule consequences. Adopting novel technology at scale can open the possibility of developing prescriptive requirements as operating experience grows.

Using the goal-based approach, verification and validation of the final design are essential. Inspection, test plans, and quality performance assessments of designs, especially those that differ from prescriptive requirements for testing and inspection, must be established to accompany goal-based approaches. This allows the design to be evaluated throughout its lifetime and continually verified to comply with the requirements established by the risk assessment and management strategies. This is accomplished by developing inspection and test plans during the design phase and implementing operational procedures for testing, inspection, and maintenance, along with associated service providers such as classification societies, to provide independent oversight.

Through the RBC process, LR incorporates testing, inspection and maintenance assurance in RBC Step 5: Construction and In-Service Assessments.

3.6 Maritime goal-based approaches

To support the adoption of new and novel technologies on ships, the IMO has developed guidance for implementing consistent goal-based standards for ships. This provides designers a process to follow when proposing novel or alternative designs that do not meet the prescriptive requirements to demonstrate an equivalent level of safety.

The IMO guidance for developing goal-based standards *(see Figure 2 IMO Guidance for Developing Goal-Based Standards)* starts with the identification of the goals (Tier I) and functional requirements (Tier II), and the associated processes for verifying conformity (Tier III). This path is compatible with other goal-based approaches and risk management systems.

The following IMO guidelines provide guidance on the use of goal-based approaches:

- *Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments* (MSC.1/Circ.1455)
- *Guidelines on alternative design and arrangements for SOLAS Chapters II-1 and III* (MSC.1/Circ.1212)
- *Guidelines on alternative design and arrangements for fire safety* (MSC/Circ.1002)
- *Generic guidelines for developing IMO goal-based standards* (MSC.1/Circ.1394)

Project teams should refer to applicable flag administration and classification society rules in the regulatory assessment. Where guidance or a process may be available for applying goal-based standards, these may be followed. If the requirements are prescriptive, the design team may need to bridge the gap and follow IMO and industry-recommended practices to document alternative design methodologies using goal-based approaches.

Two of the most important tenets of the IMO equivalency are that:

1. A proposed equivalent must demonstrate that it is equal to or higher than the existing requirement
2. Operational methods or administrative procedures are not allowed to replace particular required fittings, materials, appliances, apparatus or equipment when demonstrating equivalency

Goal-Based Standards Framework

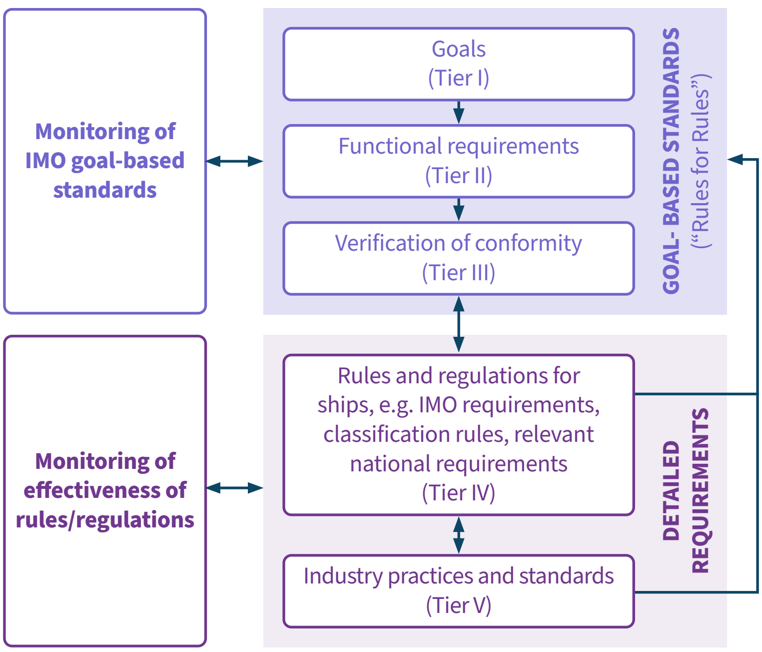


Figure 2: IMO Guidance for Developing Goal-Based Standards

3.7 Nuclear goal-based approaches

The IAEA adopted a long-term structure for its safety standards, which was goal-based and implemented to enable a consistent framework to be applied by its member states in their national regulation. Examples include:

- Safety Fundamentals (SF-1);
- General Safety Requirements (GSR); and
- General Safety Guides (GSG). These standards are supported by Specific Safety Requirements (SSR) and Specific Safety Guides (SSG).

There are various efforts from the IAEA to integrate guidance on regulatory approaches where prescriptive standards do not apply. Reference can be made to the following:

- IAEA *Proposal for a Technology-Neutral Safety Approach for New Reactor Designs* (IAEA TECDOC-1570) [9]
- IAEA Safety Standards Series No. GSR Part 1 (Rev. 1), Governmental, Legal and Regulatory Framework for Safety

Nuclear approaches for goal-based regulations are embodied in the risk principle "As Low as Reasonably Practicable" (ALARP) or "As Low as Reasonably Achievable" (ALARA). Ionising radiation is of particular concern to the public, and through years of experience with biological shielding and scientific understanding of radiation exposure, the nuclear regulators' approach is to keep exposure limits below acceptable dose limits and further reduce the risk to ALARP, a concept that is generally illustrated in *Figure 3: The ALARP Principle.* At its core, ALARP is a principle for practically balancing risk and costs.

To confirm the safe design and operation of nuclear power plants and verify the use of ALARP, NNRs typically require detailed quantitative and qualitative assessments of hazards, accidents, and postulated events that could cause failures resulting in safety or security consequences. The sited location of nuclear power plant sites can be considered unique and, therefore, pose unique security, safety and operational risks. It must be shown that risks are managed according to nuclear regulatory requirements.

Project teams are encouraged to engage NNRs early in their design to understand the nuclear-related requirements and inform the regulators of new or novel aspects long before licensing activities begin. Where prescriptive requirements do not exist or where the regulator has limited experience with goal-based approaches, new regulatory approaches may need to be proposed. New approaches are typically based on industry experiences that offer technical precedent or extensive design assessment submissions to demonstrate that the applicant can achieve acceptable levels of risk.

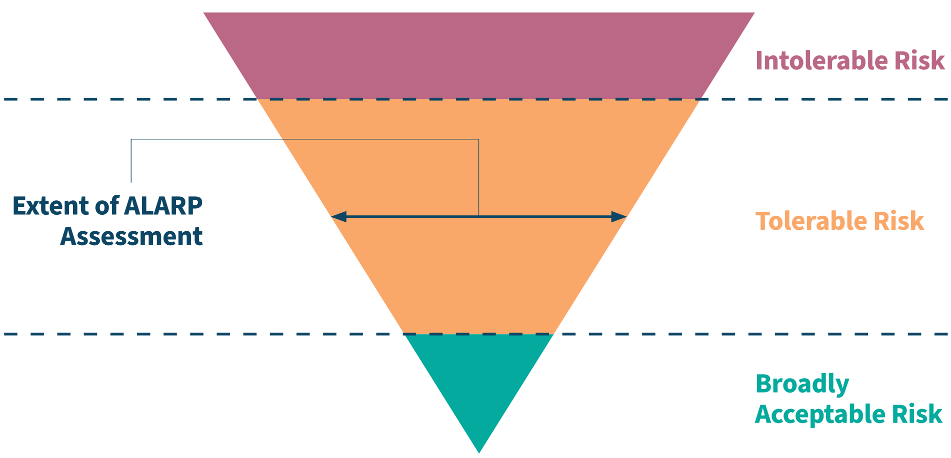


Figure 3: The ALARP Principle

SECTION 4:

Aligning regulatory frameworks

4.1 Considerations for aligning regulatory frameworks

Any project related to nuclear power for maritime is expected to comply with international and national nuclear and maritime regulations, with various degrees of national and international oversight. Both frameworks are mature and established internationally, but there is limited experience of working collaboratively. Project teams should understand these mature frameworks as much as possible.

This Section discusses the relationships between regulators that are in place or may need to be established when considering aligning maritime and nuclear regulatory frameworks.

4.2 Reconciling risk management principles

In the effort to align regulatory frameworks, both maritime and nuclear industries require risk management programmes to identify and manage risks during design and operations. Extensive engineering processes and references provide for this major activity, so it is therefore not discussed in detail within this document. Project teams should work to reconcile differences between risk management practices at nuclear and maritime interfaces.

In the context of maritime nuclear, the IMO Formal Safety Assessment (FSA) (MSC-MEPC.2/Circ.12/Rev.2) refers to the risks associated with the operation of a maritime (ship or offshore) nuclear asset that has been reduced to a level where the cost of further risk reduction (a function of time, effort, money, and complexity) would be impractical to the safety benefit gained by conducting such an action.

Project teams should be aware of the various subjective and legal interpretations of FSA, ALARP, and ALARA and the risk tolerance of the organisation and stakeholders as described in its risk management plan.

Table 1: Features of FSA, ALARP and ALARA Principles show examples in various contexts, especially between different industries.

Table 1: Features of FSA, ALARP and ALARA Principles

Feature	ALARA (Radiation Protection)	ALARP (Nuclear)	ALARP (UK Health and Safety Executive)	IMO Formal Safety Assessment (ALARP)
Primary Focus	Minimising radiation exposure and releases to the environment	Nuclear safety and prevention of radiological accidents	Safety and health risks across all industries	Maritime safety and pollution prevention
Origin	International radiological protection framework	Broad safety principles applied to nuclear context	UK health and safety legislation and regulatory body	International maritime regulatory framework
Key Concept	Reasonably Achievable (considering economics & social factors)	Reasonably Practicable (Risk reduction of gross disproportion with high hazard context)	Reasonably Practicable (Risk reduction outweighing cost unless grossly disproportionate)	Reasonably Practicable (Cost-Benefit Analysis)
Scope	Primarily radiation-related risks	Aspects of nuclear safety	Wide range of workplace and public safety risks	Risks associated with maritime operations
Regulatory Body	Nuclear regulators	Nuclear regulators	UK Health and Safety Executive (HSE)	IMO
More Information	International Commission on Radiological Protection (ICRP) www.icrp.org	ONR Technical Assessment Guide NS-TAST-GD-005 Regulating duties to reduce risks to ALARP www.onr.org.uk	UK HSE Guidelines for HSE Inspectors on 'ALARP' www.hse.gov.uk	IMO SOLAS and MARPOL MSC-MEPC.2/Circ.12/ Rev.2 www.imo.org

4.3 Designating the regulator's roles

This section discusses the relationships between regulators that exist or may need to be established when considering aligning maritime and nuclear regulatory frameworks.

Careful consideration should be given to how the mature maritime and nuclear regulatory frameworks could be aligned to support the development of nuclear energy for maritime. Maritime nuclear assets are subject to requirements and regulations of national authorities, including flag administrations, port states, and coastal states, especially considering port visits for normal trade or service. A comparison of the two regulatory approaches, including the role of classification societies and ROs on behalf of maritime industries, and the potential role as an RO to the nuclear industry, is shown in *Figure 4: Aligning Regulatory Frameworks* and *Figure 5: Parallel Structure of International Agencies to Implement Requirements.*

Classification Societies and National Maritime Administration (Flag State)
Classification societies often act as ROs on behalf of flag states. This means the flag state delegates some or all statutory inspection and certification duties to the RO. The flag state retains accountability and oversight.

Maritime Administrations and Nuclear Regulators
For a maritime nuclear asset, the maritime administration(s) and the nuclear regulator must have a close working relationship. The maritime administration is responsible for the overall safety of the ship or offshore unit, including compliance with maritime regulations, while the nuclear regulator focuses specifically on the nuclear aspects. Agreed documented divisions of responsibilities and communication are essential.

Classification Societies and Nuclear Regulators:
While nuclear regulators are primarily responsible for nuclear safety, classification societies can play a vital role in assessing the *non-nuclear* systems that support the safe operation of the reactor. This includes the hull, machinery, electrical systems, and containment structures. Due to the primarily national activity of nuclear regulators, there has not been a need to develop nuclear ROs in the same sense that there are maritime ROs to support international compliance. This role is presently a suggestion, but not yet established like a maritime RO. However, when considering nuclear power for maritime, nuclear regulators may have an opportunity to leverage ROs to extend resources and provide more effective review and oversight for certain activities.

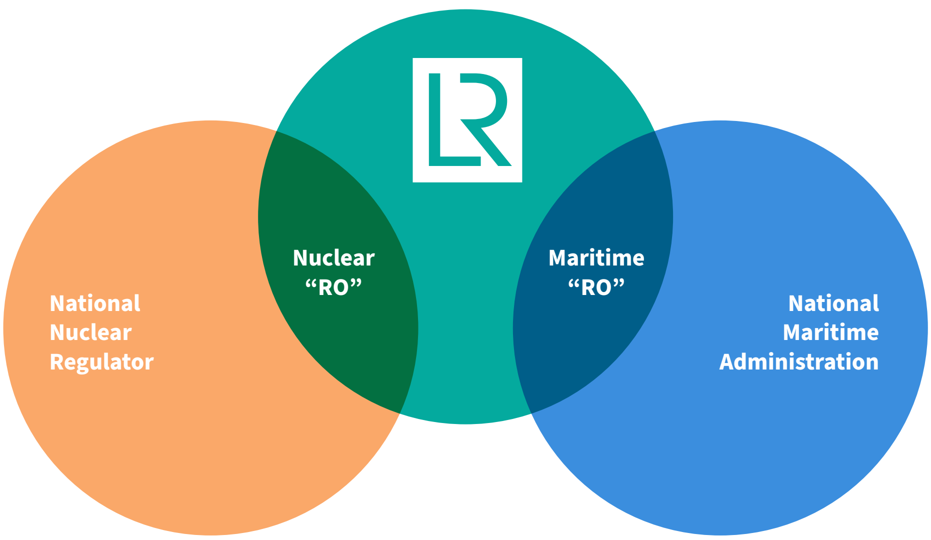


Figure 4: Aligning Regulatory Frameworks

IMO and IAEA:
The IMO and IAEA will be required to cooperate on the joint development of guidance for nuclear material, nuclear energy, and ships. Guidance documents will be critical for enabling and harmonising maritime and nuclear safety regulations. The IMO and IAEA are organised similarly, as shown in *Figure 5: Parallel Structure of International Agencies to Implement Requirements,* and may find opportunities for collaboration where subject matter overlaps.

The nuanced aspects of both mature regulatory frameworks and the effort to align them can appear to be the first challenge to overcome. There are differences in risk tolerance, cultures, and even terminology to be reconciled. The ideal target for producing international regulations and alignment at the highest level may result from demonstration projects and first movers that start at the national or regional scale. Project teams are encouraged to engage national or regional regulatory stakeholders to investigate local solutions rather than focusing on international regulatory development. When nuclear energy for commercial maritime has matured and national maritime and nuclear regulators are more familiar with the proposed technologies, countries can contribute their experience to develop international regulations, standards and codes.

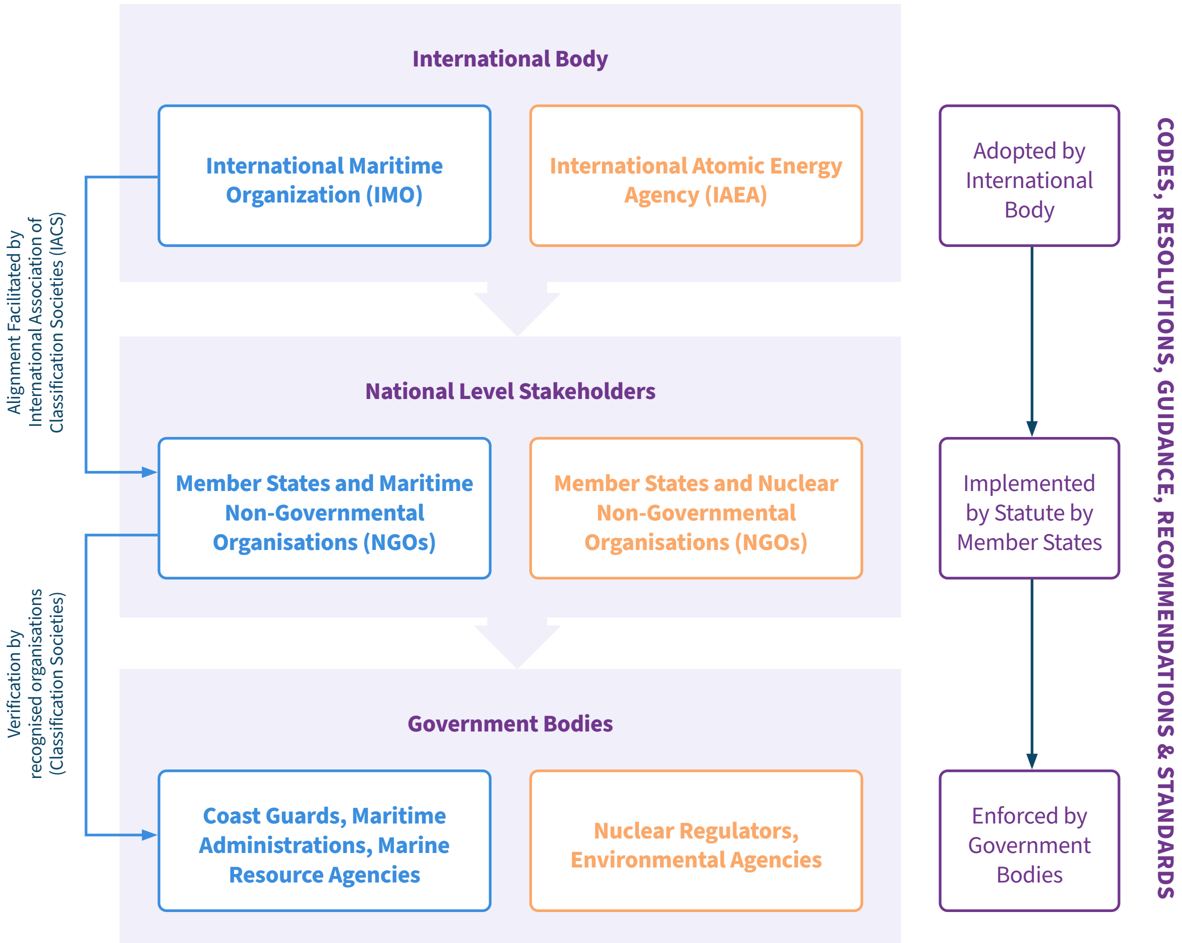


Figure 5: **Parallel Structure of International Agencies to Implement Requirements**

Chapter 3:

Requirements for implementing nuclear energy in maritime

SECTION 1:
Introduction

1.1 Introduction

When considering initiating nuclear energy for use in the shipping or offshore industries, there are simultaneous activities that should be pursued to develop and execute a successful project. This chapter introduces activities that must be addressed, covering technical and non-technical aspects of design and project development, including technology integration, financing, insurance, safety case development, security, and operating conditions. While some activities may be familiar to nuclear or maritime design teams functioning independently, these activities must include both nuclear and maritime stakeholders, consider applicable regulations, and undertake assessments of nuclear technology operating in marine environments. See *Figure 6: Requirements for implementing nuclear energy in maritime.*

Technology Integration
- Safety Criticality
- SSC Graded Approach
- Nuclear License Requirements

Safety Case
- Environmental Considerations
- Marine Conditions

Security and Safeguards
- Marine Security
- Supporting Activities for Security

Operations
- Personnel
- Emergency Response
- Upstream, Downstream and Supporting Activities

Insurance
- Assurance
- Risk Management
- Acceptable Risk

Finance
- Investment
- Financial Risk Management

Figure 6: Requirements for implementing nuclear energy in maritime

SECTION 2:
Maritime and nuclear technology integration

2.1 System integration by safety classification

Project teams should clearly map the project boundaries, regulatory authorities, and requirements applicable to their concept. These will depend on the details of project design, construction, and operations. In the effort to integrate maritime and nuclear standards, some standards may be complementary, conflicting, or supersede others.

Nuclear and maritime industries must reconcile processes that are used to classify functions and equipment according to importance, especially at interfaces. Nuclear industries use risk assessments and failure mode analyses to classify or grade structures, systems and components (SSCs) according to their importance to nuclear safety, where unacceptable risk scenarios are related to radiation exposure due to reactor or containment failure. The maritime industry has similar approaches to categorise equipment and systems, for example, services essential for safety on ships or safety critical elements (SCEs) on offshore units. For maritime systems, safety, environmental concerns, and asset damage are the primary risk drivers.

Nuclear industry practice assigns safety classes to SSCs to identify appropriate design and quality management standards. When this categorisation is done for nuclear technologies integrated on maritime assets, the project team may find that some conventional marine systems or equipment must meet nuclear quality standards, or that some nuclear-specific systems or equipment must meet maritime standards. Functions and critical systems will govern many aspects, including:

- Applicable regulations and regulatory authority
- Responsible approval authority
- Standards or codes to be used for:
  - Design and manufacturing
  - Quality programme
  - Testing and inspection regime.

This reconciliation is especially important when defining the interface between nuclear and maritime systems and identifying jurisdictional responsibility. Due to the dependence of the regulatory regime on system safety classification, a clear regulatory assessment may not be achieved until the design is mature enough to provide technical details. Therefore, this process is iterative.

For operation on maritime assets, nuclear licensing must be aligned with approvals from the maritime authority. Coordination between the project team and the nuclear and maritime authorities is necessary to establish processes for escalating and resolving conflicts and identifying jurisdictional limits.

SECTION 3:
Nuclear safety case development

3.1 Introduction to the nuclear safety case

Nuclear regulators and insurers require that risks are identified, assessed, and managed to establish consistently documented levels of safety to be within risk tolerance limits over the reactor's lifetime. These are elements of the nuclear safety case.

The safety case is a comprehensive written argument that demonstrates why the facility and related activities are appropriately managed with acceptable levels of risk that are commensurate with its operation throughout its lifecycle. This provides acceptable levels of safety for the public, crews, and the environment. The nuclear safety case is an evaluation of a reactor, intended for a specific environmental envelope, that includes the development of operational responsibilities and qualifications, situational response functions, and the comprehensive designation of liable and responsible parties in the case of incidents.

To support this, project teams need upfront decisions on operational locations or routes, and to identify stakeholders early on, including equipment supply vendors, shipyards, communities, regulatory bodies or jurisdictions, operators, clients (e.g., power offtake customers), maintenance and service providers, waste management resources, and end-of-life D&D service providers.

Considerations when developing the safety case include:

- **Public Perception and Community Engagement:** At every stage, impacts on the community and public perception should be considered as risks that may disproportionately affect certain communities or groups, depending on the operational arrangements. Regulations require that safety cases consider proximity, population densities, and the nature of certain stakeholder groups that may pose risks to the project or be subject to potential consequences.

- **Operational Suitability:** Nuclear power systems should be proven to meet the functional requirements of the maritime unit, depending on its purpose (energy demand and use). This is done during design using modelling and simulation, demonstration testing, and equipment or manufacturer certifications during procurement. Functional operations are to be demonstrated to meet a level of safety that is equivalent to conventional technology through risk management strategies.

- **Crew Training:** Operators and crew will require specialised training, including reactor operations, safety protocols, and emergency procedures as applicable to certain positions. This will necessitate special considerations and potential updates to existing maritime training standards.

- **Refuelling Cycles:** Nuclear-powered maritime assets may operate for several years without refuelling, depending on the type of reactor and power demand. Arrangements for refuelling and refuelling operations must be carefully considered throughout the maritime asset's lifetime.

- **Waste Management:** Proper handling and storage of nuclear waste onboard ships or offshore units will require compliance with strict international regulations. Onboard systems must be designed to manage radioactive waste and SNF safely until it can be discharged to a licensed facility for nuclear waste management.

3.2 Environmental considerations

As part of the safety case, the nuclear regulator looks closely at the operating envelope of the nuclear power plant, including any potential impact from the environment or environmental forces. Security considerations, occurring by intent rather than accident, are discussed separately. Environmental considerations for land-based nuclear power plants are typically documented using recognised environmental assessment methodologies, which are used to characterise seismic activity, weather, climate, flooding, or other plausible natural disasters or incidents.

Certain operational risks related to operating in the maritime environment must be addressed in the reactor's design, interfacing systems, and overall unit structure and architecture. Environmental assessments are essential for understanding the potential impacts of marine environments on nuclear ships or offshore units. The environmental assessment methodology should consider the expected operating scenarios, including normal functions, refuelling operations, and potential accidents or emergency conditions.

The following examples of impacts from the environment or environmental forces must be considered in the nuclear safety case. This illustrative list is not exhaustive, and for more detailed information about typical environmental considerations, contact LR. See also *Figure 7: Reactor Safety Case environmental considerations.*

- **Operation in wind and wave environment:** Ship and offshore structures are subject to motion and acceleration in six degrees of freedom when exposed to the ever-changing and often unpredictable loads caused by wind and waves. While there are methods to dampen harmonics and restrict motion in certain directions, constant motion can be expected under the force of the elements.

- **Water depth effects:** Water depth impacts wave kinematics and the wave spectrum. Especially in shallow waters, tidal variation and storm surge can continuously vary with water depth. Motions can also be amplified in shallow waters.

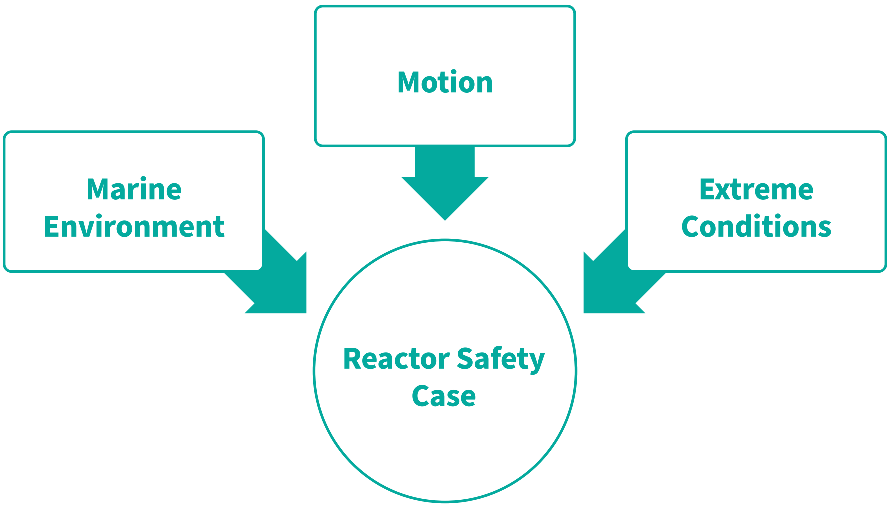


Figure 7: **Reactor Safety Case environmental considerations**

- **Environmental operating limits for equipment:** Ship and offshore unit equipment and systems are expected to operate within defined design conditions. A distinction is made between operating limits, where the asset provides its service normally, and survival limits, where it may not be operating but is designed to withstand extreme conditions with limited damage.

  These limits are based on different philosophies. Ships are designed with the knowledge that they can often evade the worst conditions, leading to a general "worldwide unrestricted trading" designation based on harsh environments like the North Atlantic (~25-year return period). In contrast, most offshore units are permanently on-station and cannot be moved, requiring them to be designed for site-specific 1,000-year or 10,000-year return conditions, considering the combined effects of wind, wave, and current.

  Therefore, inertial forces, accelerations, and inclinations during extreme conditions must be assessed to verify the functionality of reactors and safety systems.

  - For ship structural requirements, refer to the *LR Rules and Regulations for the Classification of Ships* Part 3 Chapter 4 Longitudinal Strength.

  - For machinery requirements on ships, refer to the *LR Rules and Regulations for the Classification of Ships* Part 5 Chapter 1 General Requirements for the Design and Construction of Machinery, Section 3 Operating Conditions.

  - For offshore unit structural requirements, refer to the *LR Rules and Regulations for the Classification of Offshore Units* Part 4 Steel Unit Structures.

  - For machinery requirements on offshore structures, refer to the *LR Rules and Regulations for the Classification of Offshore Units* Part 5 Main and Auxiliary Machinery.

- **Environmental operating limits for structural loads:** The motion and responses of ships and offshore units in wind and wave conditions must be defined so the structural loading conditions can be estimated, and structures can be designed to withstand environmental loads over the unit's lifetime. This can be achieved by examining the wind and wave conditions of known, harsh marine environments, modelling unit motion responses in 10-year, 100-year, and 1000-year storms (or higher), and calculating the maximum structural loads. Alternatively, a simpler approach to characterising ship and offshore unit responses in waves is based on decades of operations, resulting in prescribed equations with built-in safety factors to establish structural requirements. With the inclusion of nuclear power systems, the identification of inertial loads may need to be revisited to verify structural safety in dynamic conditions. Extreme structural load cases may require contingencies to maintain the integrity of large equipment in the event of capsizing or sinking.

- **Corrosion and radioactive exposure:** Structural elements and materials should consider the corrosive effects of wind and waves over time, especially when floating in salt water. Biological growth (biofouling) and sulphate-reducing bacteria (SRB) can add additional loads and have corrosive effects on structures in the marine environment. Materials should be designed with corrosion in mind and protected using coatings, cathodic protection devices, or specialised materials that reduce material corrosion or biological growth. Consideration should be given where requirements for materials used in radioactive environments may conflict with or impose different requirements than those for materials used in maritime environments.

- **Seismic activity:** Whether onshore, in drydock, or manoeuvring in deep water far offshore, seismic activity should be considered. Seismic activity near coasts or at subsea faults can create localised effects on nearby coasts, but can also result in major surface wave activity up to great distances away. The damaging effects of tsunamis or tidal waves are not strongly felt at the water's surface far from shore, but increased hazards occur in shallow water and susceptible coastal regions.

Given the nature of nuclear power and the marine environment, the following impacts from the nuclear technology on the maritime asset or environment must be considered in the nuclear safety case. This illustrative list is not exhaustive, and for more information about impacts from operating a nuclear-powered asset, contact LR. See also *Figure 8: Unit and Environmental Impacts.*

- **Large point loads**: Adding a large point load where reactor units are to be installed may affect the onboard loading conditions. Structural continuity should be verified under normal and extreme loading conditions (including accidental loads), and safety factors should be checked according to quantitative risk assessments.

- **Radiation and the environment:** Radiation exposure is a major concern of the public when considering nuclear energy. For all defined conditions, it must be confirmed that the possibility of exposing ionising radiation or radioactive materials to people, the environment, cargo, or other assets is managed to ensure risk levels are ALARP.

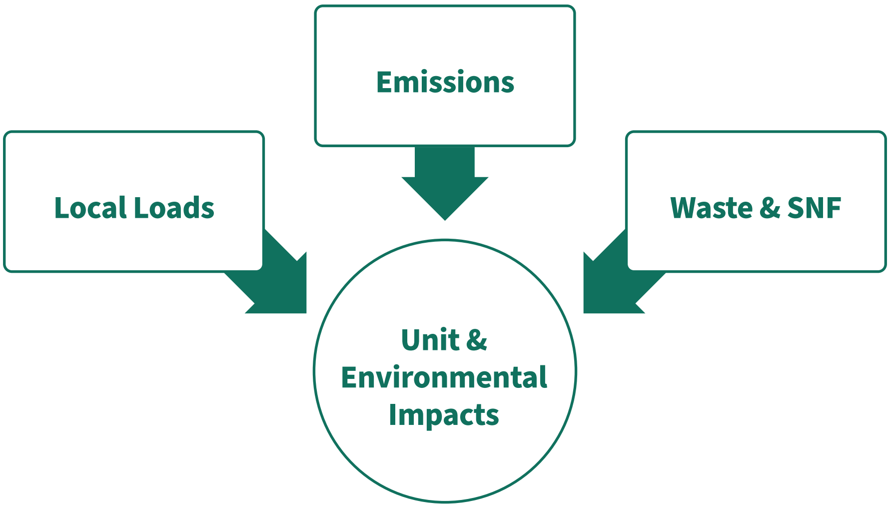


Figure 8: **Unit and Environmental Impacts**

- **Radioactive materials and waste management at sea:** Arrangements for temporarily managing radioactive materials, wastes, or SNF should account for operations in the expected marine environment. Onboard waste storage solutions must consider the safe and secure storage of nuclear waste and SNF until proper disposal is possible. If this material is not considered packaged cargo subject to the INF code, new approaches for handling should be developed and included within the risk management strategies. Consideration should be given to the requirements for safely discharging or emitting pollutants or effluents while at sea, according to UNCLOS or the flag administration requirements. International protocols for transporting and transferring radioactive waste and SNF from ships to designated facilities must be followed. Where protocols do not exist for material transport—for example, if the material is not considered a cargo—it may not be directly subject to existing regulations for the handling of packaged nuclear material. Therefore, new strategies for the handling and discharge of nuclear waste or SNF from ships must be developed and incorporated into risk management strategies for the expected operating conditions.

- **INF Code:** The IMO *International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Waste on Board Ships* (INF Code) defines requirements for ships carrying packaged irradiated materials. Consideration should be given to the INF Code standard of safety and how the goals and functional requirements may be interpreted for use in a goal-based framework.

- **Thermal pollution:** In addition to pollutants from emissions or effluents, consideration should be given to the environmental effects of thermal pollution from cooling systems. High power from reactor power systems often requires significant cooling capacity to manage thermal energy during normal operations and reactor shutdown conditions. In the most demanding conditions, the cooling arrangement may need to manage the discharge of up to all the thermal energy generated by the reactor. This is often achieved by external water coolant loops discharging hot water or air cooling and ventilation of high-temperature air. Onshore this is characteristically accomplished at power plants by large concrete cooling towers, which manage the safe release of thermal energy to the atmospheric heat sink. If power plants are located near large water resources, cooling is often achieved by water circulation systems, which intake water for internal heat exchange and discharge heated water back to the environment. The concern lies in the possibility of excess thermal pollution to the atmosphere or water, potentially impacting the ecology at, near, or downstream of discharge locations.

3.3 Structural integrity and metocean

An asset's structures must be designed and verified to be fit-for-service for a wide range of requirements. The structures provide the support for the entire hull, equipment and systems, and also provide boundaries for compartmentation in terms of stability, fire protection, and separation of spaces. Ship and offshore structures are designed to cope with extreme events and are characterised by good residual strength even in severely damaged areas.

Metocean data, encompassing wave height, period, direction, current speeds, wind speeds, and other environmental parameters, play a crucial role when establishing structural integrity and operational safety. This data is used to determine design loads for structures and mooring systems, such that the unit can withstand dynamic environmental forces.

Ships and offshore structures are designed and examined for ultimate strength, "normal" strength, and fatigue strength. The loads are largely from static and dynamic inertial loads related to motions and gravity, local loads such as slamming or slapping, and reaction loads for equipment. In addition to structural assessments, metocean data assessments are important to understand the expected accelerations onboard that are experienced by personnel, equipment, and cargoes. Ultimate and accident loads are also considered for extreme events such as collisions, dropped objects, or explosions.

In the context of nuclear technology, the metocean data and unit structure form the basis for "site characterisation," which is a key concept for nuclear regulators when evaluating operating locations. Unlike land-based applications, marine site characterisations may require evaluating conditions at multiple locations or a range of conservative 'general' boundary conditions. Nuclear developers will likely be required to provide performance analyses and demonstrate with data that the reactor can operate safely, maintain stability, and conduct a safe shutdown under the postulated conditions within the defined metocean envelope.

The structures must be designed and checked to confirm suitability for each of the load types under "normal operation" and "survival" conditions. Generally speaking, structures that support a graded safety-critical component will be designed to higher survivability requirements than structures that are not critical for survival or safety.

The marine and offshore industry has widespread capability and experience in the sophisticated structural design and analyses required for high-reliability systems. The addition of nuclear systems is additive in terms of requirements and is not likely to cause direct contradiction with sophisticated methods already in use.

Structural integrity: Appropriate assessment of wave loads is essential to ensure the unit can operate in seas without structural failure. There are many structural failure modes, including high and low-temperature brittle fracture, composite softening, combustion, corrosion, local breach of boundaries, loss of strength/rigidity, accidental damage, residual strength analysis, shock loads, or combinations of these cases. While there are many assessment methods for evaluating structural integrity, two primary analyses are listed here.

- **Ultimate strength analysis:** The hull's ability to withstand extreme loads is evaluated using ultimate strength analysis, verifying it can withstand extreme metocean conditions.
- **Fatigue analysis:** Fatigue life of selected critical locations of the hull structure is evaluated.

Mooring system integrity: For floating structures, the mooring system's integrity is crucial. Metocean data is used to analyse the dynamic behaviour of the mooring lines and the resulting dampening or restraining effect on the defined structure, verifying that the arrangement can effectively maintain the structure's position, even in extreme conditions. Similar integrity assessments are done for jacketed, jack-up, or other seabed-supported offshore structure types.

Operational safety: Metocean data informs the definition of operational limits for assets in commercial shipping and offshore industries. Nuclear regulators can use these data and assessment methodologies to assess the safety of operations under various environmental conditions, including extreme events, establishing boundaries within which the reactor can be safely operated, maintained, and shut down.

Emergency preparedness: Metocean data contributes to the development of emergency response plans, enabling regulators to evaluate the potential impacts of environmental conditions on emergency response efforts. This data helps operators and crew prepare to handle emergencies effectively in various metocean scenarios.

Collaboration and harmonisation: Effective utilisation of metocean data and analyses requires collaboration between nuclear regulators, maritime authorities, and classification societies. Harmonising regulatory frameworks and sharing expertise will support the development of comprehensive safety assessments and consistent standards for maritime nuclear assets.

SECTION 4:
Security and safeguarding considerations

4.1 Introduction to security considerations

Using nuclear energy introduces security and non-proliferation challenges, particularly in terms of addressing nuclear security threats and complying with international nuclear safeguards.

This section outlines approaches to nuclear security and safeguards that maritime stakeholders should consider and incorporate early in design planning strategies.

4.2 Potential maritime use cases and associated security considerations

Both commercial nuclear-powered ships and nuclear-powered offshore units introduce overlapping nuclear security and safeguards challenges. The operational context of each deployment scenario brings specific risks. Project teams must develop scenario-specific security strategies, based on a clear understanding of both the common threat environments and the unique operational profiles.

Commercial nuclear-powered ships. The adoption of nuclear-powered ships raises challenges over:

- The need for secure handling and transportation of nuclear materials
- Managing the risks of sabotage, theft, unauthorised access or unauthorised diversion of materials

Nuclear-powered offshore units. The mobility and deployment of nuclear power plants in international waters or politically sensitive regions potentially increase their exposure to:

- Potential threats from adversarial actions, including sabotage and unauthorised access
- Increased vulnerabilities during maritime transport, or potentially in the location they're operating in
- Managing the risks of sabotage, theft, unauthorised access or unauthorised diversion of materials

4.3 Security system components

Enabling Security Elements: A common requirement of nuclear operations is demonstrating that organisational systems are appropriately reliable and capable. Any organisation responsible for nuclear security must demonstrate aspects such as an appropriate culture, organisational resilience in key posts, relevant competency, and clear decision-making systems. In addition to enabling security requirements, the nuclear security system for maritime applications will comprise three components: a physical protection system (PPS), a cyber protection system (CPS) and insider threat mitigation.

Physical Protection Systems (PPS): The PPS for maritime applications of nuclear power will be required to:

- Apply a defence-in-depth approach, using multiple layers of barriers, components, personnel, and systems to demonstrate that it can deter, detect, delay and potentially defeat threats according to the Design Basis Threat (DBT) applied
- Integrate innovative detection and response systems to assess threats and prevent unauthorised access to assets, information or systems important for nuclear security or nuclear safety (ideally without needing a permanent armed presence)

- Establish secure interfaces between ships and port facilities during docking and refuelling operations such that additional threats are managed to the required level, whether at sea or alongside

Cyber Protection System (CPS): The function of the CPS is to deliver appropriate levels of Cyber Security & Information Assurance (CS&IA) to protect any data, information, information technology (IT) and operational technology (OT) considered to be critical to the safe and secure operation of the nuclear plant. This will become increasingly important as the maritime industry drives towards decarbonisation and digitisation. Illustrative functions of the CPS include:

- Conducting cyber vulnerability assessments tailored to maritime nuclear operations
- Deploying resilient communication encryption and multi-factor authentication protocols to protect IT and OT associated with the nuclear plant, its operation, management and protection, including integrating and managing interfaces with safety, security and non-nuclear systems
- The appropriate classification, management and control of access to information (data and hard copy), wherever it is located, pertaining to the operation and 3S of maritime nuclear assets
- Establishing Cyber Incident Response Teams (CIRTs) for rapid response to threats

Project teams should consider the existing cyber security requirements for maritime compared to the nuclear cyber protection system requirements, as subjects of contention may need to be reconciled with the appropriate regulators. Refer to the *LR Overview and Guidance for ShipRight Cyber Security Procedures.*

Insider Threat Mitigation: An insider threat is an individual with legitimate access to nuclear systems, structures or data who misuses that access for malicious purposes and mitigating insider threats is critical for securing sensitive operations and materials – effective measures include:

- Comprehensive personnel vetting processes for individuals requiring access to sensitive locations and information, including monitoring for continuous security concerns, i.e., ‘aftercare’ management [10]
- Behavioural monitoring to detect anomalies indicative of insider threats
- Reinforcing a strong security culture through regular training and awareness campaigns for individuals and organisations who operate on or support nuclear-powered maritime or offshore units

4.4 Considerations for safeguards in maritime nuclear operations

Nuclear safeguards are a separate function from security and safety. They are required to satisfy international legal obligations to control certain nuclear materials that have the potential to be diverted towards nuclear weapons proliferation. The future maritime compliance regime must satisfy IAEA safeguards protocols (including the Additional Protocol). Careful consideration should be given to the arrangement for nuclear safeguards suitable to the operation and maintenance of proposed novel nuclear technologies. Nuclear safeguards can be considered as two broad activities: Nuclear Material Accounting and Control (NMAC) and independent parties’ verification of those controls. Maritime nuclear operations will require new approaches to how safeguards are delivered and how material is accounted for. With different ownership models being proposed for reactor operations and platforms, their deployment across multiple nation states and jurisdictions, an approach that doesn’t lessen the current standards required on land will be necessary.

NMAC: NMAC requires real-time tracking, monitoring and record-keeping systems for certain nuclear fuels and waste products. Developing secure and resilient automated systems to streamline compliance for maritime and offshore nuclear operations will be key and require consideration during any maritime nuclear platform’s concept development and design stages. There will be an early need for deployable technologies to support some reactor designs (the availability of which might influence the selection of the first reactor types deployed for maritime) [11].

Challenges for Verification and Inspection: Facilitating inspections in remote or transient operational environments will require innovative solutions. Technologies such as unmanned inspection drones and portable radiation detection systems will need to be explored to meet the challenges and satisfy international legal requirements.

4.5 Supporting components of the nuclear security system

Various enabling activities to design and test future maritime nuclear security systems will be necessary to gain regulatory approval. The maritime application of nuclear power will require the following to be addressed early in the process:

- **Development of a Design Basis Threat (DBT):** Future maritime nuclear security systems must be designed against an appropriate DBT. The transboundary nature of nuclear-powered ships (and to a lesser extent, nuclear-powered offshore units) will require an innovative approach to developing a DBT that can be applied as a part of the secure-by-design process. Developing a generic international maritime nuclear DBT will require SQEP competencies, international engagement and an evidence-based approach to identifying threats and adversary capabilities. Future designs will require the application of a DBT in the design stage.

- **Emergency Preparedness and Response (EP&R):** Approved, resourced, and rehearsed plans aligned with the safety response will need to be developed, which are vital to security. EP&R plans will need to cover the maritime facility, wherever it may be located, and satisfy the appropriate national regulators of their effectiveness and compliance.

- **Security Contingency Plans:** There will need to be a range of response and contingency plans related to theft or sabotage. These responses must consider the full range of credible threats and scenarios, be resourced and rehearsed, account for external agencies' intervention and support, and satisfy stakeholder's national regulators (in addition to compliance and alignment with maritime codes and obligations).

- **Creating Maritime Nuclear Security Culture:** Developing a nuclear security culture across the broad maritime stakeholder community will be an important part of successfully adopting nuclear as an alternate power. This will require appropriate organisations and individuals to receive education and training to develop specific competencies and general awareness necessary for secure operations. There will also be a need for close collaboration with key stakeholders from the maritime industry, nuclear regulators, and the established industry (through initiatives such as NEMO and the IAEA ATLAS initiative, as well as early engagement with SQEP expertise).

SECTION 5:
Operational considerations

5.1 Introduction to operational considerations

In addition to environmental and security considerations, NNRs verify that operational considerations are evaluated systematically and potential hazards or risks are managed according to acceptable practices. This section discusses specific considerations for establishing a maritime nuclear asset, the necessary support for operations, and preparation for end-of-life activities.

5.2 Personnel

Understanding the exact requirements for potential reactor technologies and applications will depend on the justifications and arguments in the safety case. The safe and successful deployment of maritime nuclear hinges on the quality and qualification of the operating personnel. This section provides an overview of personnel considerations, emphasising qualification, assurance, and some considerations for the next generation of maritime nuclear personnel. Ultimately, personnel competence is paramount for operational safety and public trust.

Qualification pathways should be founded on the *International Convention on Standards of Training, Certification and Watchkeeping for Seafarers* (STCW) and specialised for nuclear operations.

- **STCW Code:** The STCW Code is the required standard for international maritime certification. It is expected that maritime nuclear personnel will continue to be required to follow the STCW Code, as applicable
- **Maritime nuclear familiarisation:** A mandatory module (possibly integrated into STCW) is expected to be required, giving crew basic nuclear awareness, radiation safety, and maritime-specific emergency protocol requirements, establishing a baseline level of understanding for everyone onboard
- **Specialised nuclear operator certification:** Depending on the technology requirements and its application, rigorous training requirements will be established for nuclear operators. Certifications may include those for reactor operators, engineers, health physicists, and safety officers. The scope of these qualifications will extend beyond the STCW and potentially be benchmarked against civil nuclear standards adapted for the maritime context. Key components include, but are not limited to:
  - **Competency-based training:** Demonstratable skills, exams and oral boards
  - **Simulator training:** Integrated scenarios to demonstrate the required competency level achieved

Assurance and competency mechanisms must be in place for the quality of personnel appointments.

- **Training programme design:** Relevant training should be competency-based, scenario-driven, and periodically validated and include simulations of operations and responses in abnormal operations
- **Independent verification:** Independent third-party assurance of the maintenance of the required standards will provide validation, build trust, and enable impartiality

- **Continuous professional development:** Mandatory training through refresher courses, onboard drills, and knowledge sharing not only helps maintain expertise and prevent skill fade but also helps personnel adapt to new technology and regulations

- **Regulatory oversight:** A clear understanding of the roles and responsibilities of maritime and nuclear stakeholders and personnel will be key for effective personnel oversight

Crew operating levels should be optimised, but this does not imply operator-free systems. Depending on the technology, its operations, and regulations, automation and enhanced safety features might shift focus from continuous human control to a more strategic monitoring, diagnosis, and intervention role. This could lead to optimisations in crew sizes and training requirements. The nuclear and maritime regulators must approve approaches that differ from industry norms. Data justification and safety analyses will be needed to establish operator requirements. This will ultimately be driven by the functional safety requirements and the minimum personnel required to perform them reliably with the support of technology.

The operation of nuclear technology requires highly competent personnel. By prioritising robust qualifications and rigorous assurance, balanced against the requirements as determined by the licensing process for the specific technology, the maritime industry can responsibly manage nuclear power's potential while providing for the high levels of safety and public confidence.

5.3 Emergency response

Any emergency response arrangement must be proportional to the risk and scaled accordingly. Emergency response planning for assets in territorial, foreign national, and international waters must be addressed to facilitate safe and responsible operations. While some proposed nuclear technologies may promise enhanced safety and walk-away safe designs, the requirement for comprehensive emergency preparedness is absolute. This section outlines key considerations when establishing effective emergency response planning.

In the maritime context, emergency response plans must account for the following situations:

- **Deployment distance and extended response time:** Potential incidents may occur far from shore and require self-sufficient response efforts because offsite assistance will likely be longer than expected compared to land-based civilian nuclear use cases

- **Dynamic operating environment:** Sea state, weather, and asset motion will potentially impact response actions, evacuation and access with response arrangements considering and accounting for situations occurring during harsh or escalating marine environmental conditions

- **Specific hazards:** Nuclear material onboard requires a re-evaluation of risk and emergency scenarios must account for potential conflicts between conventional safety arrangements, such as layout, evacuation routes and firefighting systems, against radiological or specific hazards

- **International waters and jurisdictional complexities:** Planning must address coordination challenges across national boundaries and the international protocols yet to be determined

Phased emergency responses are recommended for complete situation assessment, appropriate response, and safe clean-up.

- **Prevention and preparedness:** Proactive prevention through a robust safety culture, rigorous maintenance, comprehensive training, and clear delineation of responsibilities can address issues before they require response, remediation, or repair

- **Detection and initial response:** Reliable radiation monitoring systems, alarm response protocols, and crew trained in initial response procedures are critical for early identification and quick mitigation of incidents

- **On-site emergency response:** The onboard crew must be aware of the defined incident management procedures, and responders must be aware of critical decision points when managing escalating incidents
- **External Emergency Response:** Defined communication protocols will be necessary for engaging shore-based or distant emergency response organisations for support, technical guidance, and site management
- **Post-Emergency and Recovery:** Environmental monitoring, decontamination, waste management, and incident investigation will be essential to pair with efficiencies gained from lessons learned following emergency incidents and recovery efforts, as necessary

Effective emergency planning will be integral to any responsible maritime nuclear operating framework outlined by international (IMO and IAEA) and national (maritime and nuclear regulators) organisations. Comprehensive processes and procedures will be required to manage risks, demonstrate a commitment to safety, safeguard personnel and the environment, and build confidence through public support.

5.4 Upstream and downstream services

Providing regulatory pathways and licensable technology is only part of the solution. For the maritime nuclear industry to be safe and economically viable, a robust supply chain and support ecosystem will be required. This section identifies several considerations when establishing the necessary services, which are important for operational readiness and long-term sustainability.

Upstream services should support the secure fuel and equipment supply for procurement and production.

Fuel supply and storage: Developing the required supply of nuclear fuel and scaling up to meet demand at fuelling/refuelling locations may be a considerable effort. Developing an upstream supply chain will likely require alignment with civil SMR operations for existing and proposed types of nuclear fuel. This should incorporate 3S by design and meet regulations for transporting and storing nuclear material.

Equipment supply chain: Safety case assessments will determine the grade and standard required for equipment design, testing and procurement, but it should be expected that nuclear-grade equipment will be required for certain aspects of design. This will require high-quality component manufacturing. The maritime industry provides standards through a Type Approval process for components, which could be adapted to meet the expectations of a maritime nuclear supply chain (refer to the LR Type Approval Programme Webpage for more information). Vendor qualification and cybersecurity in the supply chain can also support international engagement by aligning export control requirements for vendors[1].

Manufacturing facilities and integration in shipyards: The production, manufacture, handling, transport, and assembly of nuclear material may require licensed facilities and operators according to the nuclear regulator. The project team should carefully consider which stakeholder facilities may require additional certification, qualification, or license approvals to support procurement, manufacturing, assembly, and functional operational tests leading to operations.

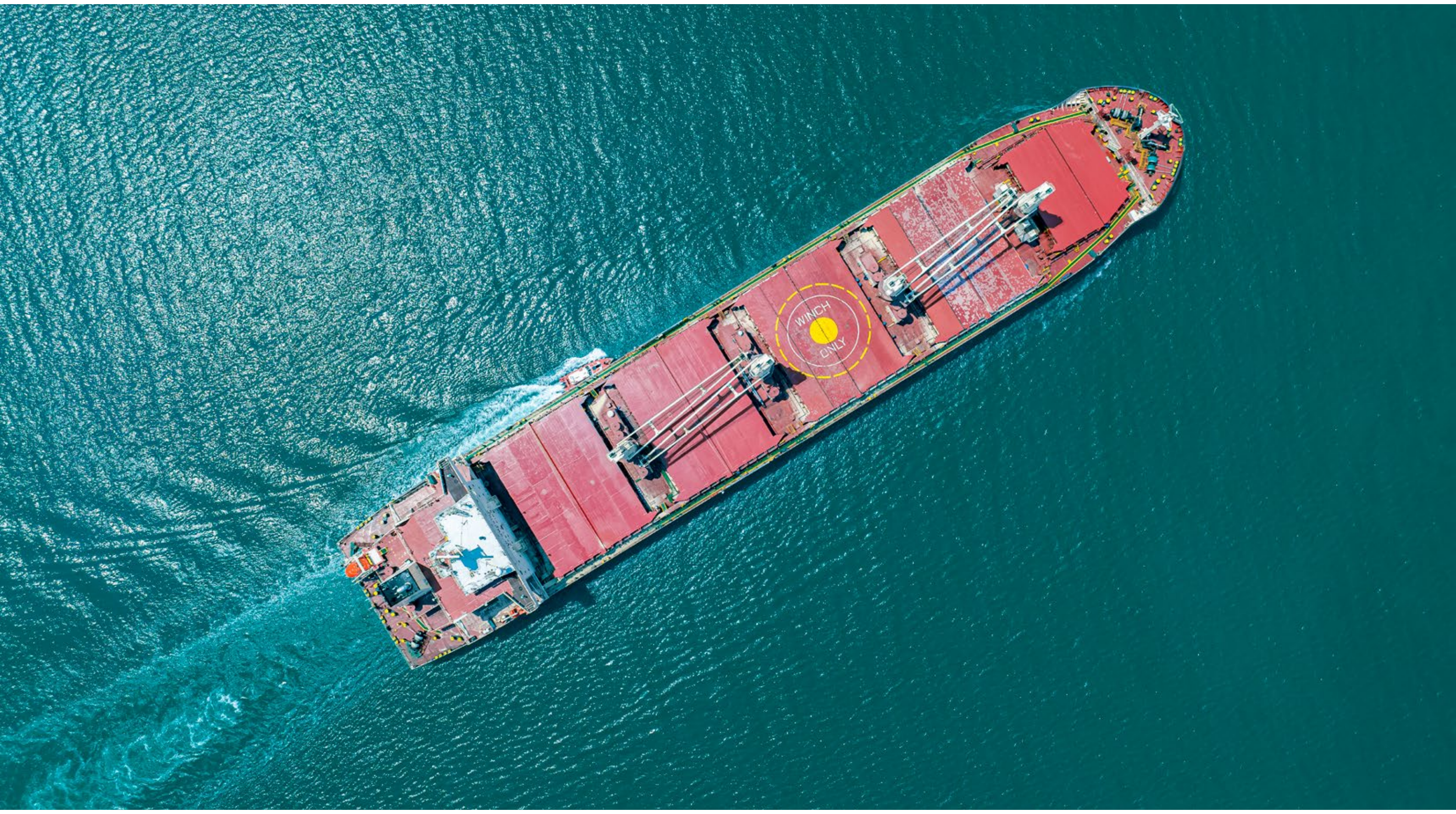
Downstream services include maintenance and waste management.

1 International traffic in arms (ITAR) and export controls are not discussed in the scope of this document. They would be addressed on a project-specific basis according to the countries involved.

Shipyards and maintenance: Maritime states may need to invest in strategically located, adapted and nuclear-licensed shipyards/dockyards, including any land-based facilities required to support maritime nuclear servicing and maintenance. How oversight and permissions will be managed for different operators to conduct maintenance on the nuclear elements remains to be determined. The opportunity exists to adapt existing infrastructure and integrate additional safety and security requirements (i.e. radiological protection, physical security) to support the development of the required skilled workforce.

- Shipyards and other land-based facilities will also need to be engaged in the end-of-life activities for reactor D&D and unit recycling, in association with the stakeholders involved with SNF and nuclear waste management.

Spent nuclear fuel/nuclear waste management: The transport, handling, and storage of SNF and nuclear waste have been ongoing for many decades. The process and standards are already in place, but the challenge is to scale the SNF and downstream nuclear industries to meet the potential demands of maritime nuclear applications. Some modifications will be required to align policies and processes with maritime safety and security requirements. Several major nuclear nations are planning or constructing deep geological repositories to store SNF and defined grades of nuclear waste material. Special consideration should be given to the availability of SNF and nuclear waste management services throughout the asset's lifetime.



5.5 Quality assurance and verification services

A robust and comprehensive Quality Assurance (QA) framework is paramount for implementing safe and reliable operation of maritime nuclear assets. This framework should encompass all stages of the project lifecycle, from design and construction to operation, maintenance, and eventual decommissioning. It provides a systematic approach to managing quality and verifying that activities are performed to the required standards and specifications. Essential aspects of QA include:

Documentation and standards: A well-defined system of documentation is fundamental to a robust QA framework. This includes policies, procedures, work instructions, and records that clearly outline the requirements and processes for activities. These should align with relevant international standards (e.g., ISO 9001), NNR requirements, and maritime industry recommended practices. Specific attention should be paid to the traceability of nuclear-grade components and materials; this is consistent with the maritime industry's use of Type Approval and supply chain assurance where appropriate.

Inspection and testing: Inspection and testing regimes must be implemented at all stages to verify that materials, components, and systems meet the specified requirements. This includes non-destructive testing, pressure testing, functional testing, and other relevant verification methods. Clear acceptance criteria and procedures for handling non-conformances should be established.

Auditing and review: Regular internal and external audits should be conducted to assess the QA framework and identify areas for improvement. These audits should verify compliance with established procedures and regulatory requirements. Management reviews should be conducted periodically to assess the overall performance of the QA system and ensure its effectiveness.

Non-conformance management: A systematic process for identifying, documenting, evaluating, and resolving non-conformances is essential. This process should include root cause analysis, corrective and preventative actions, and verification of the effectiveness of non-conformance management assessments.

Training and competence: Adequately trained and competent personnel involved in maritime nuclear projects are a critical aspect of QA. Training programmes should cover relevant quality standards, procedures, and the importance of adhering to the QA framework. Accurate records of personnel qualifications and training should be maintained.

Continuous improvement: The QA framework is a living system that is regularly reviewed and updated to reflect lessons learned, changes in regulations, and advancements in technology. A culture of continuous improvement should be fostered throughout the organisation to ensure that quality remains a top priority.

Regulatory oversight: Regulatory stakeholders play a crucial role in overseeing the implementation and effectiveness of the QA framework. Regular inspections and assessments by these bodies will provide independent assurance that the required quality standards are being met. The QA framework should facilitate transparent and effective communication with regulatory authorities.

SECTION 6:

Insurance and reinsurance considerations

6.1 Introduction to insurance and reinsurance considerations

In addition to financial capital and operational budgets, insurance must be acquired for all activities of the product's lifetime to guarantee compensatory measures for specific losses, damages, illness, or casualty during project development and operations. Existing insurance frameworks for nuclear and shipping activities are mutually exclusive; therefore, it may appear difficult to understand the strategy to acquire appropriate insurance for each unique maritime nuclear application. Outside of government or state-sponsored maritime nuclear applications, such as Russian nuclear-powered icebreakers, where insurance is provided by a state-controlled company, the liabilities arising from nuclear technologies in shipping have been excluded from global liability and compensation regimes currently in force. Similarly, for land-based power plants, the liabilities related to floating site conditions or transporting a fuelled or operating reactor have been excluded from nuclear liability and compensation regimes.

6.2 The role of classification societies in insurance

The role of the classification society is important for insurance. Classification of ships or offshore units and certification of technologies provides assistance to the insurer's understanding of risk. To obtain confidence in a new technology's risk profile and safety, regulators and insurers rely on third-party 'assurance' frameworks that provide independent review and technical certifications of processes, equipment, systems, structures, or products, often serving multiple regulators.

Marine classification services draw their origins from merchants and underwriters concerned with the safety and quality of merchant ships. Now, classification societies provide independent validation and verification services to owners and their insurers to confirm that ships and offshore units are fit and maintained for service to protect people, environment, and assets from the potential hazards of maritime trades. Frameworks were developed to establish an acceptable level of risk, and suitable technical codes and standards were developed over time so third-party assurers could verify compliance, allowing the marine asset to be eligible for insurance. When no technical codes or standards exist, insurance companies and firms use quantitative risk assessments and evaluate risk management strategies used before issuing appropriate insurance policies.

In common with all IG P&I Group Clubs, NorthStandard's P&I Rules for 2025/2026 state that it is a condition of every ship that it "must be and remain fully classed with a classification society approved by the managers or, provided agreed by the managers, remain fully approved by the government authority responsible for ship certification for the trade in question (hereafter 'society/authority')". It is then incumbent upon the member to inform NorthStandard about any recommendations made by the classification society and comply with recommendations made by the classification society within any specified time period.

6.3 Insurance of non-marine nuclear reactors

Land-based nuclear reactors, as well as nuclear transportation liability, are insured through nuclear insurance pools. The insurance is based on a very low frequency, very high severity risk accumulation. An example of such an insurer is Nuclear Risk Insurers (NRI) and more information on nuclear pools and how they work can be accessed on their website.

6.4 P&I Insurance

The main purpose of the IG P&I Group is to provide the very high levels of cover and financial security necessary to meet the third-party liabilities that arise following a marine accident. IG P&I Group Clubs share claims in excess of US$10 million (May 2025), with claims up to US$3.1 billion covered through a combination of a pooling arrangement and group reinsurance.

However, the insurance of nuclear liabilities caused by ionising radiation or radioactivity from any nuclear fuel or nuclear waste is excluded from P&I Insurance (see for example P&I Rule 4.4 under Excluded Risks [12]). Liability from such nuclear risk is also typically excluded from other marine insurances such as hull and machinery insurance and war risks insurance.

6.5 Liability framework for civil nuclear ships or offshore units

For land-based nuclear, there are the global liability and compensation regimes of the Vienna and Paris Conventions. However, these would not apply in the context of nuclear reactors operating in the commercial maritime environment.

For maritime incidents there is a suite of global liability and compensation regimes that provide for a predictable framework for victims of a marine accident, however, nuclear is either not part of these, or expressly excluded. In 1962, the Convention on the Liability of Operators of Nuclear Ships (the Brussels Convention) was adopted to try and fill the gap for nuclear in commercial shipping, however, it was never ratified and, therefore, is not in force. Accordingly, currently there is no global liability and compensation regime for nuclear in civil maritime and so it is a new technology and liability without global limitation of liability. Such clear frameworks and rights of limitation help to ensure insurable limits of liability for P&I Clubs and their reinsurers.

6.6 Liability for new technology

Insurers and reinsurers will need to understand and price the risk of this new nuclear technology for maritime. Reinsurers may look to the IG P&I Group for acceptance of the technology for maritime. This will require substantial dialogue between nuclear experts, insurers, reinsurers and treaty reinsurers.

Understanding the difference between existing pressurised water reactor technology and the new Advanced SMR/Generation IV technologies being developed is critical. The Advanced SMR or Generation IV technologies being developed for commercial shipping may allow for a much smaller Emergency Planning Zone (EPZ), which will be within the confines of the ship, and feature inherent passive safety systems so that they are “walk away safe.” Because nuclear reactors for commercial maritime will need to move into ports, and inland waterways etc., reduction of the EPZ to an acceptable size for insurers will be vital for commercial insurability.

6.7 Insurance and reinsurance conclusion

Obtaining appropriate insurance for novel applications of nuclear technology in commercial maritime use cases is not legally forbidden, but the existing regulatory framework is not adequately developed. Furthermore, it will require significant time and effort to understand and evaluate the risks (technical, security, environmental, financial, operational, market, regulatory) and document risk management strategies, including how an incident response would be executed, to the satisfaction of insurance and reinsurance stakeholders as part of the decision as to whether insurance coverage is available. A predictable limitation on liability will be vital and so, while there is an absence of a global liability and compensation regime, it may be that an interim marine insurance market will develop based on low aggregate limits.

SECTION 7:
Finance and financial planning

7.1 Information on finance and financial planning

Project financing and economics are not discussed in depth in this document, but it is an essential underlying aspect. Project teams should have a strong understanding of economic risks and management strategies for their proposed use case. Confirming that the product is technically feasible to build, insure, operate, and decommission will be necessary to pursue financial backing.

Acquiring appropriate project financing can be a major effort, especially when navigating the complex stakeholder matrix of the maritime industries. Because nuclear projects are long-lived, the project team should consider appropriate options to attract and retain investments and continuously manage financial risks throughout the unit's lifetime.

Although not necessarily directly related, the regulatory and financial frameworks for a large first-of-a-kind project can be mutually supportive. For example, the confidence in regulatory oversight to review and manage technical project risk can, in turn, encourage public and private funding opportunities, effectively managing certain economic risks. To achieve the vision of a nth-of-a-kind reactor potentially suitable for many maritime applications, the financial planning should target multiple unit production, economies of scale, and lessons learned through repeatable manufacturing processes.

Like the regulatory efforts, the project team should identify the financial stakeholders that may need to be involved throughout the product's lifetime early in the effort, including financial assurances for upstream infrastructure, personnel pipeline and downstream D&D activities. Financial opportunities should be pursued where incentives exist for decarbonisation and energy security initiatives. In the shipping industry, these opportunities include the Poseidon Principles, the Sea Cargo Charter, and the Zero Emission Maritime Buyers Alliance (ZEMBA), for example. National or regional initiatives may more directly support aspects of commercial maritime nuclear projects. Where possible, project teams should investigate suitable finance opportunities, including corporate financing, sustainable bonds, project financing through special purpose vehicles (SPVs), capital through export credit agencies (ECAs), joint ventures, carbon trade schemes, and possible funds supporting infrastructure and resources for developing economies [12].

Other project strategies to manage financial risks include assembling diverse technical risk assessment teams for appropriate design strategies or qualifying technology and supply chain maturity during product development.

Chapter 4:

Adoption strategies roadmap

SECTION 1:

Introduction

1.1 General

This section is a guide for stakeholders to develop, initiate and execute a successful project to enable nuclear energy for maritime. This generic roadmap is intended to be applied to any region or maritime application (ships or offshore units) but remains flexible enough to accommodate nuanced details of nuclear and maritime industrial design and global regulatory approaches.

1.2 Before starting: develop and tailor your plan

Based on the strategies presented here, the first step towards project development is to engage the appropriate stakeholders to help tailor the approach according to regions, jurisdictions, and activities unique to every project. The plan should identify specific codes, regulations, and policies, and equip the necessary stakeholders with tactics to accomplish every step of the roadmap. Some steps are initiated early in the project and continue throughout the unit's life.

Project teams should consider existing strategies to establish and execute plans. These early planning activities typically involve identifying the scope of the project, the stakeholders involved, the requirements for the stakeholders, the timeline, and the process to comply with the requirements. Structured project planning tools help to provide clarity, transparency, and accountability. For example, the project team may use a Permitting, Licensing, Authorisation, Notification and Compliance (PLANC) management register tool.

1.3 Taking action in the near term

It may prove beneficial for 'fast followers' to wait for technology to naturally develop or allow first adopters to take the risks of implementing new technologies and absorbing the higher costs of technology demonstration, especially for technologies that could be easily retrofitted onboard without significant changes or impacts to overall operations or safety. However, due to the security and regulatory complexities of nuclear technologies, engaging with technology and regulatory development as a first mover rather than a fast follower is recommended for the following reasons.

Technology Development: Initial action can showcase industry demand and the potential market for new technologies early in their development, allowing for opportunities to tailor technology to meet the criteria and constraints of potentially unique applications. First movers should pursue early engagement from many potential end users, such that the developed technology and associated regulations avoid becoming too specific to be suitable for every use case.

Regulatory Change: Especially when technology development can progress faster than regulatory frameworks, early engagement is necessary to drive regulatory change, establish a clear licensing pathway, support the development of any necessary engineering codes and standards, and encourage regulatory harmonisation as much as possible across multiple-use regions.

Supply Chain Development: First movers have the opportunity to build the national or regional supply chains around their projects. They secure access to key suppliers and help develop the workforce with the unique skills required for nuclear construction and operation. Fast followers may find the supply chain is already at capacity and the skills have been secured by their competitors.

Social License: Public acceptance is a major factor for any nuclear project. First movers lead the public conversation, build trust with communities and stakeholders, and are responsible to establish a positive narrative that affects the entire industry. This "social licence" is an invaluable asset that may be more difficult for a fast follower to earn.

Strategic Partnerships: Early adopters often form strategic partnerships with technology developers, research institutions, and governments. These partnerships can lead to favourable terms, shared IP, and long-term collaborations that are not available to those who enter the market later.

LR can provide advisory and administrative services to project teams pursuing joint industry projects, collaborative research, demonstration and testing efforts, or pilot projects between stakeholders before initiating a large-scale project.

1.4 Pre-licensing, technology readiness, and regulatory assessment

Before starting on the project progression and development path, some first steps must be taken in preparation. This may include pre-licensing, engineering development, technology demonstration, and regulatory framework clarification activities.

NNRs define pre-licensing as any activity to engage regulators before a full license application is submitted. These activities are intended to benefit both the licensee and licenser with a shared technical understanding of new or novel aspects of the license, typical of land-based nuclear power plants where the site or some aspect of the design is treated as 'bespoke.' For project teams defining operations in a marine environment, pre-licensing will be critical to prepare the nuclear regulators, both to develop technical acumen and to prepare designated resources. Project teams should consider what pre-licensing activities are available to engage NNRs as early as possible. Regulatory engagement, including pre-licensing and licensing activities, should start before full project initiation and continue throughout the project's lifetime, including the operation and decommissioning of the licensed product.

Developing new technologies or deploying in new operating environments requires the full force of engineering teams and design cycles. Technology development should follow a systematic process for demonstrating maturity in its expected operating environment. This often requires materials and parts testing, which may require specialised facilities, institutes, and personnel. Resources and costs during the design and demonstration stages may be significant. Still, committing resources during upfront planning and engineering design can be effective to prevent costly changes later. Careful consideration should be given during technology development, testing, and demonstration phases to a methodical approach in upfront resource dedication, necessary stakeholder involvement, and targeted milestones for technology maturity before major steps are made along the roadmap as presented. Refer to the LR *Guidance Notes for Certification through Technology Qualification*, which is a process to facilitate the assessment and certification of a novel technology or innovative elements within mature technologies.

Technology can develop faster than regulations, but it cannot be effectively deployed without the appropriate regulatory frameworks and oversight dedicated to safe implementation with the public interest in mind. Technology must be developed with regulations in mind, including codes and standards for materials and equipment design and manufacturing, personnel certification, security and non-proliferation policies or regulations, and other applicable laws and regulations according to the intended area of operation. Project teams should develop a preliminary regulatory assessment before initiating major project steps commensurate with the technology maturity at that stage. A single regulation, code, engineering standard, or law could present obstacles that complicate project development and plan progression. A strong understanding of applicable regulations, codes, and standards is necessary for project planning and managing risks associated with design changes later.

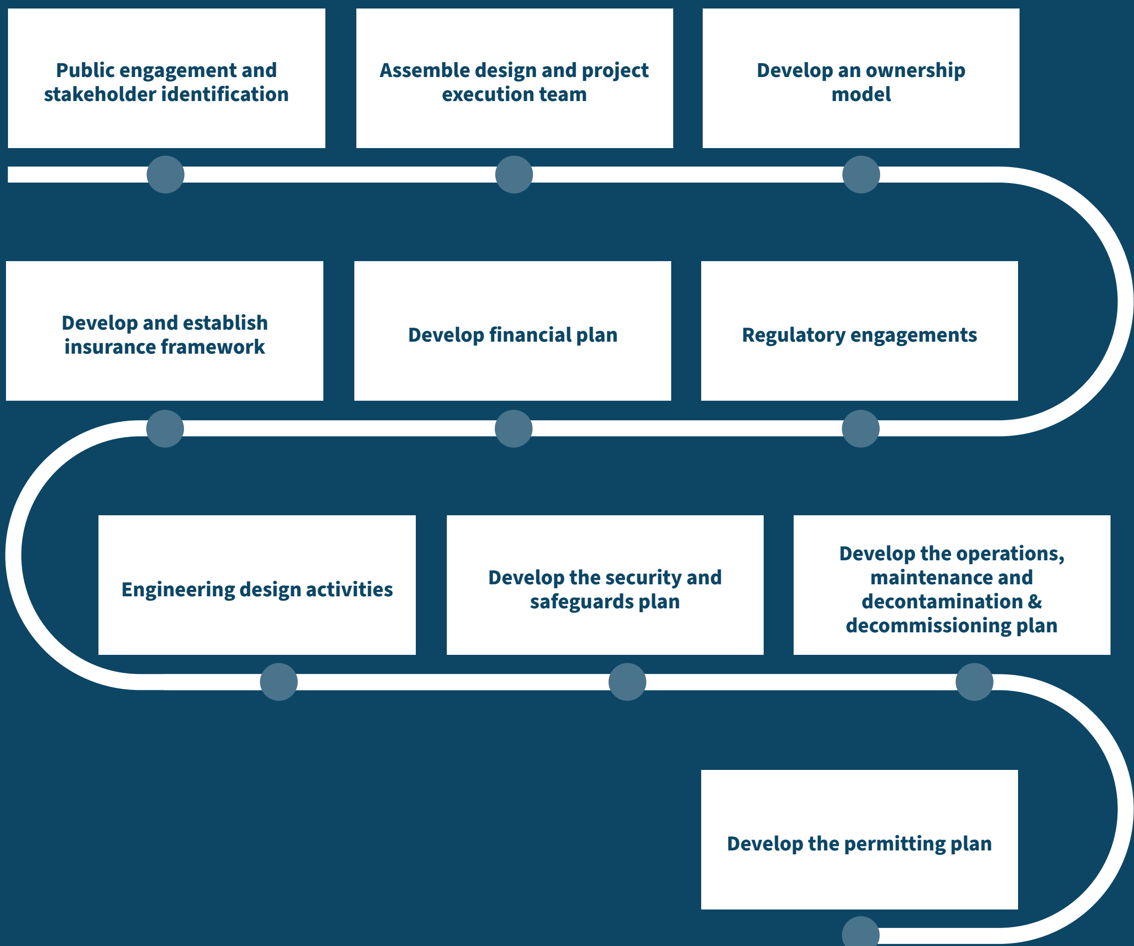
If not already done, the project team should systematically consider stakeholders and engage them during pre-licensing and technology demonstration activities for transparency, partnership, teambuilding, relationships, and the growth of effective teams across functional platforms.

SECTION 2:
The roadmap

2.1 General

This section is intended to support project teams in comprehensive planning and successful project achievement in the first-of-a-kind nuclear technology for maritime, from conception to deployment. However, by the nature of maritime applications functioning at scale, these projects will likely develop a few specific nuclear technologies that can be deployed quickly and suit multiple use cases. This will require a broader perspective on project execution with a focus on multiple unit deployment and the targeted intention for process improvement through iterations of these presented steps and lessons learned.

The presented order of the roadmap may be pursued in sequence or simultaneously unless noted or recommended otherwise. Some steps may require iteration or repetition as the design matures.



2.2 Public engagement and stakeholder identification

Public perceptions impact every aspect of project development, including market demand, risk perception, policy and regulation development, and available talent pipelines. Even if not considered part of the public, project stakeholders also contribute to public perception. Business cases for nuclear projects should include aspects of public impact, including project stakeholders and end-users. Society can promote or oppose the development of new technology, so understanding public perspectives at an early stage is critical. This includes communities, industries, companies, or markets that may be involved or affected by the proposed solution.

When proposing nuclear projects, a clear public engagement plan should be developed. This could include public information campaigns and policies related to consent-based decisions. When successful, public engagement and stakeholder engagement campaigns that offer visibility into project intentions, benefits, risks, and status can build trust among stakeholders and accelerate progress.

When developing a public engagement plan, the project team should consider specific risks that may arise from certain groups, and actions or methods to manage those risks. Look for industry guidance on how to engage the public and develop strong support from stakeholder groups, such as the IAEA 2021 *Guide on Stakeholder Engagement in Nuclear Programmes* (IAEA Nuclear Energy Series No. NG-G-5.1) [13], or examples of public engagement campaigns and strategies in similar industries or regions.

The project team should address these questions related to public engagement and stakeholder identification:

- What is the general perception of nuclear technology (or the specific proposed nuclear technology) in the region of intended operation, transportation, manufacture, procurement, or D&D?
- In the regions of intended operation, transportation, manufacture, procurement, or D&D, what are the demographics, population centres and densities, historical experience with nuclear technology, and public policy or politics related to nuclear? What are the unemployment rates in those regions, or historical industries that employ the regional populations?
- What are the most plausible risks to business or project development related to (regional or international) public opposition?

2.3 Assemble design and project execution team

Decisions regarding assembling project team members and how teams function can significantly impact the success of large projects. This is partially an outcome of project stakeholder identification, with a specific focus on developing an effective, dynamic, and motivated group of individuals for successful project execution. Project teams include parties involved from the start of planning activities to the end of an asset's lifetime at D&D. Refer to relevant resources for project team development, for example, the IAEA Nuclear Energy Series No. NG-T-1.6 *Management of Nuclear Power Plant Projects* [14], or examples of successful team development and performance from related or similar tasks.

The project management should address these questions related to team assembly and project planning:

- Is the project team aligned on terms and definitions, especially for international and diverse project teams?
- Does the project team have sufficient expertise, experience, and knowledge to accomplish their tasks effectively at every project development and deployment stage?
- What regional, cultural, or geopolitical considerations must be addressed when developing project teams?
- What specific risks do team members pose to project execution, and what risk management strategies should be used?

2.4 Develop an ownership model

Consider early in the project how the product will be operated, what the function or output is, where it is operating, and what are the nature of business agreements or existing arrangements. This step is closely related to insurance, such that the assignment of liability to responsible parties must be established to provide assurances of safety, due diligence, and appropriate reparation in the event of accidents. New arrangements may be required, where maritime industry stakeholders are not known to accept liabilities related to operating nuclear power plants, and nuclear power plant operators do not typically operate on maritime units outside of nuclear navies.

Frameworks for ownership and operation of nuclear power plant(s) for maritime should be carefully considered, as these arrangements can affect the technical and regulatory requirements of the product. Consider how land-based nuclear power plants are owned and operated, and how the sale of energy is achieved through established partnerships or business contracts, for example, power purchase agreements (PPAs). Refer also to the stakeholders involved in the operation of ships or offshore units, for example, the relationships between ship owners, operators or management companies, ship brokers, and charterers.

Ownership arrangements can become more complex for assets that transit international borders, while nuclear material must remain under the responsibility of appropriate authorities according to the NPT. Consider the most effective ownership arrangement for the project's success at full scale and long-term operations.

The project team should address these questions related to ownership models:

- Are ownership arrangements in place such that designated responsibilities are established at every point of the product's lifetime, including disposal and waste management?
- Are the risks of stakeholders involved in the ownership model managed at every point of the product's lifetime?
- What requirements related to the responsible handling and accounting of nuclear material are applicable at every point in the product's lifetime, and how can the ownership model be designed to provide continuous oversight of nuclear material?

2.5 Develop financial plan

Establishing or enabling financial support to novel nuclear applications for maritime is often seen as one of the most significant challenges for project success and can be achieved in many ways. Existing methodologies for financing nuclear and maritime assets should be considered, specifically for the unique or novel use cases. Financial planning is closely related to public perception, stakeholder identification, and ownership arrangements. Funding may be available from a combination of public and private funds; however, the project team must not only consider the capital and operational resources needed (including those needed for D&D), but also the financial commitments required for insurance, which is discussed in the next subsection.

Project costs can be estimated and assessed upfront in design activities, but are borne by the responsible parties as agreed in the project execution and ownership models. Consideration should be given to the financial opportunities and challenges associated with operational trade-offs. For widespread adoption, projects must demonstrate confidence in financial planning and economic feasibility.

The project team should address these questions related to financing and developing a financial plan:

- What financial responsibilities do stakeholders have over the product's lifetime?
- What are the differences in cost between nuclear technology and alternatives?
- What is the capital expense (CAPEX) of installing nuclear for your maritime application? Who pays the CAPEX?
- What will the operational expenses (OPEX) be over the course of the product's lifetime? Who pays or is responsible for the OPEX?
- What financial assurances are in place or established to pay for D&D activities?

2.6 Develop and establish insurance framework

Implementing suitable and appropriate insurance frameworks for all applicable stakeholders is essential to any operating plan, especially those that pose risks or are perceived to pose risks.

The project team should address these questions related to insurance and liability planning and engage with insurers as early as possible to discuss the risks to be covered:

- What specific risks require insurance coverage that are not already covered by existing insurance?
- Are there other insurances specific to particular operating regions or jurisdictions?
- Identify the relevant stakeholders to be involved to establish appropriate insurance coverage.
- Are there any particular periods or lifecycle phases requiring specific risks to be covered, which are not covered elsewhere?

2.7 Engineering design activities

Technical design efforts may not need to start in earnest until some essential questions in the prior stages can be addressed. However, since technology development can occur faster than regulatory or policy development, starting this task later may not be a problem for some teams. Often, the earnest effort to initiate detailed engineering design activities occurs during the second or third round of design, where each iteration results in a refinement of design specifications to meet more specific criteria and constraints.

Engineering design will not be able to progress far without an initial understanding of the regulatory landscape of applicable regulations, codes and standards according to the product's function and operating location(s). However, depending on the engineering design, the same could be said for the regulatory assessment. Technical and regulatory assessments are expected to occur iteratively.

Appropriate teams should be assembled to carry out design activities. An engineering design plan should be developed that sets clear goals or objectives for the design team and sets working expectations for achieving them. Numerous guidance documents are available from the maritime and nuclear industries and regulatory bodies to assist in engineering design. Many of these include the documented process related to goal-based regulations, incorporating risk assessments into design activities, and incorporating essential aspects of the envisioned product into the design from an early stage. This can include designing for economy, 3S by design, ergonomic design, and designing for reliability, for example.

Engineering design activities extend beyond the product's physical design, but include continuous improvement processes, operating and maintenance plans and activities, shipyard and infrastructure design, and other activities related to the end-of-life D&D.

Engineering design involves developing assurance activities for equipment and systems, where inspections and test plans are produced that define the responsible oversight authority of various functions or systems, as well as define training and certification requirements for personnel. The LR RBC Step 5 covers construction and in-service assessments, which must be developed over the course of the other design activities to uniformly generate assurance plans for the project.

The project team should address these questions related to engineering design activities and technical development:

- What are the design criteria and constraints for every aspect of procurement, manufacturing, testing, operations, maintenance, emergency, and D&D phases of the product's lifetime?
- What regulations, policies, laws, or other systems are in place that may affect the engineering design approach and process?
- What are the operating conditions, and what accident or emergency conditions can be expected over the product's lifetime?
- What risks or safety concerns can be managed by engineering design solutions, and how do these decisions affect the overall engineering approach?
- For what equipment, components, systems, functions, material, or applications are engineering design codes and standards missing, not applicable, or unavailable?
- What process for goal-based standards is suitable for the applicable regulators and stakeholders?
- What engineering design stakeholders must be involved during the design activities over the product's lifetime?

2.8 Develop the security and safeguards plan

Security and safeguards arrangements should be started from project kick-off due to the importance of nuclear material protection and the roles of stakeholders involved. The applicable NNRs are to be consulted for the management and handling of nuclear material and information, especially when it is to be transported or considered mobile across multiple jurisdictions.

Project teams are encouraged to engage with security and safeguards stakeholders simultaneously with early engineering design and regulatory requirements. Arrangements for security and safeguards should be designed into the product, as they can impose essential design criteria or constraints that may cause roadblocks or major redesign efforts later. This approach will deliver a more cost-effective and proportionate solution.

The project team should address these questions related to security and safeguards, and developing a security plan as presented in this order:

- What stakeholders must be involved, such as governments, nuclear regulatory agencies, maritime authorities, private operators, or others, to resolve issues of overlapping responsibilities?
- What policy or guidance exists or needs to be developed that covers nuclear security and safeguards for maritime applications?
- What DBTs are identified for the product, or what new/unique DBTs must be investigated?
- What physical design arrangements must be made for security? What engineering solutions can be implemented to reduce security or proliferation risks?
- What are the costs of implementing security and safeguards for maritime nuclear use cases?
- What investments may be needed for advanced surveillance, detection and defeat technologies that are suitable for maritime applications?
- What are the security crew and personnel requirements, including training, certification, drills, and clearances?

2.9 Develop the operations, maintenance and decontamination & decommissioning plan

An operation, maintenance and D&D plan, including international arrangements for emergency response, should be developed simultaneously with engineering, regulatory, and security plans. These plans must consider user interfaces, performance expectations, and costs related to availability, repair, downtime, and testing/recertification, for example. Considerations should be given during design to promote operability, maintainability (such as equipment accessibility), and D&D activities.

Project teams should consider if owners and operators require certain product performance, such as reliability/availability, and accommodate solutions in the design and operations plan to meet those requirements. Maintenance and repair plans should consider potential isolated operations and remoteness from supply chains, including spare parts storage and procurement processes, placing orders, and quality assurance programmes for spare parts or maintenance/service personnel. Impact assessments should evaluate the consequences of shutdowns, delays, repairs, and testing on overall safety, security, operational functionality, and associated costs.

Operations, maintenance and D&D activities may be inherently related to onshore facility support, especially when handling nuclear or radioactive materials. To evaluate availability, early consideration should be given to the types of facilities and personnel required, as well as the appropriate quality assurances, certifications or licenses needed to carry out the services.

The project team should address these questions related to creating an operations, maintenance, and D&D plan:

- What stakeholders and personnel will be involved in operations, maintenance and D&D, according to the areas of operation?
- What infrastructure gaps may exist between currently available and necessary functions to support the proposed operations, maintenance and D&D activities?
- What design features should be incorporated to support operations, maintenance and D&D activities?
- What supply chain gaps may exist between currently available services or provisions and those necessary to support the operations, maintenance and D&D activities?

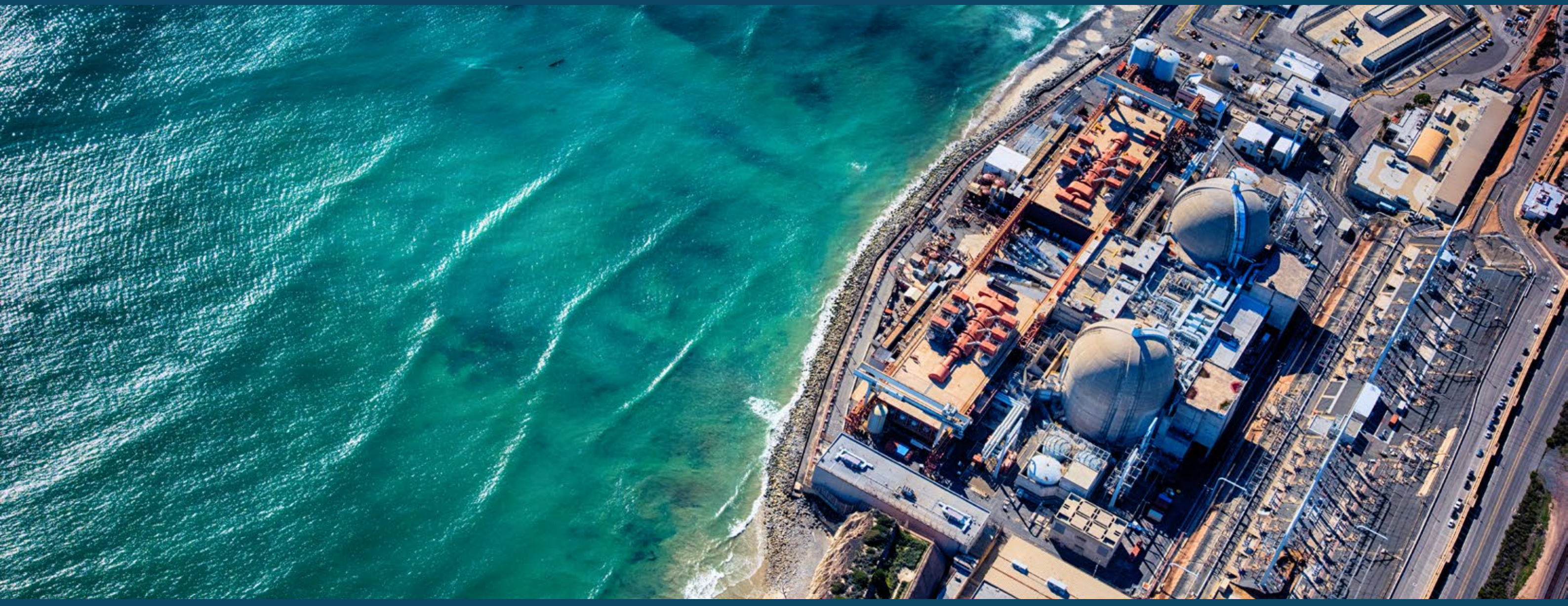
2.10 Develop the permitting plan

Permits may pose a separate but related challenge from regulatory frameworks. Permits are considered more localised than regulatory frameworks, where nuclear licenses from regulators may only be provided once local permits have been received for activities in specific regions or communities. The project team should be aware of local communities, jurisdictions, and authorities that may require permits to use local resources. Permits are often related to the fair use of natural resources, such as land, water, and air, as well as any potential impacts that extend beyond the point of occurrence. For example, permits may relate to the land where a nuclear fuel handling facility is built and operated, a river from which a facility draws and discharges liquids into, and the atmosphere into which thermal or gaseous pollutants are emitted.

By nature, permitting activities engage the local communities for social license to operate. Project teams should take the opportunity when applying for permits to engage the communities, offer educational activities, and allow for flexibility or modifications in design, construction, fabrication, operations, maintenance and decommissioning, based on input from communities and permitting frameworks. Project teams are likely required to submit information regarding their purpose, environmental impacts, risk management plans, and emergency response in the case of incidents. For this reason, public engagement for social license to operate should start early and be continuously pursued, but a tangible goal of public engagement may be the receipt of permits to build, operate, transport, store, or disassemble.

The project team should address these questions related to permit planning and procurement:

- What natural resources do your procurement, construction, fabrication, operations, or decommissioning activities involve? In using these resources, do you require a related permit, and if so, from whom?
- What are the likely jurisdictions for permits for points of trade, build, docking, maintenance and disposal?
- What is the timeline for applying for and receiving the permits? What are the costs of obtaining and maintaining the permits?
- What engineering design solutions can be accommodated to simplify the permitting process?



2.11 Regulatory engagements

Regulatory engagement should begin as early in the process as possible. Project teams should investigate methods and strategies for approaching and engaging regulators when proposing nuclear technology for maritime use cases. Nuclear regulatory agencies may lack the experience or resources to develop internal experience with nuclear operations in marine environments. During pre-licensing, information should be provided frequently to regulators regarding the project plan, progress, and technical developments, to inform them of the license application status and when they can expect industry engagements.

Project teams should be prepared to approach nuclear regulators with a goal-based framework when novel technology or environmental operating conditions are proposed. Goals and functional requirements should be presented assuming that the nuclear regulator does not have experience reviewing the proposed technology that is intended to operate within commercial maritime environments. Complete proposals must be documented with appropriate reasoning or explanation and provided with associated plans, assessments, results and follow-up action items necessary to support overall license applications.

The project team should address these questions related to regulatory engagement:

- What nuclear regulatory authorities must be involved at every phase of the product's lifetime, including upstream and downstream activities?
- What maritime regulatory authorities must be involved at every phase of the product's lifetime, including upstream and downstream activities?
- What is the typical engagement period during pre-licensing and licensing activities?
- What regulatory activities are carried out after license(s) are issued (e.g., inspections, safeguards oversight, etc.)?
- Which project stakeholder is responsible for costs related to regulatory engagement and licensing?

Chapter 5:

Conclusion

SECTION 1

1.1 Conclusion

Nuclear energy presents a compelling opportunity for the maritime sector, offering a route to meet future energy demands while achieving sustainability and energy security targets. Nonetheless, considerable challenges exist before widespread implementation. Foremost, there is a lack of a unified international regulatory framework that effectively integrates the distinct maritime and nuclear industries. As of 2025, clear guidance on commercial applications from maritime administrations and NNRs is still expected.

Beyond regulation, integrating advanced reactor designs into marine settings requires stakeholder collaboration, including comprehensive integrated safety cases that address the unique operational risks. Ensuring robust nuclear security and implementing effective safeguards in the design phase are paramount. Further challenges include managing SNF and waste, securing adequate insurance amidst regulatory uncertainty, implementing training requirements for specialised personnel, addressing public perception, and establishing the necessary support infrastructure, including supply chains and maintenance facilities.

Successfully navigating these challenges requires early, collaborative engagement between stakeholders. Where prescriptive regulations are absent, a goal-based approach demonstrating equivalency will be necessary. Ultimately, fostering innovation, particularly in 3S and ownership/operational models, will be essential to unlock the potential of nuclear power suitable for the maritime environment.

1.2 Next Steps

Tailor guidance for specific projects. Adapt the approach presented within this document to the unique requirements of individual maritime nuclear projects. This requires careful delineation of the specific roles, responsibilities, and scope of authority between the relevant regulatory authorities and the licensee for each case.

Foster feedback and refinement. Actively encourage dialogue and solicit feedback from stakeholders engaged in this subject. Share feedback on this document with LR for the ongoing refinement and improvement of this product, providing for its practical relevance and effectiveness.

Support LR's Rules and assurance framework development. Lend support to LR's ongoing initiative to establish relevant Rules and an integration framework. The objective is to integrate maritime classification rules and nuclear licensing requirements into a unified, holistic process specifically designed to enable the classification of maritime nuclear assets and bridge the regulatory divide.

Engage with LR training initiatives. Explore and participate in potential training programmes offered by LR. Key areas for knowledge enhancement include the specific challenges and solutions for the integration of industrial equipment and systems, the fundamental principles of nuclear energy, safety, and security, and other pertinent topics relevant to the safe implementation of nuclear technology at sea.

SECTION 2:

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- *Guide on Stakeholder Engagement in Nuclear Programmes (IAEA Nuclear Energy Series No. NG-G-5.1)*
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- *International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code)*
- *International Maritime Dangerous Goods Code (IMDG Code)*
- *International Regulations for Preventing Collisions at Sea (COLREGS)*
- *Code for Recognised Organisations (RO Code)*

Further Reading

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- ISO 19901-1 *Metocean design and operating considerations*
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