MIT Maritime
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# NUCLEAR SHIP SAFETY HANDBOOK

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*In Appreciation of*

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Their contributions have enhanced the quality and accuracy of this important body of work, ensuring it meets the highest standards focused on the key safety considerations for further developing nuclear propulsion in the maritime industry.

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# Contents

# Abstract

At present, there exists no clear, unified public document in the incorporation of design safety for nuclear civilian ships. Historically, there has been developed research into this area due to political development in the “Atoms for Peace” era. However, as of recent, the only development has been through standards institutions related to Floating Nuclear Power Plants (commonly known as FLOPPS) and by the Russian Federation with their nuclear icebreaker development. This paper uses this research data and standards and combines it with the operational experiences during civilian maritime nuclear operations to provide unique insights into potential issues and resolutions in the design efficacy of maritime nuclear operations. The goal, therefore, is to provide a strong basis for initial safety on key areas that require nuclear and maritime regulatory research and development in the coming years to prepare for nuclear propulsion in the maritime industry.

The paper is isolated into multiple chapters in the areas that involve overlapping nuclear/maritime safety design decisions that will be encountered by engineers. Chapter 1 establishes the principles and philosophy behind the safety discussion for nuclear maritime and discusses key topics that relate to the overall ship design. Chapter 2 provides design details on the reactor compartment and other considerations when designing the reactor compartment. Chapter 3 describes the various hazards the reactor plant should be resilient against and avenues in establishing resiliency. Chapter 4 discusses the propulsion system and key considerations when evaluating different propulsion designs. Chapter 5 provides emergency power considerations for design determinations. Chapter 6 provides an event tree analysis on the major initiating events when operating a nuclear ship. Chapter 7 outlines the port operating procedures including avenues for establishing porting requirements for nuclear ships.

## Introduction

This document will contain considerations for a safety analysis in the use of a Commercial Maritime Nuclear Propulsion (CMNP) system. To achieve this objective, we have used the combination of various operational experiences, engineering reports, and government documents in order to develop a comprehensive understanding of providing reasonable assurance for the safety of a commercial nuclear service ship. This document does not serve as a new standard, nor does it claim to supersede existing legal doctrine. Instead, this document serves to provide a starting point to enable engineers, ship builders, scientists, and regulators to begin developing a regulatory landscape to enable the use of CMNP technology. As such, this document analyzes the interaction between the nuclear and marine safety requirements to provide guidance in assuring design resiliency and uses existing nuclear and marine safety requirements to promote the discussion.

> "*The principal contribution of hazard analysis is to make people think before the accident instead of afterwards… not the paper result*"
>
> - Dr. C. O. Miller, Director of the Bureau of Aviation Safety[1]

## Definitions

Control Zone: An area outside a restricted area but within the site boundary, to which the licensee can limit access for any reason.[2]

Defense-in-Depth: An approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. Defense in depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures.[3]

Hazard: A real or potential condition that could lead to an unplanned event or series of events (i.e. mishap) resulting in death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.[4]

(Propulsion) Direct Drive: A system that directly integrates the reactor into the propulsion system using a gas, traditionally steam, to generate shaft power. This is how most existing nuclear propulsion systems operate.

(Propulsion) Indirect Drive: A system that uses the reactor to generate electric power, which, in turn, feeds into the propulsion system.

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[1] Dr. C. O. Miller, "Requirements for Systems Safety Programs as Delineated by MIL-STD-882," National Aeronautics and Space Administration, 1971, 10.

[2] U.S. Nuclear Regulatory Commission, "Controlled Area," U.S. Nuclear Regulatory Commission, March 9, 2021, https://www.nrc.gov/reading-rm/basic-ref/glossary/controlled-area.html.

[3] U.S. Nuclear Regulatory Commission, "Defense-in-Depth," U.S. Nuclear Regulatory Commission, March 9, 2021, https://www.nrc.gov/reading-rm/basic-ref/glossary/defense-in-depth.html.

[4] U.S. Department of Defense, *Department of Defense Standard Practice - System Safety*, MIL-STD-882E (Department of Defense, 2023).

Risk: The intersection of magnitude, probability, and timeframe of a hazard understood through an engineering, sociopolitical, and environmental lens.

Resiliency: A complex unit in space and in time, whose sub-units cooperate to preserve its integrity, its structure and its behavior and tend to restore them after a non-destructive disturbance.[5]

Reactor Enclosure: The area within the Reactor Compartment where the reactor and its containment structure are kept. Some designs may combine the enclosure and the Reactor Compartment into a single structure. However, they are kept separate for the handbook due to the potential use of modular reactor systems.

Reactor Compartment: The area within the ship where the Reactor Enclosure is accommodated.

Reactor Containment: A seal-tight structure that is meant to prevent or minimize the releases of radioactive effluents in case of accidents.

Reactor Vessel: A container, typically made of steel, within which the reactor core is located.

SCRAM: The sudden shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator. Also known as a "reactor trip".[6]

Take-Home system: An independent propulsion system with the purpose of redundant maneuverability during periods without reactor power, usually in the case of emergency operations.

# Chapter 1: Ship Requirements

## Chapter 1.1: Guiding Principles

A nuclear ship must be designed to achieve the following two criteria to provide reasonable assurance of safety. All statements made throughout this document revolve around these two principles:

1. Equivalent Safety – Any nuclear-powered vessel should be as safe as a conventional vessel of a similar class.[7]
2. Radiation Resiliency – Safeguards must be established in the ship's design to provide reasonable assurance that, in cases of accident scenarios, there is no undue radiation hazard.[8]

Equivalent safety means that the risk level of a nuclear ship should be near similar from that of a traditionally powered ship of the same class. Therefore, the onboard nuclear power plant should uphold vigorous safety standards to meet the parallel safety equivalences in maritime operations. Aligning with the equivalent safety principle would require nuclear ships to follow existing marine and nuclear codes. The meshing between the two codes and systems makes assuring safety in this context a unique challenge for engineers. However, using equivalency as the goal enables a better understanding of design considerations through the translation of existing practices. Designers should attempt to ensure

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[5] Paul A. Weiss, *Hierarchically Organized Systems in Theory and Practice* (1971).

[6] U.S. Nuclear Regulatory Commission, "SCRAM," U.S. Nuclear Regulatory Commission Glossary, March 9, 2021, https://www.nrc.gov/reading-rm/basic-ref/glossary/scram.html.

[7] US Coast Guard, *46 CFR Part 61 - General*, 1968.

[8] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships," International Maritime Organization, March 12, 2024.

that the final result of a nuclear-powered vessel would have a similar risk profile to prevent undue hazard to nearby populaces.

The concept of equivalent safety relies on the belief that a nuclear-powered vessel should be considered as a ship with a reactor rather than a reactor with a ship. The difference between these two ideas is that equivalency views the reactor as a component within the ship system, while the other view understands safety in reference to the reactor and ship secondary. This would entail that the requirements a nuclear regulator will enforce only applies as it relates to the reactor system and not that of the ship. On the other hand, the requirements for the ship would also only apply to the ship itself. When these two boundaries cross, the more conservative of the two would hold, as aligned with the theory of precautionary principle. Equivalency provides a holistic understanding and a system's engineering view of the problem. As such, designs should consider the reactor enclosure as a black-box to simplify ship design through system-of-systems logic, but will likely have large overlaps when submitting safety documentation.

Radiation resiliency is the other key concept for designing safety. Traditional ship safety primarily considers the safety of the crew and the integrity of the ship's vessel. However, due to the impacts of hazards due to radiation, reactor-powered vessels should place radiation safety above maritime safety, in cases where they differ. Changing the primary concern to one of radiation impacts the considerations of ship design and construction because the focus will be to ensure radiation control rather than ship integrity. For example, ship crew may scuttle the ship in order to avoid release of radioactive affluents in extreme events.

The concept of radiation resiliency also means that designers must prove reasonable assurance of safety through design choices. The use of engineering safeguards, active or passive components, and defense-in-depth are all critical to ensure that proper design resiliency is developed. These design choices need to first understand the hazards posed on the system through hazard analysis. Through the hazard analysis, systems shall be placed to control the release of radiation.

The principle of radiation safety relies on defense-in-depth having multiple independent barriers between the source of radioactivity (i.e., the reactor fuel) and the environment. In land-based reactors, the barriers are made up of the reactor fuel cladding, reactor coolant system (which includes the reactor vessel), and finally the reactor containment. In maritime shipping, the reactor enclosure, reactor compartment, and the hull are effectively added to the traditional barriers. These barriers are illustrated in Figure 1. It is through these guiding principles of equivalency and resiliency that the handbook will be developing its discussion for reactor safety.

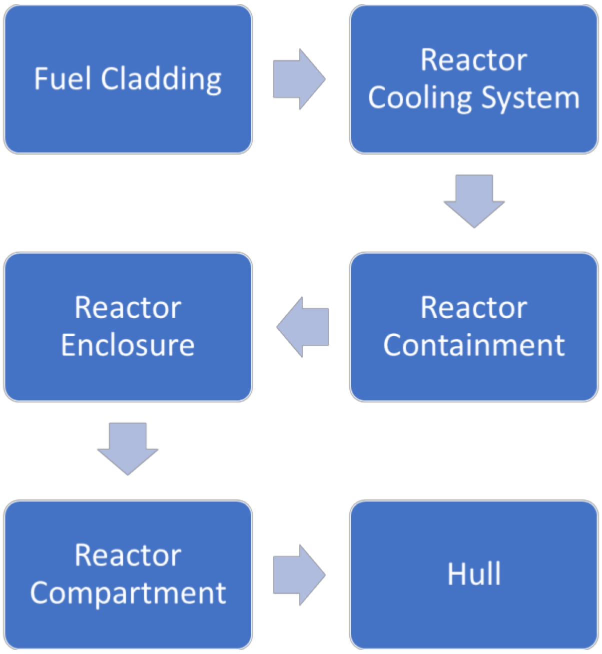

Figure 1: Defense-in-Depth for Maritime Environments[9]

## Chapter 1.2: Existing Regulations and Statutes

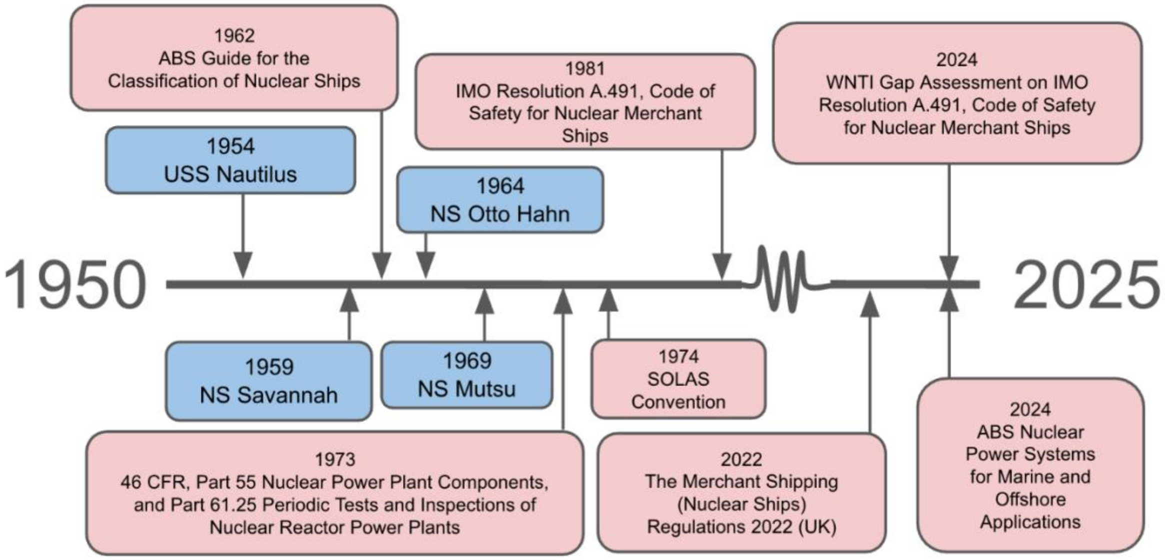

Figure 2: Existing Regulations and Statutes Timeline[10]

As it exists at the time of publication, there are few current regulations in place for nuclear ships. Figure 2 outlines the relevant codes and ships that will be descried. Issued by the United Nations and

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[9] Please note: Fuel cladding is not present in certain reactor designs, such as molten salt fueled reactors.
[10] Anthony Valiaveedu et al., "Navigating the Regulatory Seas for Commercial Maritime Nuclear Propulsion," *MIT Science Policy Review* 6 (August 2025), https://doi.org/10.38105/spr.cb0t0jkorb.

supplemented with the International Maritime Organization's (IMO) code, SOLAS Chapter 8 details the safety requirements for nuclear boats.[11] However, these regulations are specific for the use of pressurized water reactor technology and do not account for the significant operational experience of nuclear and maritime industries accrued since their publications in 1974 and 1981.

Russia and the UK have issued more recent legislation than international authorities. Russia has established a clear organizational framework for nuclear ships with support by the state's classification society, which has led to the deployment of several nuclear ships by Russia, particularly icebreakers.[12] Notably, the Russian civilian nuclear fleet has not deployed to many foreign waters, and therefore is able to omit some international regulations and diplomatic considerations. In 2022, the United Kingdom released legislation endorsing the existing IMO code and establishing an organizational framework for promoting commercial nuclear ships.[13] The UK's work has been supported by the Lloyd's Register, who have increased their efforts in CMNP.

In contrast, the United States has not made substantial commitments in support of modern infrastructure development for CMNP beyond the American Bureau of Ships' work on Floating Nuclear Power Plants.[14] Yet, the US may still be the best suited of any country for long-term sustainable nuclear vessels; it contains the largest expertise in the sector of nuclear propulsion and systems and has established prior treaties regarding port acceptance of nuclear ships through the NS Savannah and its existing nuclear navy. As the international acceptance process may result in large uncertainty for future nuclear vessels, the diplomatic groundwork for future nuclear ships should not be understated. Current users of nuclear propulsion systems for navy vessels, such as the US, UK, and France, could offer a more streamlined process for their nuclear flag ships because of their experience with nuclear submarines as well as their solidified nuclear and maritime regulations and experience. Additionally, such countries have the necessary political and financial resources to process nuclear ship development, regulation, and diplomacy.

As it stands in the US, the Coast Guard published a since expired document which stated that the nuclear regulator would have "primary review and inspection responsibility".[15] Consequently, it can be assumed that Nuclear Ships were to build upon existing nuclear regulations for licensing decisions. This guiding philosophy emphasizes that nuclear safety must be the highest priority for nuclear boats due to the unique risk release of radioactive material poses to public health and safety and environmental impacts compared to traditional maritime safety considerations.

There are two notable ships that should be used as guides for international shipping: the NS Savannah and the NS Otto Hahn. The Savannah was a US nuclear shipping vessel deployed primarily as a diplomatic symbol of atomic peace. The use of the Savannah by the US enabled public documentation on nuclear propulsion safety through the use of engineering reports, safety analysis reports, treaties,

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[11] Resolution A.491(XII) CODE OF SAFETY FOR NUCLEAR MERCHANT SHIPS (1981). https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.491(12).pdf.

[12] RMRS, "Rules for the Classification and Construction of Nuclear Ships and Floating Facilities," 2022.

[13] The Secretary of State, "The Merchant Shipping (Nuclear Ships) Regulations 2022," Statute Law Database, accessed November 19, 2024, https://www.legislation.gov.uk/uksi/2022/1169/contents/2023-03-29.

[14] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications* (ABS, 2024).

[15] U.S. Coast Guard, *Commandant Notice 1600* (US Coast Guard, 2004).

etc.[16] The ship successfully sailed to multiple ports and, notably, the Panama Canal. The experiences gained from the Savannah's design and operation can support future designers in determining effective solutions. The second ship is the NS Otto Hahn, a German ship sailed primarily throughout Europe. Considered the NS Savannah's successor in nuclear technology, there was strong collaboration between the US and Germany when designing and deploying the vessel.[17] The Otto Hahn can be better leveraged by future engineers in reactor design and system integration as it suffered less technical issues than the Savannah, such as main cooling pump and buffer seal failure.[18]

## Chapter 1.3: Hull Design

In all ships, hulls are designed to withstand the effects and impacts of various external forces. In a nuclear ship, the hull also must act as the final controlled zone of protection in the event of a reactor accident. Existing marine rules on hull requirements can generally be used to ensure the protection of the nuclear ship's integrity, but some special considerations must be incorporated. It is expected that the material in the hull to have no activated materials, as such materials are to be isolated by the reactor compartment.

Nuclear ship designers should consider incorporating a double-bottom hull because the risks and hazards associated with grounding are exacerbated by potential damage to nuclear systems, structures, or components (SSCs) onboard.[19] Grounding usually damages the hull amidships, where most designs would place the reactor.[20] This positions nuclear ships in a more precarious position than conventional ships because their engines are typically placed further aft. Furthermore, if SSCs or waste storage are impacted by grounding, they could release hazardous materials or negatively affect reactor control. Implementing a double-bottom hull can significantly reduce the risks from grounding. The depth of the double bottom should provide adequate protection against the aforementioned risks.[21]

The double-bottom of a hull should place unique considerations for the potential event of leak-by from the reactor compartment. Additionally, the Reactor Compartment's bilge tank should have segregated capability for radioactive material surge in instances where an independent surge tank is not included for such storage.[22] The bilge system for a ship that can encounter radioactive waste shall be made

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[16] Andrew W. Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships* (U.S. Atomic Energy Commission, 1962).

[17] Halvor Schøyen and Kenn Steger-Jensen, "Nuclear Propulsion in Ocean Merchant Shipping: The Role of Historical Experiments to Gain Insight into Possible Future Applications," *Journal of Cleaner Production* 169 (2017): 152–60, https://doi.org/10.1016/j.jclepro.2017.05.163; *Final Safety Review N.S. Otto Hahn* (n.d.).

[18] George G. Sharp Inc., "Lessons of Savannah," U.S. Department of Commerce Maritime Administration, September 9, 1966.

[19] American Bureau of Shipping, "Guide for the Classification of Nuclear Ships," American Bureau of Shipping, 1962; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[20] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

[21] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships"; American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

[22] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

separate and independent from other bilge systems.[23] The pumping installation should have monitors to identify radiation levels and ability to treat and store or (depending on levels) release. Isolating bilge systems exposed to radioactive waste helps contain contamination and reduce risk of contamination spread. These choices would support the ship's hull in acting as the absolute final defense from radioactive dispersal and avoiding radionuclides from further contaminating the vessel. This is particularly important in marine environments due to the lack of contamination controls available at sea.

Ballast tank evaluation should consider flooding of the ballast tank and an adjacent ballast tank under the Reactor Compartment for maximum hazard evaluation in a grounding event.[24] Current marine codes evaluate the flooding of only one ballast tank, which may be insufficient for the applicable risk level in nuclear applications.

## Chapter 1.4: Maneuverability

A nuclear ship shall have at least the same maneuverability as a ship in similar class. Paralleled maneuverability enables nuclear ships to conduct standard operations, use conventional docks, and meet safety requirements for traditional ships.[25] For instance, during power operations, the reactor must be continuously able to provide the necessary power for emergency stopping as set by existing marine rules. Keeping careful considerations on the load-following response times will be crucial for evaluating the acceleration, deacceleration, and reverse acceleration. For reference, the NS Mutsu's requirements were to "to change the propulsion direction from ahead to astern by reducing the power from 100% to 18% in 5 s and then raising the power level from 18% to 80% in 30 s; or from astern to ahead by reducing the power level from 80% to 18% in 5 s and then rising the power level from 18% to 100% in 30 s".[26]

When designing for adequate stopping distances, nuclear ships face increased engineering complications compared to conventional ships. Due to the energy conversion process of reactors, they are not suited for rapid changes in power output and therefore quick vessel deceleration. Ship designers must account for this challenge to ensure equivalent safety. Appropriate solutions may differ if the ship uses a direct or indirect drive system, and as such, design-specific evaluation needs to be done on the impact that transients play in changing maneuverability functions for the ship. The N.S Savannah, a passenger cargo nuclear ship with a 596ft length, had a stopping distance of about 4,380ft. At about 7.5x the ship's length, the Savannah's stopping distance is significantly less than the IMO's required 15x maximum.[27] Though operationally more similar to conventional ships, nuclear ship designers must also

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[23] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships"; American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

[24] American Bureau of Shipping, "Guide for the Classification of Nuclear Ships."

[25] First Atomic Ship Transport Inc., *NS Savannah Safety Assessment Revision 3* (The Maritime Administration, 1968).; Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

[26] Zhibo Zhang and Jin Jiang, "On Load-Following Operations of Small Modular Reactors," *Progress in Nuclear Energy* 173 (August 2024): 105274, https://doi.org/10.1016/j.pnucene.2024.105274.

[27] International Maritime Organization, "STANDARDS FOR SHIP MANOEUVRABILITY," International Maritime Organization, December 4, 2002.

consider turning maneuverability while designing. The NS Savannah completed turning circles at full speed with tactical diameters of less than 5x length, and advances of less than 4.5x length, meaning her performance was within IMO maneuverability guidelines.[28]

Special concern should be made in design for loss of steering events, as loss of steering "is a major contributing factor in case of marine and navigation accidents".[29] Loss of steering can cause some of the most dangerous situations for a nuclear ship, such as collision, grounding, or breaking up. Collision and grounding (as discussed in Chapter 1.3) may result in damage to the SSCs and waste storage, resulting in the release of radioactive products, if not adequately designed for. Lastly, if a nuclear ship is unable to maneuver, they will be more susceptible to attacks from bad actors attracted by the power plant.

Following the same regulations as traditional ships, nuclear ship designers should incorporate duplicate and fully independent steering systems, including the power units and steering gear controls at the primary control room.[30] Should one steering system fail, an alarm system must report the failure and automatically start utilization of the second steering system. Redundancy in steering systems mitigates the ships risk for loss of steering events and the resulting repercussions, such as collision, grounding, or stranding. As a major risk contributor to a nuclear-powered ship is its ability to relocate, ensuring strong design protections involving the propulsion mechanism will be crucial. Chapter 4 will describe the propulsion mechanisms in greater detail.

## Chapter 1.5: Fire-Protection

Onboard reactors increase the risks associated with ship fires, particularly loss of power. If fire damages the onboard power system, especially reactor cooling or control mechanisms, it could trigger meltdown or other dangerous reactor states if backup systems and fire control are not in place. Additionally, some reactor designs may be exposed to fire within the reactor containment. Fire remains a large contributor to the PRA of reactor systems and marine vessels, and as such, every aspect of the ship should be engineered to prevent fires and limit their impacts if they occur.

Due to the transmutability of a fire between locations of a vessel, the Nuclear Ship should be rated for fire protection set by an authoritative nuclear regulatory body to reduce the risk of fire damage to nuclear components. Moreover, the ship should be equipped to detect and suppress fire in the compartment of origin.[31] Designers should choose fire-extinguishing agents that allow for easy decontamination because of potentially difficult to decontaminate spaces or exposure to radioactive

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[28] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; The Maritime Administration, *Updated Final Safety Analysis Report Rev. 7* (2013), 1–2, https://www.maritime.dot.gov/sites/marad.dot.gov/files/docs/national-defense-reserve-fleet/ns-savannah-program/6096/nss-ufsar-rev-vii-2013.pdf.

[29] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[30] American Bureau of Shipping, "Guide for the Classification of Nuclear Ships."

[31] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

products. With loss of power being a significant consequence for nuclear ships, even if the ship does lose power, its fire fighting ability should not be compromised.[32]

The reactor containment and other critical reactor safety systems might need enhanced fire fighting systems to protect against dangerous reactor events. In the event of a fire, “the reactor system and containment must maintain integrity”.[33] Going further, if systems are imperative for power plant or ship operation, they should be equipped with individual fire-extinguishing equipment and alarms, and physically divided by structural fire protection. Ship designers should pay special attention to protection from external fires in the reactor control room.[34]

Fire hazard analysis should appropriately evaluate the entire ship instead of solely the Reactor Compartment as the bounds of the analysis. The acceptance of NFPA 805 could provide a fruitful design base for a risk informed fire protection system for resiliency against fire damage. Beyond the ship itself, fire hazard analysis should account for risk of fire and explosion stemming from ship cargo or other external sources.

## Chapter 2: Reactor Compartment Requirements

The Reactor Compartment encompasses the Reactor Enclosure and, within it, the Reactor Containment. The reason for distinguishing this boundary is for the instance of multiple modular reactor systems being used for power redundancy or independent propulsion trains in future ship design. For instance, if two modular reactor systems are used, the module would comprise the Reactor Enclosure and would be housed inside the Reactor Compartment, as shown in Figure 3. In some instances, the Rector Compartment may be the same as the Reactor Enclosure. In general, the Reactor Enclosure may have different safety requirements than the Compartment if separate. The Reactor Compartment should aim to act as the final radiation control area within the ship, as it is preferred that all nuclear equipment and coolant remain within the Reactor Compartment for radiation control.

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[32] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

[33] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

[34] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

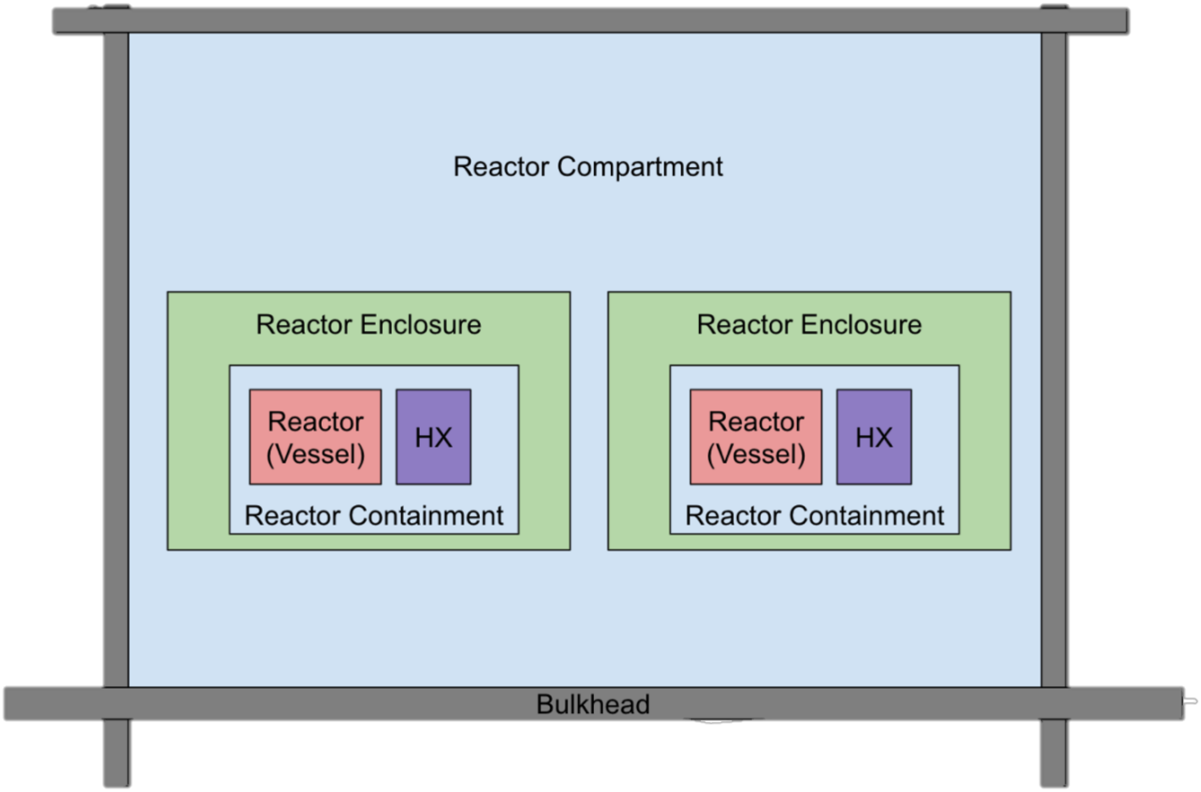

Figure 3: Reactor Defense Layers Design

## Chapter 2.1: Location Preference

The Reactor Compartment contains the most of the radiologically critical components of the ship, and therefore should be placed in a well-protected area. The location of the Compartment should mitigate the effects of collision, grounding, or other external events and forces on the reactor.[35]

The preference of location is towards aft of midships, as it provides the largest stability for the reactor system during transients. The Compartment shall be at least above the double bottom, as stated in Chapter 1.3. In addition, the Enclosure should be placed inboard away from the hull in order to avoid direct loads during a hull breach. More specifically, the bulkheads forming the Reactor Compartment should be placed so that there is adequate spacing (generally inboard at least one-fifth of the extreme breadth of the ship) between the Reactor System and the hull so that an external missile or collision

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[35] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*; World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships”; Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

does not exceed existing marine rules for penetration.[36] Furthermore, these bulkheads must be gas and water-tight to avoid ingress or egress of fluids that can impact reactor operations or radiation safety.[37]

## Chapter 2.2: Reactor Enclosure

The Reactor Enclosure is the final boundary between distinct reactor systems on the ship. As such, the Reactor Enclosure's primary goal is to isolate major reactor components, thus creating modular reactor systems. If reactors are segregated, damage, accident scenarios, or maintenance will be less likely to affect every reactor. The specific design basis requirements may change according to reactor designs, but they can promote resiliency against external hazards (e.g., missiles and flooding) and radiation shielding.

Lowering the risk of damage or reactor shutdown, in turn, lowers the risks of radiation release, reduced maneuverability, or other unfavorable events. In scenarios of single reactor systems, the Reactor Enclosure and Reactor Compartment separation enables the segregation of components to reduce failure. Lastly, if one reactor needed to be removed from the ship, the other reactors could remain in the ship, simplifying the operation. Separated Reactors enhance the propulsion system's reliability and safety through segregation and redundancy.

In order to be effectively segregated, each Reactor Enclosure must provide missile protection.[38] Internal missile protection will reduce the likelihood of one reactor damaging both itself and another reactor. Individual external missile protection lowers the chances of both reactors being impacted by an accident, and will allow unimpacted reactors to continue operation if others are in disrepair.

Similarly, Reactor Enclosures should also deliver radiation protection for each reactor.[39] Replicate radiation protection would limit the radiation emission to only the specifically affected reactor, reducing exposure. Additionally, if one reactor needed to be shut down due to radiation leakage, other reactors could continue to operate unaffected.

## Chapter 2.3: Translational and Vibrational Movements

Key power plant components within and outside of the Reactor Enclosure are exposed to translational and vibrational movements from the ship, which may wear down, damage, or otherwise compromise SSCs. Traditional reactor equipment is designed around static environments and therefore would not experience fatigue from marine operations. As such, it is insufficient to use traditional acceptance criteria for reactor components to be used on a marine vessel.

Given the sensitivity of the equipment used in the Reactor Compartment, it is important that the effects of vibrational and translational movement to the SSCs is mitigated to avoid malfunction of reactor

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[36] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[37] International Maritime Organization, "STANDARDS FOR SHIP MANOEUVRABILITY."

[38] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*; Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[39] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

equipment.[40] For example, translational movements resulted in an inadvertent trip for the NS Savannah.[41] Snubbers and dampeners will play a crucial part in assuring operational safety and play a larger part in risk analysis.

## Chapter 2.4: Flooding

The Reactor Compartment should be designed against flooding accident scenarios. Under flooding conditions from the marine environment, the Reactor Compartment and power plant will potentially be exposed to seawater intrusion, temperature changes, pressure differentials, and disruptions to the reactor cooling system. Maintaining Reactor Compartment integrity when exposed to these conditions is critical for protecting and securing the Reactor as well as the surrounding environment and population zones. The resulting necessary design choices should be identified by analyzing the two main flooding conditions, shallow and deep sinking, individually. Generally, shallow sinking is characterized by depths of less than 30 meters.[42]

In a shallow sinking scenario, the Enclosure would be partially or fully submerged with minimal pressure differences. Shallow sinking may have larger direct consequences during accident situations due to larger direct environmental releases. Incomplete submergence of the Reactor Containment could result in harmful reactor materials dispersing through the air, potentially contaminating population zones or fisheries.[43] Additionally, in a partial flooding situation, any two-phase cooling system could be affected by sea water intrusion. To prevent reactor overheating, the Containment should be designed to enable passive cooling in order to ensure safe shut down if the cooling system is impacted by seawater intrusion. Dependent upon design, additional pumps or mechanisms would be necessary to enable injection of additional seawater for indefinite cooling purposes.[44]

Deep sinking conditions, particularly pressure differences, must be a strong consideration for the reactor enclosure. As the Compartment sinks, the pressure difference between the ocean and interior of the enclosure would greatly increase, which could damage the protective structures within the Reactor Compartment. In addition, the Reactor cooling system may also be compromised during sinking. The Containment must be able to equalize the pressure imbalance to ensure protective barriers are maintained for the fuel. One design solution could be to implement Passive/Automatic flooding valves, which can prevent overpressure crushing of the reactor fuel by the containment and enable salvage

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[40] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; American Bureau of Shipping, "Guide for the Classification of Nuclear Ships"; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[41] Colin Campbell, "First Chief Engineer Returns to N.S. Savannah in Baltimore," *Baltimore Sun*, n.d., https://digitaledition.baltimoresun.com/tribune/article_popover.aspx?guid=5d09ff78-eaed-4c31-a101-734e71cf27f1.

[42] *Final Safety Review N.S. Otto Hahn*.

[43] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

[44] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

operations.[45] Designers should analyze situations where the ship sinks with the reactor compartment still intact, as they would need to ensure that containment cooling and integrity remain despite deep sinking. Possibly ships could implement pressure valves on the reactor compartment and enclosure in addition to the containment.

Specific analysis would require analyzing pressures during potential deep sinking conditions and the impact of seawater on reactivity of the plant. Naval experience on submarine accidents reports deep sinking did not result in significant releases of radiation, unlike shallow sinking.[46]

In both shallow and deep sinking, significant temperature changes and potential seawater intrusion can occur. Compartment and Reactor components would require protection against temperature shock and sea-water interaction to minimize Reactor damage and therefore harmful material release. The Compartment must defend against temperature changes and seawater intrusion, particularly corrosion, as the enclosure may be submerged in ocean water for an extended period while awaiting salvage. However, the major hazard for shallow sinking will be decay heat removal and deep sinking will be underwater pressure damage.[47]

## Chapter 2.5: Waste Handling

Nuclear ships must safely control the potentially hazardous waste produced by reactors. Waste handling brings two primary concerns for nuclear ships: storage and offboarding. Overall, the generation and accumulation of radioactive waste should be minimized to reduce the spread of hazardous material onboard. Similarly, waste handling facilities and procedures should meet the requirements determined by the amount and characteristics of the waste created. All shipboard areas that may be exposed to radioactive waste (including escape paths) must have means for monitoring waste and radioactivity levels. Waste storage and transportation facilities should be designed to facilitate decontamination and cleaning. Additionally, materials that contact waste should be corrosion-resistant and have biological shielding if needed. Waste system leaks should be quickly detectable to prevent contamination.

In case local authorities require nuclear ships to hold waste while in their jurisdiction, nuclear ships must have on-board waste storage facilities capable of holding all material and liquid waste from operations. Such storage requirements are established already by IAEA and NRC guidance and can be utilized for interim storage. Storage can be done through dedicated on-board tanks or through specialized bulkheads (including the double bottom if appropriately engineered). Marine reactor waste storage faces different accident scenarios, and as such, collision protection should be accounted for. Otherwise, radioactive waste could leak-by during accident conditions and increase potential risks. Additionally, this waste should be stored within the Reactor Enclosure to limit radioactivity exposure.

All stored waste should be removed while ported at the flag-nation or at a foreign port (depending on acceptable arrangements made), as storage on-board should not be considered final storage. On-board storage is not final in order to avoid situations of built-up radiological hazards that pose increased risk

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[45] US Coast Guard, *46 CFR Part - 55 Nuclear Powerplant Components*, 1978; American Bureau of Shipping, "Guide for the Classification of Nuclear Ships."
[46] Jim Haddadin, "Navy: No Threat from USS Thresher Wreckage," *Foster's Daily Democrat* (Portsmouth), April 8, 2013, https://www.fosters.com/story/news/2013/04/08/navy-no-threat-from-uss/48972327007/.
[47] American Bureau of Shipping, "Guide for the Classification of Nuclear Ships."

during transportation in high-population zones. Designs for storage must be adequate to store all waste during operations. To better design the ship and predict emergency situations, analysis should be done to quantify releases during accident conditions.

Waste can be processed for offboarding. Offboarding procedures should use dedicated pump systems rated for radiological hazards and isolated from other pump systems. Such pump systems should have sensors available to measure the waste amount as well as amount dumped. A navigational chart should have established radiological offboarding requirements during the transit operations of the ship for reference and approval by the nation-state. For example, the US would have different requirements for international waters than Russia. Even within the US there would be different requirements based on the state. The use of radiological charts would ensure understanding of permissible offboarding and ensure that levels are legally acceptable. In addition, operations of offboarding any waste or release of radiological affluent would necessitate mapping of location and radiation level. Such documentation would be transmitted to the appropriate authorities by the next available port visit for review.

# Chapter 3: Reactor Plant Requirements

## Chapter 3.1: Forces on Plant systems

Ship movement can have a significant effect on the nuclear power plant. Traditional plant equipment uses static, land-based specific dynamic conditions (e.g., seismic motion) when designing components. On ships however, the fatigue and shocks caused by oceanic movements may damage SSCs and are therefore of significant concern. Onboard plants must be adapted to the constant forces and inclinations of a ship’s daily movement at sea, as well as the more significant movement they may experience when operating in extreme weather.[48] Historically, withstanding Beaufort scale 11 conditions and the resulting forces was the standard nuclear ship systems needed to uphold.[49] Regulators will likely maintain the Beaufort scale 11 standard to ensure safety systems remain operable in all meteorological conditions, especially when traveling through critical areas like the Panama Canal or the Drake Passage. Wave states beyond Beaufort scale 11 only occur less than 0.05% of days, which further aligns with NRC Regulatory Guide 1.221 requiring safety systems to withstand wind forces that occur around 1e-7 times per year.

Violent Storm conditions will cause significant accelerations and vibrations on the plant systems. For example, the Otto Hahn reactor plant reported accelerations and vibrations of +/- 0.2 g and 0.08 to 0.14 Hz during operation.[50] Withstanding 0.5g of acceleration was a conservative guideline for historic nuclear ships when considering extreme environmental conditions, though they are unlikely in traditional sea lines.[51] Ships should be designed for realistic sea conditions and reactor systems designed to follow relevant codes. To prevent power plant equipment vibration, designers should implement

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[48] RMRS, “Rules for the Classification and Construction of Nuclear Ships and Floating Facilities”; World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships.”

[49] D Ulken, H. Blanshi, H. Kuhl, “Technical Operation Expereinces of the N.S. Otto Hahn and Problems of Port Entery,” Gesellschaft fur Kernenergieverwertung in Schiffbau und Schiffahrt, May 31, 1972.

[50] Martin Kolb, “Performance of the 1. Core of the ‘Otto Hahn,’ by M. Kolb and W. Schumacher,” Rio de Janeiro, Comissão Nacional de Energia Nuclear, 1972, Library of Congress.

[51] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

snubbers and/or dampeners. Similarly, stational structures, such as pipes, will need to operate in a ductile manner to avoid embrittlement failures.[52]

Ocean conditions can cause the nuclear components in these ships to experience angles of inclination. Through measures of ship movements, these angles are internationally agreed upon. It is important to isolate components required for reactor operations and those for ship operations. Nuclear components must remain operable in more extreme conditions than traditional ship components due to the higher consequences of plant malfunction. If reactor operators are unable to adequately manage the reactor in significant seas, reactor safety will be compromised. Most critically, reactor cooling, controls, and shutdown must remain operational at extreme angles of inclination.

Table 1: Angles of Inclination[53]

| Equipment | Angles of Inclination (degrees) (see Note[1]) | | | |
|---|---|---|---|---|
| | Athwartships | | Fore-and-Aft | |
| | Static | Dynamic | Static | Dynamic |
| Main and Auxiliary Machinery essential for propulsion and reactor safety | 15 | 22.5 | 5 (see Note[2]) | 7.5 |
| Emergency Operations Machinery | 22.5 | 22.5 | 10 | 10 |

NOTES

1) Athwartships and fore-and-aft inclinations may occur simultaneously

- Where length of the unit exceeds 100 meters, the fore-and aft static angle of inclination may be taken as: $500/L$ degrees, where L = length of the unit (in meters)

## Chapter 3.2: Reactivity Control

Reactivity control plays a critical role in safe reactor use. Reactor controls must be designed to prevent emergency situations, and to remain operable when they do occur. Particularly, reactivity control must be adapted to ship movement and inclination, as ship movement may affect reactivity.

Ship movement could shift materials in SSCs, affecting reactions and coolant movement. Careful consideration should be placed in how reactivity is impacted by ship angles of inclination, especially for reactor designs that involve partially filled reactor vessels (e.g., Boiling Water Reactors). Additionally, the impact of ship angles on cooling during wave motions must be addressed. In any conditions, the reactivity control mechanisms should have the ability to render the core subcritical.

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[52] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[53] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

Reactor control mechanisms must be engineered for the marine environment.[54] Control mechanisms for reactor operations traditionally depend on locking mechanisms. These types of controls can potentially become unreliable hazardous in dynamic environments (such as maritime) due to potential damages to the mechanical locks and dynamic movements. Hydraulic controls are one design choice that may increase part and rod movement reliability.

## Chapter 3.3: Shutdown Control

Shutdown control, compared to reactivity control, focuses on the process and equipment necessary for effective SCRAM during normal and emergency operations. Traditional SCRAM requirements for nuclear systems are established within existing nuclear regulations. However, additional SCRAM signals may be required beyond those established on land-based plants:

- Hi-Shock SCRAM – signals upon an instantaneous force to initiate shutdown to prevent damage from a potential missile (e.g., another ship striking)
- Seawater intrusion SCRAM – signals upon seawater intrusion in the reactor containment, as it can mean potential loss of maritime operations (e.g., sinking)
- Movement-based SCRAM – signals upon the NS experiencing movement beyond operational limits due potential inoperable equipment in such situations (e.g., hurricane)

The unique issue related to ship design is the lack of remote locations. As such, a secondary shutdown room, redundant to the primary control room, is necessary. The secondary shutdown room would contain independent and redundant controls to engage all emergency shutdown controls.[55] The room would require more limited capabilities and requirements than a traditional control room. In addition, special fire protection and missile protection should be strongly considered to avoid single point failures during emergency use. The secondary control room should be physically apart from the primary control room to reduce the likelihood of both being damaged.[56]

The shutdown systems may require diversity in means for reactor SCRAM. A method for reactor shutdown through chemical or mechanical means would be beneficial for supporting safeguards during transportation. This would prevent start-up by unauthorized personnel. Nuclear ships may attract increased attention from bad actors, therefore making prevention against unauthorized start-ups more important. Chemical shutdown will also be crucial in anti-gravity events where traditional rod control operations may become inoperable, or in mechanical failures due to environmental conditions. In

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[54] World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships”; Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; American Bureau of Shipping, “Guide for the Classification of Nuclear Ships.”

[55] World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships”; American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

[56] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*; RMRS, “Rules for the Classification and Construction of Nuclear Ships and Floating Facilities”; World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships.”

addition, multiple methods of decay heat removal will also be required for post-shutdown operations to avoid fuel overheating and degradation.

## Chapter 3.4: Loss of Onboard Cooling

Reactor cooling is essential for keeping the reactor in a safe state. Primarily, cooling removes fission and decay heat during reactor operations. As such a critical part of reactor safety, cooling systems must be able to manage the reactor in every scenario. The importance of and regulatory attention to effective cooling systems has been underscored by the 2011 Fukushima nuclear accident, where the plant's emergency cooling systems failed to prevent fuel degradation.[57]

Cooling systems must have redundancies that prevent a single failure from rendering the system inoperable. In marine environments, indefinite cooling requirements during emergencies can be resolved through the injection of sea water, typically enabled by piping and water storage in bilges. Seawater injection would be used only in the event the ECCS is disabled. It is an absolute last resort because interaction with seawater will cause significant damage to the reactor and risk contamination of the nearby environment. The use of seawater cooling would be a requirement for any maritime reactor due to the risk of reactor compartment and hull integrity failure.[58] Seawater can also provide an ultimate heat sink in case of emergencies.

Designers should give special consideration to active components of the cooling systems and their ability to operate for extended periods of time. Active components' interaction with seawater must be evaluated, as they should be able to ensure safe shutdown cooling in design basis and beyond design basis accident conditions. Additionally, designers should consider the duration active components are operable accident conditions, particularly factoring fuel supply, due to the isolated nature of maritime operations. As such, reactor cooling will require a risk-informed process to ensure adequate fuel supply to reach a nearby port/drop site, or to use a passive cooling system.

The seawater injection cooling system must have access to seawater feed in any condition or some alternative method for emergency cooling. For instance, seawater feed intake ports must be positioned such that water may still be accessed in a grounding event.[59] Furthermore, nuclear ships should have feed ports on both the starboard and port sides to ensure cooling lines are maintained in a sinking event. This concept is illustrated in Figure 4, one example of a seawater feed system design, for the purpose of clarity. In case that controlled cooling is unstable, nuclear ship engineers may need to integrate a procedure for scuttling the reactor.

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[57] U.S. Nuclear Regulatory Commission, *Compliance with Order EA-12-049, Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events*, JLD-ISG-2012-01 (U.S. Nuclear Regulatory Commission, 2017), https://www.nrc.gov/docs/ML1700/ML17005A188.pdf.

[58] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[59] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; RMRS, "Rules for the Classification and Construction of Nuclear Ships and Floating Facilities"; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

Seawater injection cooling introduces potential risks from seawater-reactor plant interactions, posing special concerns for non-LWR systems. For example, a sodium/water interaction during an accident scenario can result in an explosion. In addition, temperature shock due to sea water injection must be evaluated in accident conditions for all plant types, as such rapid changes in temperature can challenge the integrity of fuel cladding. Seawater injection should not be considered a primary source of cooling due to potential contaminants and should be resorted to rare accident events.

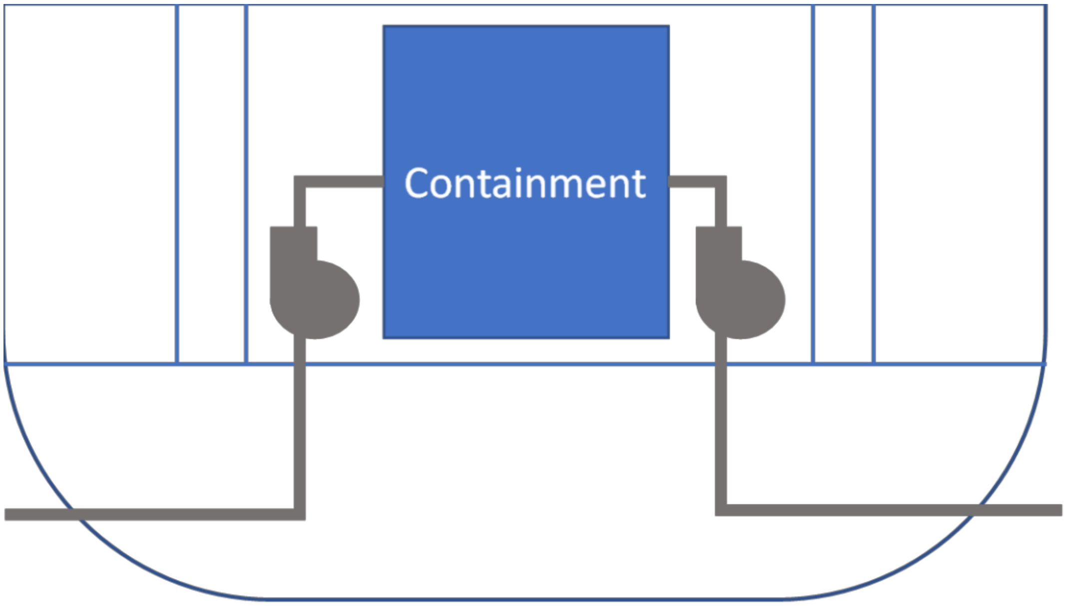

Figure 4: Example of Potential Seawater Injection Cooling Design

## Chapter 3.5: Salvage

During scenarios of high consequence, there can be a strong likelihood of the reactor to sink. This scenario, related to sinking, focuses on the post-accident resiliency to ensure that the nuclear fuel and other radioactive material can be removed from the environment to reduce damages. Due to the potential severity of such event, it should be presumed that the ship's propulsion has failed and unable to move the reactor.

The main objective in a salvage scenario would be to remove the nuclear fuel from the waterway and placed in proper containment. Leaving the fuel in place, place risks international safeguard concerns, public and environmental harm, and legal liability. Fuel must be designed to maintain integrity during thermal shock scenarios in such instance. Tagging can also be used to track where fuel bundles would be located in cases where containment integrity is lost.[60] The tracking and integrity of the fuel can enable salvage operations to remove the fuel and monitor releases in an effective manner. In addition, in cases where the reactor vessel maintains integrity, design should enable the capacity to lift reactor vessel

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[60] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships"; American Bureau of Shipping, "Guide for the Classification of Nuclear Ships."

structures to ensure safe lift of reactor fuel. The design philosophy of the Reactor Enclosure can simplify the operations accordingly.

# Chapter 4: Propulsion System Requirements

## Chapter 4.1: “Take-Home” System

Nuclear ships need a back-up motor in case the reactor-driven primary fails or cannot be used. The “take-home” motor will allow for ship movement if the reactor breaks down, similar to requirements of traditional ships. The secondary propulsion system would lower the risk of grounding, collision, or other accident scenarios where the ship’s primary propulsion system is inoperable, but it must maintain maneuverability. In fact, in congested or narrow seaways, the secondary system should be on active standby to supplement the reactor’s power system during potential accident scenarios (which increase in likelihood in such setting). Nuclear ships may also use the “take-home” motor during an accident scenario where the reactor is inoperable, and the nuclear material must be moved away from population zones. In an indirect drive system, emergency propulsion can be supplemented by diversity of power sources.[61]

The “take-home” system may also be used in cases where nuclear ships would like to enter port under non-nuclear power. This strategy may allow the ship to have more streamlined port acceptance and enter areas that may be unable or unwilling to support an operating reactor. Additionally, the “take-home” motor can enable ships to emergency port by undergoing safe shutdown prior to entering foreign waters, therefore allowing them to potentially be accepted by states without sufficient nuclear capabilities. A potential avenue to support this acceptance avenue can be using existing nuclear material export agreements, as the reactor would be inert at the time of entrance and would not have authorization for restart until reaching international waters.

Unlike traditional “take-home” systems, nuclear “take-home” systems may have more extensive requirements due to travel requirements from accident conditions and approved port distances. The secondary propulsion system must be robust enough to safely maneuver the ship. This “back-up” system should have sufficient power to permit the ship to operate safely in port or harbor and to maintain steerageway in sea conditions corresponding to a wind force of Beaufort 6 approaching the ship on the beam, with the ship in any normal condition of loading.[62] Similarly, the “take-home” system would need capability to dock and undock the ship.[63] Lastly, a cold start of the emergency propulsion

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[61] World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships.”

[62] World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships.”

[63] World Nuclear Transport Institute, “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships.”

system should be fast enough to adequately respond to a potentially hazardous situation, which would likely be around 2 minutes.[64]

The take-home motor design should also account for a single-point failure in terms of propulsion design. Potential failure in terms of security (i.e., sabotage by a bad actor) can result in emergency use of an alternative system for propulsion. Such analysis can be resolved by evaluating how diversity in maneuverability is developed.

## Chapter 4.2: Direct Drive Propulsion

Direct drive propulsion systems integrate the reactor system fully into the ship's system. This results in different considerations within propulsion. The use of propulsion steam should be independent from the radioactive/primary loop of the reactor system in order to avoid issues related to environmental releases. This will further support ALARA goals for radiation protection for occupants on such vessels. In addition, direct drive propulsion would necessitate that an independent motor system be used for emergency propulsion to ensure that failures along the propulsion steam line does not impact the emergency propulsion system.

The piping system to the turbine would need the highest standard of quality assurance related to welding failures. In addition, since part of the reactor's cooling is reliant on turbine operations, in cases of propulsion speed adjustments, cooling must have alternative components (like steam dumps) to undertake thermal loads to ensure reactor power stability. Such power diversion should have careful consideration of environmental damages due to environmental thermal discharge limits set by nations, especially in waterways. Adequate systems to enable such power fluctuations (such as power storage banks or steam dumps) should be strongly considered to maintain maneuverability. (See Maneuverability chapter)

## Chapter 4.3: Indirect Drive Propulsion

Indirect drive systems use an energy storage system between the reactor and propulsion system. This creates a segregation of the reactor system from the propulsion system to prevent compounding failures. In the US Navy, this has been actively investigated in the form of an electrical battery charged by the nuclear reactor turbo-generator and driving an electrical motor connected to the propeller.

Creating segregations between systems increases the inherent defense layers against compounding failures, but should have careful focus on the reliance of electrical system. Such systems can increase the risk of fires and high-energy arc faults and will require careful fire protection evaluations. In addition, careful planning is needed to ensure independence of the electrical motor to the reactor system to avoid electrical load faults. Having a reactor failure should not impact the electrical motor, nor its emergency power source.

# Chapter 5: Emergency Power

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[64] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*; First Atomic Ship Transport Inc., *NS Savannah Safety Assessment Revision 3*.

## Chapter 5.1: Power Capacity

In general, emergency power supplies for ships and nuclear systems are well documented. In traditional maritime operations, emergency power is generally used to ensure propulsion operations. In nuclear, emergency power is generally designed for safe-shutdown down of plant operations. In many cases the classification of the two can overlap.[65] When developing emergency power for maritime nuclear systems, the same level of reliability shall be awarded for maritime use as land-use due to the similar level of risk for a reactor failure.[66] Therefore, proposed "passive" reactor designs that do not use emergency power systems on land could be warranted for maritime use if proven effective in the given environment.

Separately, defining emergency power will be needed to differentiate the risk associated with nuclear vs propulsion, in a system-of-systems lens. Differentiation will be needed to define equipment for emergency nuclear power vs emergency maritime power to assist with regulatory compliance and overall systems safety. In any case that the nuclear emergency power fails, two sets of alternative power sources for each reactor will be required (with aggregate capacity to carry load independently).[67] This assures that continued power is maintained within the ship's safety systems and maneuverability is kept. In addition, nuclear emergency power will be needed to effectively support shut and cooldown, maintain a safe reactor state, and power reactor controls, monitoring equipment, HVAC, and security systems.[68] The requirements for long-term emergency cooling can be potentially met by flooding the reactor cavity using emergency systems.

The fuel requirements for 'Emergency' and 'Stand-By' power will be limited to the required levels to reach port in accordance with available port operations procedures. This value will also be adjusted to account for required fuel for 30 days to assure reactor shutdown.[69] 30 days is provided to account for the potential time for government response to such event. Separately, shore power should be enabled to support shutdown operations in the ship during potential events at port.[70]

## Chapter 5.2: Required Power Locations

Various locations will require habitability throughout the ship during emergency events that require emergency power requirements for nuclear and maritime power systems. In the event of a nuclear incident habitability evaluations will be required for the bridge, as it can result in potential external damages to the reactor (e.g., collisions). In addition, survival craft systems for evacuations will be reviewed under a nuclear safety standpoint for operations in emergency scenarios which may adjust power reliability requirements.[71] Such survival crafts should also be encouraged to maintain

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[65] US Coast Guard, *46 CFR Part - 55 Nuclear Powerplant Components*. US Coast Guard, "46 CFR Part 55 - Nuclear Powerplant Components," 1978.

[66] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

[67] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

[68] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

[69] RMRS, "Rules for the Classification and Construction of Nuclear Ships and Floating Facilities."

[70] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

[71] American Bureau of Shipping, *Requirements for Nuclear Power Systems for Marine and Offshore Applications*.

decontamination chambers due to potential delayed rescue. Additional power may be needed for supporting radiation instruments and meeting evacuation requirements.

## Chapter 6: Accident Scenarios

To provide context into the design options that have been listed, event trees were drawn to emphasize the concepts of defense-in-depth and probabilistic defenses promoted in the document. These event trees were modified from safety documents from the NS Mutsu.[72] The scenarios isolated are those that are perceived to be unique to maritime operations for nuclear systems.

### Chapter 6.1: Collisions

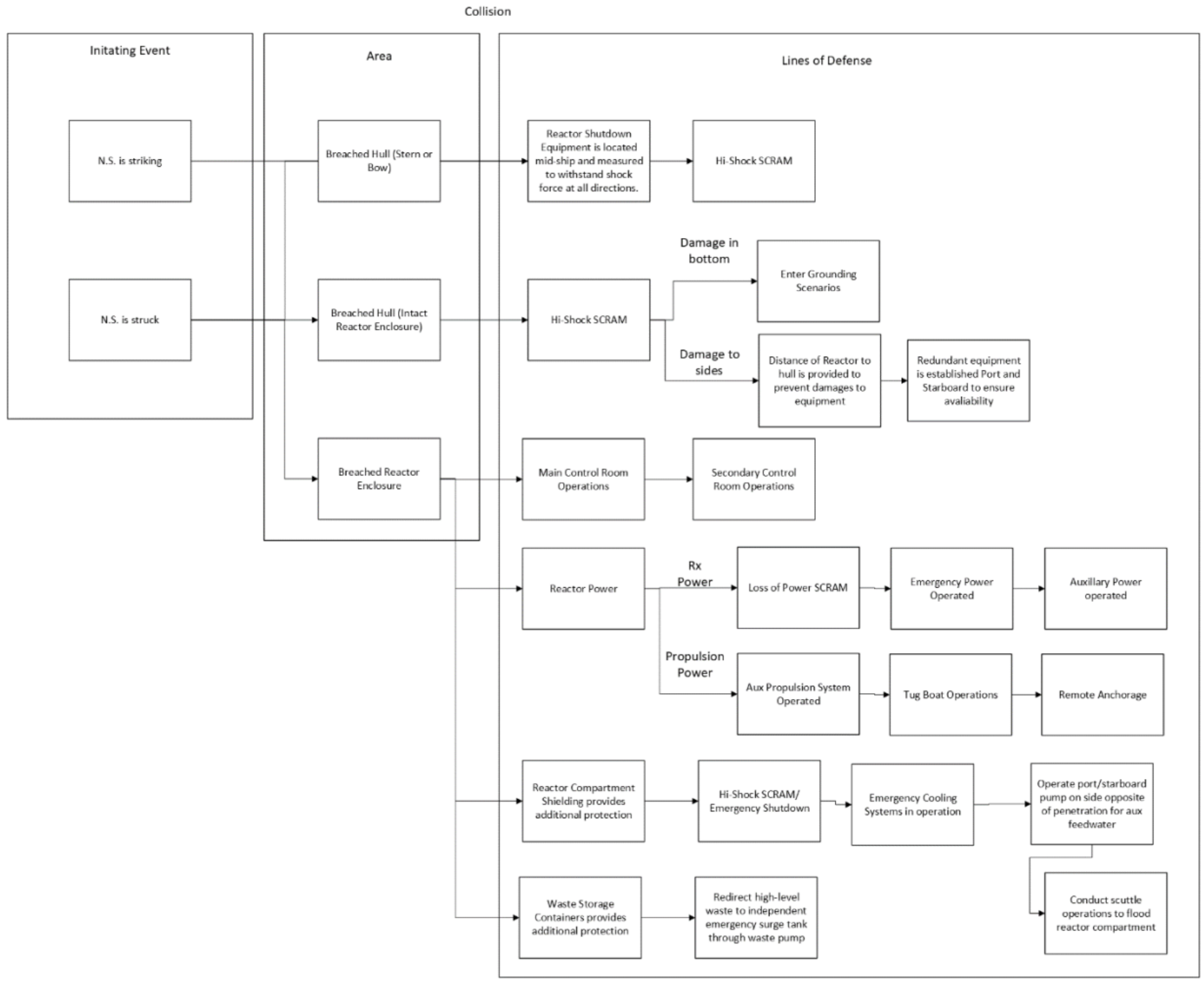

Figure 5: Collision Event Tree

The event tree for collisions in Figure 5 describes the engineering judgement behind safe design for such vessels. We consider two initiating events which have the Nuclear Ship (NS) as the agent or principle in a

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[72] "N.S. Mutsu Accident Diagram," Japan Nuclear Ship Development Agency, n.d., N.S. Savannah Library.

striking scenario. This is unique to maritime nuclear, due to in-motion collisions, and can pose to be one of the more significant design-basis accidents for the system.

There are three main scenarios for collision: hull damage to the bow or stern, hull damage with the reactor enclosure intact, and hull damage with failed reactor enclosure integrity. These three scenarios were chosen as they provide the most plausible scenarios for collisions to occur during operations. An impact to the bow/stern is more likely during scenarios where the NS strikes another object or during passage in congested waterways. Other ships can also impact the sides of the NS in congested waterways or from operational error (RMS Queen Mary incident).[73] This side impact is likely to be more probable during actual operation and is of most interest for design resiliency due to the proximity of the reactor. In the case of an actual breach, the impact analysis will likely be severe and may be more comparable to the nuclear related B5b rule ("maintain or restore core cooling, containment, and spent fuel pool cooling capabilities under the circumstances associated with loss of large areas of the plant due to explosions or fire").[74] In fact, the B5b rule will play an increasingly important requirement for NS design.

In the specific situation for impacts in the bow/stern, the reactor is located mid-ship for the explicit purpose to avoid collision impacts damaging the reactor system. The direct damage of a head-on collision at such locations has little ability to reach the location of the reactor.[75] In the case that the collision does begin to do severe damage to the NS, the use of the hi-shock SCRAM signal implementation should initiate with appropriate post-scram procedures to follow. This will push for reduced reactivity and adjust reactor operations from active to shutdown.

The second scenario evaluates impacts related to damages towards the port/starboard side of the NS. Impacts in these locations, especially near the reactor compartment, increase the likelihood of reactor equipment to be damaged. Such a shock will in any case result in a Hi-Shock SCRAM signal. The mid-ship location of the reactor, with established distances to the hull in either side (historically, 1/5 the beam of the ship), should be designed probabilistically to provide reasonable assurance that an incoming ship will likely not breach the reactor enclosure. In the chance that equipment does get damaged during the collision, redundant equipment is provided on either side of the NS to ensure shutdown capabilities.

The third scenario, and one of highest consequence, is situations where the NS' reactor compartment is damaged. This has the potential to result in the inoperability of various components within the NS' system. Thus, it becomes important to maintain systems of independence and redundancy due to such collision events. Ensuring that two separate shutdown control systems are in place can avoid situations where a missile caused by collision can result in the main control room becoming inoperable. Loss of power due to reactor issues will require the operation of secondary power sources (traditionally diesel generators) to enable operation of emergency reactor systems. In addition, the "Take-Home" system will initiate to avoid the loss of propulsion. In the case of complete loss of propulsion, tugs can be used (assuming the NS is near a port) or otherwise the ship can maintain remote anchorage for emergency relief from the flag nation. One of the more significant concerns is core cooling. The collision can result

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[73] A.N. Other and NHSA Webmaster, "SS Queen Mary & the Loss of HMS Curacoa 1942," Naval Historical Society of Australia, September 1998, https://navyhistory.au/ss-queen-mary-the-loss-of-hms-curacoa-1942/.

[74] Nuclear Regulatory Commission, *10 CFR 50.155(b)(2) - Mitigation of Beyond-Design-Basis Events*, 10 CFR 50.155(b)(2), August 9, 2019.

[75] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

in damages to existing reactor infrastructure that can cause inoperable conditions to various pumps and water sources. As such, feedlines will need access in port and starboard sides of the NS for access to seawater along with redundant equipment in either side for operations.[76] In the event where cooling can no longer be verified, scuttling operations should commence to intentionally sink the reactor for cooling. Separately, such collision can impact existing waste holdings in the reactor compartment. Such events can have reduced risk by redirecting the waste into a secondary tank for storage.

## Chapter 6.2: Grounding

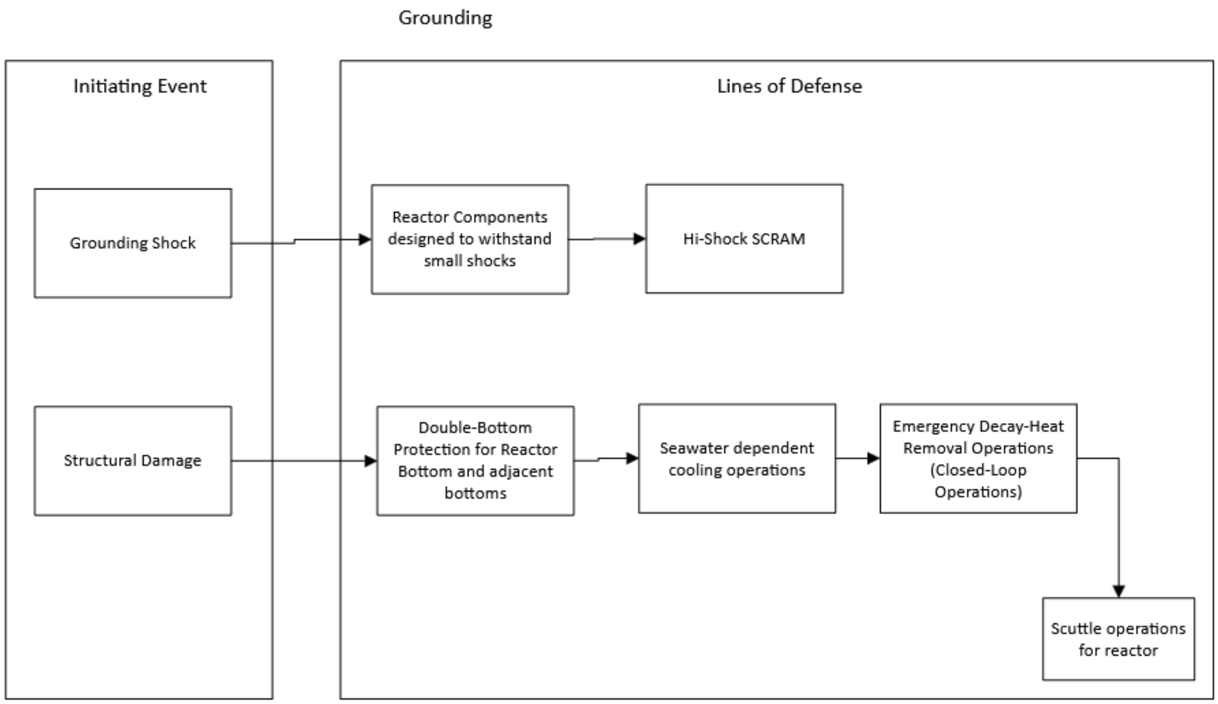

Figure 6: Grounding Event Tree

The second event analyzed is grounding. The bottom of the NS is protected by traditional ship design features (i.e., double-bottom). These traditional features are generally designed to withstand small shocks. However, in the case of large shocks, the reactor will initiate a Hi-Shock SCRAM sequence.

In the event that flooding occurs in the double-bottom, the NS is designed to incur flooding within IMO standards (the flooding of a single compartment).[77] In addition to this, the compartments are also designed for flooding of the bottom of the reactor compartment and its adjacent bottoms. Therefore, the grounding event is likely not to result in significant reactor equipment damage. In the situation where primary cooling mechanism fail (e.g., pump failure for auxiliary cooling), closed-loop cooling can still operate for the reactor system, in addition to the port and starboard cooling pumps. The design

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[76] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

[77] World Nuclear Transport Institute, "Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships."

requirements ensures that the reactor compartment maintains air-tightness to avoid radionuclide release into the ship system, therefore the closed-loop cooling should suffice in such event.

## Chapter 6.3: Environmental Conditions

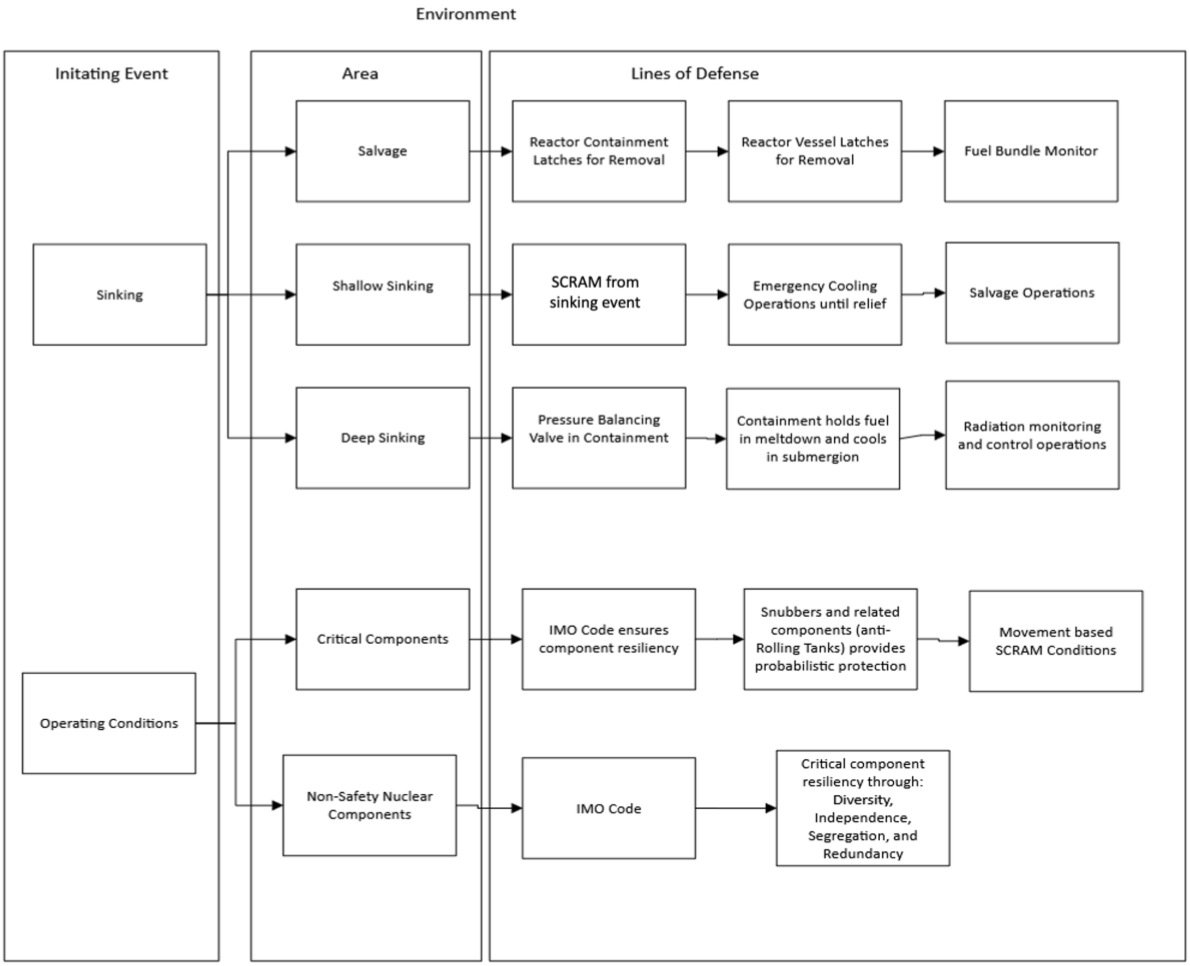

Figure 7: Environment Event Tree

The third event is environmental. The first section of this scenario involves the NS sinking. Sinking is defined in two realms: shallow and deep. In deep sinking, the reactor vessel is deep under the sea. The containment for the reactor should be designed with pressure balancing valves to avoid containment failure. If the valves fail to acuate, a rupture disk should provide the pressure-equalizing function. Should the core melt, the containment is expected to hold the fuel melt and maintain cooling. In the event that all barriers fail, the location of the wreck will be monitored for continuous radiation monitoring and cleanup operations. As witnessed with past naval nuclear submarine accidents, such events do not release significant amounts of radiation.[78] In a shallow sinking scenario, the risk is more severe due to potential releases to the atmosphere and marine environments, along with potential cooling issues. A SCRAM signal initiated by the start of a sinking condition will be required with

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[78] Jim Haddadin, “Navy: No Threat from USS Thresher Wreckage.”

emergency cooling systems in operation. Due to the nature of the sinking event in a shallow scenario, the possibility of relief operations is likely and responders can transport the reactor for scuttling or provide additional equipment.

In the event that the reactor requires salvaging, the installment of latches for the enclosure, the containment, and its contents will be required for the use of helicopters or ships to transport the reactor out of the NS. Finally, markings and trackers built into the reactor will be valuable for recovering the fuel rods in the event of utter catastrophe in the marine floor.

Separate to sinking scenarios, the other aspect to the marine environment is weather related conditions. It is important to note that, as mentioned previously, severe weather events are high-intensity, short-term scenarios, compared to the long-term, low-intensity scenario of cyclic fatigue. As such, the operating conditions related to non-safety nuclear components are less stringent due to their categorization. However, as such components can impact the reactor, its operational conditions must meet existing IMO code and provide further defenses through the principles of independence, redundancy, diversity, and segregation of components. For critical components, which include safety-grade nuclear components, IMO code provides adequate operating conditions for such equipment. However, additional features such as snubbers and other types of dampeners will also be of high importance for the NS to reduce fatigue or shock on the NS's nuclear components.[79] This will provide a layer of protection to avoid entry into conditions beyond design. In the event that movements do occur beyond operating conditions, it can be argued that the reactor components may become inoperable or non-functional. Therefore, a movement-based SCRAM signal would likely be necessary to mitigate such situation.

# Chapter 7: Port Operating Procedures

## Chapter 7.1: Port Acceptance Process

Nuclear ships face unique port acceptance processes surrounding port operating procedural plans and domestic and international port acceptance. Per the ACRS meeting regarding the NS Savannah, each NS type would require a unique operating procedure per port. This is largely due to the difference in environment and capacity for which each port is designed. Operating conditions would be specified for each planned docking at the unique port.[80] Establishing shipping lanes specific for nuclear ships through multilateral treaties can ease potential political burdens.

In the US, such activity would require approval procedures by the USNRC and USCG, with the USNRC reviewing acceptance criteria for each port as a siting zone. Local port regulations would still be applicable for entry.[81] This is contrary to international acceptance process. Since the nuclear vessel would fly the flag of its domestic country, the port operating plan must represent the policy of the flag nation.[82] Operation under flag nation policy is especially important as the sea trial acceptance process will be called into question in the event of an accident, and officials related to the licensing would be

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[79] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

[80] Atomic Energy Commission, "N.S. Savannah Port Approval Procedures," Report to the General Manager by the Director of Reactor Development (Atomic Energy Commission, n.d.).

[81] Atomic Energy Commission, *N.S. Savannah Port Approval Procedures*.

[82] Atomic Energy Commission, *N.S. Savannah Port Approval Procedures*.

called for testimony. Therefore, any international port entrance will require the concurrence of the flag nation prior to submitting for port authorization in a foreign nation.[83] During engagement between a flag and foreign nation, the more restrictive of requirements for port operations will be accepted, with approval authority resting with the foreign nation. For instance, a nation may request the nuclear ship enters port under diesel power, with the reactor shut down.

Prior to port entry, various activities need to be reviewed and confirmed by the Nuclear Ship. This would include testing of all radiation filters within containment to reduce plume from an accident scenario at port.[84] In addition, tests of alternative propulsion systems would need to be verified in the event of emergency response. These prior to port checks can reduce risk of equipment failure for potential accident conditions while near the public.

## Chapter 7.2: Docking Requirements

When the Nuclear Ship is docked, moored, or her mobility is compromised, codes related to Floating Nuclear Power Plants (FLOPPS) may be applicable. Otherwise, the Nuclear Ship can also enter a cold shutdown state for its reactor to reduce risk of radioactive release.

Existing stationary plant norms related to Emergency Planning Zones will be ill suited for a Nuclear Ship, as its primary benefit is its maneuverability, and ship needs result in a significantly smaller reactors than what currently exist. As such, the combination of time and radiation exposure may be better suited to evaluate the multiple zones instead. The designated zoning size and specific layout must therefore also be dictated by both the port city's characteristics (such as emergency response abilities and geography) as well as the reactor's (such as power and coolant).[85] More clearly, the design of the control zone and Low-Population Zone should be situated around set exposure limits. However, regulations stipulate that "the population center distance, as defined in § 100.3, must be at least one and one-third times the distance from the reactor to the outer boundary of the low population zone."[86] This causes potential docking issues for Nuclear Ships near major cities (e.g., Boston).

Due to the nuclear propulsion mechanism of the ship, a 2-hour and a 24-hour zone needs to be established with the equivalent radiation levels of a controlled zone and low-population zone respectively.[87] These zones are variable and dependent upon the fission product inventory of the reactor in order to conduct operations for emergency removal. This will support attempts to maintain control over potential damages while a reactor temporarily moors enroute to a final docking station.[88]

## Chapter 7.3: Remote Anchoring Locations

For reactor accident scenarios, the ability to transport the reactor can be beneficial in reducing the potential damages. As such, remote anchoring locations will be pre-determined prior to port entry that can establish sufficient distance between population zones and the reactor itself. This location is to be

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[83] Atomic Energy Commission, *N.S. Savannah Port Approval Procedures*.

[84] Kramer and US Atomic Energy Commission, *Nuclear Propulsion for Merchant Ships*.

[85] Nuclear Regulatory Commission, *10 CFR Part 50 - Domestic Licensing of Production and Utilization Facilities*, 10 CFR Part 50, n.d., https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/full-text.html.

[86] Nuclear Regulatory Commission, *10 CFR 100.21 - Non-Seismic Siting Criteria*, 10 CFR 100.21, n.d., https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/part100-0021.html.

[87] First Atomic Ship Transport Inc., *NS Savannah Safety Assessment Revision 3*.

[88] First Atomic Ship Transport Inc., "Port Operating Criteria," First Atomic Ship Transport Inc., 1969.

reached prior to 2 hours post-accident, in relation to the 2-hour zone described earlier.[89] This concept is illustrated in Figure 8.

When designing these locations, the ability for the Take-Home Motor to operate should be considered in the event of tug boat delays. The motor should enable travel distance within 2 hours and have sufficient fuel for such travel.

Stand-by tug service should be accredited to arrive at least 30 minutes prior to the start of fuel melt, in order to provide additional propulsion assistance in cases where the emergency propulsion is unavailable.

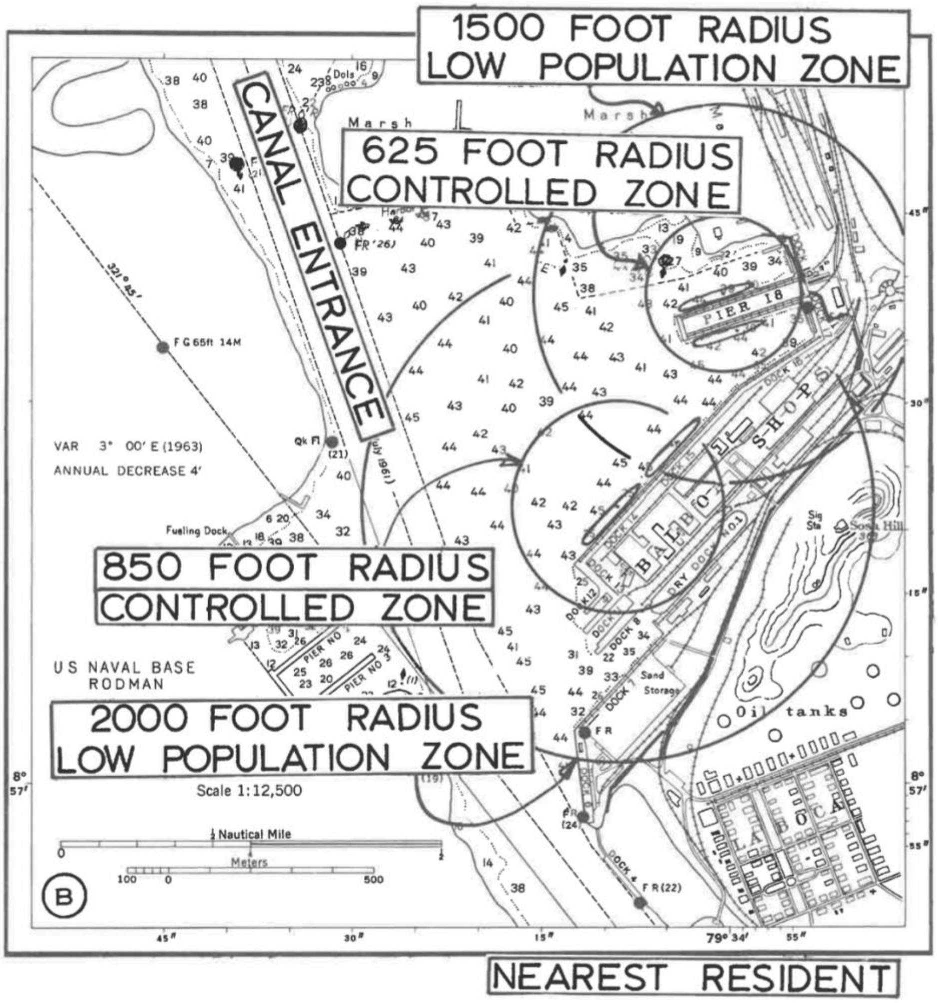

Figure 8: Port Operating Procedure Zone Chart of Panama Canal Entrance[90]

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[89] First Atomic Ship Transport Inc., "Port Operating Plan for Boston, Massachusetts," First Atomic Ship Transport Inc., 1964; First Atomic Ship Transport Inc., "Port Operating Criteria."

[90] First Atomic Ship Transport Inc., "Port Operating Plan for The Panama Canal Transit and the Ports of Balboa and Cristobal," First Atomic Ship Transport Inc., n.d.

# Appendix 1: Annotated Bibliography

Modern Nuclear Ship Regulations and Sources:

- American Bureau of Shipping. “Requirements for Nuclear Power Systems for Marine and Offshore Applications.” ABS, October 2024.
    - The American Bureau of Shipping is a maritime classification society. They published these requirements for static marine nuclear power plants that are not designed for maritime operations.
- World Nuclear Transport Institute. “Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Gap Analysis of the Code of Safety for Nuclear Merchant Ships.” International Maritime Organization, March 12, 2024.
    - The World Nuclear Transport Institute is a non-governmental membership organization. They analyzed gaps in the 1981 IMO Resolution A.491(XII) on the Code of Safety for Nuclear Merchant Ships (the Nuclear Code), and submitted their findings to the IMO.
- The Secretary of State. “The Merchant Shipping (Nuclear Ships) Regulations 2022.” Statute Law Database. Accessed November 19, 2024. https://www.legislation.gov.uk/uksi/2022/1169/contents/2023-03-29.
    - In 2022, the UK government published these regulations, which overall endorse the 1981 IMO code. These regulations only apply in UK waters.

- RMRS. “Rules for the Classification and Construction of Nuclear Ships and Floating Facilities,” 2022.
    - The Russian Maritime Register of Shipping is a Russian classification society. As Russia maintains an active merchant nuclear fleet, they have issued more recent nuclear ship guidance.

Older or Historic Nuclear Ship Regulations and Guides:

- American Bureau of Shipping. “Guide for the Classification of Nuclear Ships.” American Bureau of Shipping, 1962.
    - The American Bureau of Shipping is a maritime classification society. They published this as a guide instead of regulation “due to the lack of experience in operation of nuclear merchant ships and because the various reactor concepts which are being considered for use will each pose different problems.”

- US Coast Guard. “46 CFR”, 1960s-1970s
    - The US Coast Guard released these regulations throughout the 1960s and 1970s regarding nuclear merchant ships.
- “IMO Resolution A.491(Xii).” International Maritime Organization, November 19, 1981. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.491(12).pdf.
    - The International Maritime Organization is the United National agency responsible for shipping concerns. This resolution offers specific guidance regarding nuclear merchant ships and is still in place in 2025.

N.S. Savannah Archive and Historic Ship Documents:

- Kramer, Andrew W. and US Atomic Energy Commission. Nuclear Propulsion for Merchant Ships. U.S. Atomic Energy Commission, 1962.
    - Written under the advisory of the Atomic Energy Commission, this book thoroughly analyzes commercial marine nuclear propulsion. It has a strong focus on the N.S. Savanah and details the thought processes of the ship's design.

- Atomic Energy Commission. "N.S. Savannah Port Approval Procedures." Report to the General Manager by the Director of Reactor Development. Atomic Energy Commission, n.d.
    - The report was found in the N.S. Savannah Archives. It documents a report from the Director of Reactor Development to the General Manager. It considers "a regime under which additional domestic port visits and foreign voyages would be undertaken by the N.S. Savannah. The report was written after July, 1962.

- First Atomic Ship Transport Inc. "NS Savannah Safety Assessment Revision 3." The Maritime Administration, October 1968.
    - The operators of the N.S. Savannah, the First Atomic Ship Transport Inc (FAST) wrote the Safety Assessment as required by SOLAS Convention Requirements. It provides a detailed analysis of the ship and its engineering.

- The Maritime Administration. "Updated Final Safety Analysis Report Rev. 7," May 1, 2013. https://www.maritime.dot.gov/sites/marad.dot.gov/files/docs/national-defense-reserve-fleet/ns-savannah-program/6096/nss-ufsar-rev-vii-2013.pdf.
    - Similar to the Safety Assessment from FAST, this is the final Safety Analysis report.

- First Atomic Ship Transport Inc . "Port Operating Criteria." First Atomic Ship Transport Inc., 1969.
    - The report was found in the N.S. Savannah Archives. FAST wrote this document detailing the "basic limitations" on the Savannah's port operations. It discusses accident plans, port entry acceptance, and other relevant port operation information.

- First Atomic Ship Transport Inc . "Port Operating Plan for Boston, Massachusetts." First Atomic Ship Transport Inc., 1964., ———. "Port Operating Plan for The Panama Canal Transit and the Ports of Balboa and Cristobal." First Atomic Ship Transport Inc., n.d.
    - These reports were found in the N.S. Savannah Archives. The port operating plans for Boston and the Panama Canal trip outline the operation and emergency procedures for the Savannah's time in and approaching port.

- "Final Safety Review N.S. Otto Hahn," n.d.
    - This review was submitted by the N.S. Otto Hahn's designers to comply with SOLAS Convention requirements. The final safety review provides a detailed analysis of the ship and its engineering.

- "N.S. Mutsu Accident Diagram," n.d.
    - This diagram was found in the N.S. Savannah Archives. During the creation of the N.S Mustu, event trees of accident scenarios were created and documented on this diagram from the original designers.

- Martin Kolb. “Performance of the 1. Core of the ‘Otto Hahn,’ by M. Kolb and W. Schumacher.” Rio de Janeiro, Comissão Nacional de Energia Nuclear, 1972. Library of Congress.
    - This document was found in the Library of Congress in D.C. It discusses the behavior of the Otto Hahn’s reactor.

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American Bureau of Shipping. “Pathways to a Low Carbon Future LNG Carrier Nuclaer Ship Concept Design.” American Bureau of Shipping, 2024. https://ww2.eagle.org/content/dam/eagle/publications/whitepapers/pathways-to-low-carbon-lng-carrier.pdf.

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Colin Campbell. “First Chief Engineer Returns to N.S. Savannah in Baltimore.” *Baltimore Sun*, n.d. https://digitaledition.baltimoresun.com/tribune/article_popover.aspx?guid=5d09ff78-eaed-4c31-a101-734e71cf27f1.

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———. “10 CFR Part 50 - Domestic Licensing of Production and Utilization Facilities,” n.d. https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/full-text.html.

U.S. Nuclear Regulatory Commission. “Compliance with Order EA-12-049, Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events.” U.S. Nuclear Regulatory Commission, February 2017. https://www.nrc.gov/docs/ML1700/ML17005A188.pdf.

———. “Controlled Area.” U.S. Nuclear Regulatory Commission, March 9, 2021. https://www.nrc.gov/reading-rm/basic-ref/glossary/controlled-area.html.

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Valiaveedu, Anthony R., Nat Edmonds, and Drew Honson. “Navigating the Regulatory Seas for Commercial Maritime Nuclear Propulsion.” *MIT Science Policy Review* 6 (August 5, 2025). https://sciencepolicyreview.pubpub.org/pub/bbyy4txd.

Zhibo Zhang and Jin Jiang, “On Load-Following Operations of Small Modular Reactors,” *Progress in Nuclear Energy* 173 (August 2024): 105274, https://doi.org/10.1016/j.pnucene.2024.105274.

## Appendix 2: Initial Literature Review

**References:**

- USCG – US Coast Guard
- CFR – Code of Federal Regulations
- IMO – International Maritime Organization's Resolution A.491(XII) on the Code of Safety for Nuclear Merchant Ships
- ABS.Nuclear Ships – American Bureau of Ships' Guide for the Classification of Nuclear Ships
- ABS.FLOPS – Requirements for Nuclear Power Systems for Marine and Offshore Applications
- MARAD – First Atomic Ship Transport Inc., NS Savannah Safety Assessment Revision 3
- Kramer – Nuclear Propulsion for Merchant Ships
- RMRS – Russian Maritime Register of Shipping's Rules for the Classification and Construction of Nuclear Ships and Floating Facilities

**General guidelines:**

1) **General Principles for Nuclear Ships:**

a) Be as safe as any other vessel in their class with the respect to the usual hazards at the sea which shall include safety at sea or in port for crew, food, water supply, passengers, public, or waterways. USCG.46 cfr.61.25-1; USCG.46 cfr.79.15-1

b) To the maximum extent practicable, the complete control system shall be so designed that no operational restrictions are imposed upon the nuclear ship that would not also apply to a conventionally powered ship of like size and power. IMO A2.7, 4.4.4.5, page 158

   i) No privileges in sailing rules shall be afforded to nuclear ships that do not equally apply to conventionally powered ships of similar type, IMO A2.10, 7.1.1.1, page 234

c) Prevent hazardous radiation exposure from a credible accident which shall include the events of collision, grounding, flooding, sinking, heavy weather, fire, and explosion. ABS.FLOPS, 4.1.1

d) Minimize risk of production of nuclear weapons. ABS.FLOPS, 4.1.1

2) **Redundancy, Independence, Segregation, and Diversity Requirements for Nuclear Operations in safe ship design.**

a) Ship shall incorporate redundancy, independence, segregation, and diversity means in systems and components essential for ensuring safe operations for maritime nuclear operations, as defined below: ABS.FLOPS, 4.1.2 [A.419(XII) 3.1.13.2],

   i) Redundancy - replicating systems or components to provide excess capability for fulfilling essential functions so that fundamental safety functions can be fulfilled following a single failure. IMO A2.4, 1.3, page 54-57

   ii) Independence - requires that functioning of one system does not rely in any way upon functioning of another given system. IMO A2.4, 1.3, page 54-57

        - iii) Segregation - physical separation of systems performing common function to reduce probability of concurrent loss from a common external cause. IMO A2.4, 1.3, page 54-57
        - iv) Diversity - protection of systems and components performing the same task from common cause failure (CCF), by having them differ from each other as regards design, operation, manufacturer, etc. IMO A2.4, 1.3, page 54-57

3) **Electrical Requirements: Needs for effective and safe electrical system**

- a) Except where otherwise modified by the provisions of this Chapter, conventional main and auxiliary requirements shall comply with SOLAS Regulation II-1/26 and electrical systems with SOLAS Chapter II -1. IMO A2.8, 5.1.0, page 182
- b) The reliability of the electrical installation shall be commensurate with the requirements for both nuclear and ship safety given in this Code and in SOLAS Chapter II-1 – Part D – Electrical Installations and ABS regulations. IMO A2.8, 5.8.1, page 190
    - i) Ship must enable all electrical services required for safety to be available during emergency conditions. (SOLAS II-1 Reg 40-1.2). ABS.FLOPS, 7.1.1, POW 4
- c) Main and emergency electrical systems, in any state, are to be capable of shutting down the reactor and maintaining a safe state for a sufficient period. ABS.FLOPS, 7.1.2, POW-FR1; ABS.FLOPS, 7.2.1, 2.1
- d) The design of the electrical power system shall permit appropriate periodic inspection and testing of equipment important to nuclear safety and ship safety. IMO A2.8, 5.8.9, page 192;
- e) A single generator failure, along with prime mover and auxiliaries, shall not:
    - i) Cause a reactor trip. IMO A2.8, 5.9, page 194; ABS.FLOPS, 7.1.2, POW-FR31
    - ii) Cause loss of maneuverability of the ship. IMO A2.8, 5.9, page 194
    - iii) Will still permit full electrical power necessary for maintaining the ship in normal operational and habitable conditions to be restored within a few minutes. IMO A2.8, 5.9, page 194; ABS.FLOPS, 7.1.2, POW-FR31
    - iv) Affect NPP ability for startup from dead ship conditions or minimum conformable and habitable conditions during reactor startup. IMO A2.8, 5.8.11, page 193

**Marine Accidents: Accident situations introduced by marine operation**

1) **Collision: Contact between two ships, or ship and object in water.**
    - a) The reactor and containment vessel must be designed to withstand collision conditions. USCG.46 cfr.79.05-10; IMO A2.5, 2.3.7, page 90
        - i) The reactor shall be designed to limit mechanical and cyclical stresses under the effects of vibration, shock loading and accident conditions. IMO A2.5, 2.4.1, page 91;
        - ii) Decay heat removal must be maintained in collision scenario. Kramer, 244 - 256
        - iii) Collisions should be analyzed based upon harbor approach areas, due to the heavy traffic and high speed of ships. MARAD, 12-4-6

- b) The design adjacent to the reactor compartment should be given special consideration to provide maximum practicable protection to the nuclear plant in case of collision. ABS.Nuclear Ships.2.3;
    - i) Collision protection should be provided to prevent containment shell penetration, rupture, cracking, leaks, and uncontrolled lease of radioactive materials, should the ship be struck. ABS.Nuclear Ships.2.3; ABS.FLOPS, 4.1.2, SAFE-FR1 (ENV); IMO A2.6, 3.5.2, page 136
    - ii) When considering collision scenario, the striking ship should be considered to be a ship with bow structure similar to the sketch (see Figure 9), operating at a speed of 15 knots at the time of collision. The struck ship should be considered at all design speeds. ABS.Nuclear Ships.2.3
    - iii) Collision protection should extend far enough in the fore and aft direction to be effective when the striking ship approaches at any angle between 300 and 150° and should extend vertically far enough to ensure that the top and bottom of the containment cannot be damaged. ABS.Nuclear Ships.2.3
- c) The ship shall be designed to withstand and avoid collision conditions. IMO A2.5, 2.3.7, page 90
    - i) The ship shall comply with the subdivision and damage stability IMO Guidelines under SOLAS Chapter II-1. This shall also apply to the extent of vertical, bottom and Longitudinal damage. IMO A2.6, 3.4.1, page 129
    - ii) When collision protective structures specially designed to limit penetration of a stricken ship are fitted abreast of the AMR compartment or the propulsion machinery space. Lesser extent of side damage can be accepted given equivalent flooding protection is provided. IMO A2.6, 3.4.1, page 129
    - iii) When assessing collision situations, ship design shall consider possible interactions between NPP, ship, cargo, intended service, and possible resulting ship damage and flooding of compartments. IMO A2.4, 1.3.9, page 53; IMO A2.5, 2.7.1, page 105
    - iv) A nuclear ship shall be fitted with an anti-collision aid and at least two radars, The Operational requirements of the radar system shall comply with resolution MSC.192(79). IMO A2.6, 3.7.1, page 140
- d) In the cases where the ship is the striking vessel, the ship shall be able to withstand a shock of 1g without damage to the reactor. [MARAD, 12-4-6]

2) **Grounding: An incident when the ship makes contact with the seafloor or underwater obstruction.**
- a) Ship design must provide location, structural support, construction, and protection of and around reactor that gives maximum practical defense in case of grounding. USCG.46 cfr.79.05-10; ABS.Nuclear Ships.2.3
    - i) Protections must prevent penetration, rupture, cracking, leaks, or damage of reactor compartment in grounding situation. ABS.FLOPS, 4.1.2, SAFE-FR1 (ENV)
    - ii) Protections must control and account for release of radioactive materials, including waste, in grounding situation. ABS.FLOPS, 4.1.2, SAFE-FR1 (ENV)
- b) Ship design must consider effect on sea water intake in case of grounding.
    - i) Ship design must account for limited sea water intake through board and bottom openings. RMRS, PART VIII, 7.5

        - ii) Ship design must account for grounding in tidal water with regular interruption of sea water supply.
    - c) Reactor system must withstand damage associated with grounding conditions, including structural failure and compartment flooding. ABS.FLOPS, 5.1.1, STRU 2; IMO A2.5, 2.7.1, page 105
    - d) No primary system or containment failure can result from the ship resting on its side. MARAD, 12-6
        - i) Sea water intake and cooling systems must account for any inclination caused by grounding. IMO A2.5, 2.7.3, page 107, MARAD, 12-7
    - e) Ship design must account for shock load, penetration effect, and potential for break up due to grounding. IMO A2.5, 2.3.7, page 90; MARAD, 12-7; Kramer, 256-257
    - f) Emergency power system and cooling system must withstand grounding conditions. Kramer, 256-257
    - g) Ship shall comply with the subdivision and damage stability IMO Guidelines under SOLAS Chapter II-1. This shall also apply to the extent of vertical, bottom and Longitudinal damage. IMO A2.6, 3.4.1, page 129
- 3) **Sinking, Flooding, and Capsizing: (SFC) When ship fills with water, sinks, and/or turns on side and water enters ship. SFC includes both deep water situations, where factors such as depth and pressure must be considered, and shallow water conditions, where surface proximity and increased possibility for environmental and human contamination must be considered.**
    - a) Ship design must limit reactor damage and fissile product release in SFC situation in an intact, damaged, or cargo loading condition. IMO A2.5, 2.7.2, page 107
        - i) Ship design must provide adequate decay heat removal and shut down operation in case of SFC.
            - (1) If primary cooling or power systems fail due to SFC, emergency generator and cooling system, until submerged, must support decay heat removal. Kramer, 257 - 259
            - (2) Ship design must provide reactor heat sink to prevent core melt in case emergency generators and cooling systems are inoperable due to SFC. Kramer, 257 - 259; IMO A2.7, 4.3.2.5, page 154
            - (3) The reactor shutdown systems shall be able to operate automatically in accident conditions which includes when the containment is flooded, the ship is submerged, and it is inclined at an angle as defined in the Safety Assessment. IMO A2.7, 4.3, page 150
        - ii) Containment vessel should be designed to withstand SFC. IMO A2.7, 4.11.1.4, page 173
            - (1) Containment vessel and its internal components should be designed to remain in place regardless of orientation in the event of the ship sinking. USCG.46 cfr.55.15-3; IMO A2.5, 2.3.9, page 90; ABS.Nuclear Ships.3.8;
            - (2) Containment vessel must contain radioactive materials in case of SFC. Kramer, 257 - 259
                - (a) Containment must account for pressure difference caused by sinking, corrosion, ocean movement, and salvage operations and timing(if any).

        Kramer, 257 - 259; MARAD, 12-10; USCG.46 cfr.55.15-15; ABS.Nuclear Ships.3.8; ABS.FLOPS, 4.1.2, STRU-FR41
        - (i) Consideration should be given to the provision of a positive means for flooding the containment in case of accidental sinking of the ship. ABS.Nuclear Ships.9.2.4; USCG.46 cfr.55.15-15; ABS.Nuclear Ships.3.8
        - (ii) Containment vessel should withstand hydrostatic test 1.25 times the maximum allowable working pressure. USCG.46 cfr.61.10-5
    - b) Nuclear waste handling arrangements should prevent displacement of safety systems in SFC conditions. RMRS, PART XII, 5.16
- 4) **Fire and explosion: Fire or explosion on ship caused by vessel systems, cargo, crew, or external factors.**
    - a) All systems shall be designed, arranged, and located so as to minimize the probability of fires and explosions. IMO A2.6, 3.8.2, page 141
        - i) Risk of explosion or fire originating from either the cargo, other systems or equipment present on the asset, or external sources shall be analyzed. IMO A2.6, 3.9.8, page 143
        - ii) Ship should limit explosive, flammable, or fissile cargo. Kramer, 261; IMO A2.10, 7.1.1.4, page 235
        - iii) Ship must protect from external hazards, particularly smoke, toxic gasses, and fires. RMRS AP1 9.6; ABS.FLOPS, 4.1.2, SAFE-FR1 (ENV); IMO A2.5, 2.7.8, page 109
    - b) All systems shall be designed, arranged and located so as to reduce the risk of damage caused by fire and explosion to the ship, its cargo, crew and the environment. (SOLAS II-2/Reg 2.1.3); IMO A2.6, 3.8.2, page 141
    - c) In case of fire, reactor system and containment must maintain integrity. ABS.FLOPS, 6.1.1, FIR 1; SOLAS II-2/Reg 2.1.1
        - i) Additional fire protection structure, equipment and systems may be required to ensure that the integrity of the shielding, the containment structure, the safety enclosure, and essential reactor safety systems is maintained. IMO A2.6, 3.9.1, page 141; ABS.FLOPS, 4.1.2, STRU-FR1
        - ii) Systems within spaces such as the reactor compartment and spaces containing equipment essential to the continued safe operation of the reactor and the NPCS or necessary to ship's operation, such as standby generating sets or auxiliary power sources, shall be segregated and physically separated by structural fire protection and be provided with individual fire- extinguishing equipment. IMO A2.6, 3.9.7, page 143; ABS.FLOPS, 8.2, Requirements for Fire Safety
        - iii) The reactor control station should be provided protection against external fires or explosion. ABS.FLOPS, 4.1.2, STRU-FR1
    - d) The ship must provide adequate systems to detect, contain, control and suppress or swiftly extinguish a fire in the compartment of origin. ABS.FLOPS, 8.1.2, Functional Requirements; (SOLAS II-2/Reg 2.1.4)
        - i) All spaces containing safety systems and equipment essential to the safety of the NPCS and personnel shall be fitted with a fire detection and alarm

        system, and a remote fire suppression system which uses an agent that is as non-corrosive as practicable. IMO A2.6, 3.9.3, page 142
        ii) Consideration should be given to: use of fire-extinguishing agents that permit easy decontamination; limited use of ionization detectors in spaces which may have high radiation levels. IMO A2.6, 3.9.4, page 142
        iii) Loss of power may not limit the ship's ability to address fire or explosion. Kramer, 259 - 261
    e) The design of the ship and the reactor shall take account of shock loads from explosion, pressure waves and missiles generated by failure of pressured systems or rotating machinery. An analysis of the explosion hazard for the particular ship should be prepared and submitted to show that the design will protect the containment against such explosions. ABS.Nuclear Ships.3.7.3; IMO A2.5, 2.3.7, page 90; IMO A2.5, 2.7.5, page 108
5) **Salvage: Rescue of disabled or damaged ship at sea**
    a) The reactor compartment shall be so designed as to facilitate the salvage of the reactor or recovery of its essential parts from the ship in the event of a shipwreck without prejudicing the safety of the reactor installation in normal service. IMO A2.6, 3.1.4, page 117
    b) If the ship is inaccessible to salvage, fission products must have negligible environmental contamination or procedures to permit sampling, purging of containment contents, and decommissioning the vessel. MARAD, 12-1; ABS.Nuclear Ships.3.8; MARAD, 12-11
    c) The marking and the surveillance of the wreck shall be arranged as far as practicable. IMO A2.4, 1.9.3, page 69
6) **Aircraft Impact: Impact from aircraft**
    a) Ship design must consider a collision from an aircraft. IMO A2.5, 2.7.7, page 109; RMRS AP1 9.6; RMRS, PART IV, 5.1

**Emergency Systems and MCA Scenario: Systems required during emergencies due to failure of primary systems or accident scenario**

1) **Emergency Power Systems: Power generators and supply for back up and emergencies.**
    a) The NPP shall be designed to have a reliability at least equal to the reliability of a conventional propulsion plant. IMO A2.8, 5.7, page 189
    b) A temporary and final source of emergency power, as required for ocean-going passenger vessels over 1,600 gross tons, shall be provided to insure an uninterrupted power supply to nuclear instrumentation, control, and safety systems. USCG.46 cfr.79.05-01
    c) In accordance with present Rules, ship's service should be provided by at least two generator sets and the aggregate capacity should be sufficient to carry the sea load under normal operation with any one generator in reserve. ABS.Nuclear Ships.8.3
    d) The self-contained emergency source of electrical power situated above the bulkhead deck and outside the machinery casings should in addition to its usual duties also provide sufficient power to operate any other devices necessary for the safe securing of the nuclear installation, such as control rod mechanisms and cooling pumps. Controls for the emergency operation of these devices should be

located above the bulkhead deck anti outside of the machinery casings. ABS.Nuclear Ships.9.3

e) The emergency power must power reactor safety systems as long as required to support safe shutdown, cooldown and maintenance of a safe state under worst case power history. ABS.FLOPS, 5.1.2, AUTO-FR7; ABS.FLOPS, 2.4, Table 3:
    i) Ship must have at least 2 different means of decay heat removal available after reactor shutdown. MARAD, 1-8
    ii) Systems essential for reactor shutdown and holding in safe state [A.491(XII) 5.10.3.1]. ABS.FLOPS, 7.1.2, POW-FR1
    iii) All reactor protection and safety systems [A.491(XII) 5.10.3.3], and related safety loads, including: a. Controls and monitoring equipment of reactor safety systems [A.491(XII) 5.11.4.1], b. Radiation protection monitoring systems [A.491(XII) 5.11.4.2], c. Any other reactor controls and monitoring equipment [A.491(XII) 5.11.4.3]
    iv) Emergency lighting in all reactor control spaces or emergency control areas. ABS.FLOPS, 2.4, Table 3
        (1) Emergency lights shall be fitted in spaces as follows: RMRS, PART X, 6.2
            (a) Central control station;
            (b) Reactor emergency cooling station;
            (c) Spaces to be attended by personnel within the controlled area and compartments important for safety of the steam supply system;
            (d) Radiation monitoring station (if located separately);
            (e) Special switchboards of the steam supply system (if available);
            (f) Storage places of new and wasted fuel assemblies.
            (g) All storage and outfitting positions for radiation protection gear and decontamination stations, including systems and components for the purpose of decontamination, if fitted. ABS.FLOPS, 2.4, Table 3
    v) Primary and secondary HVAC systems ABS.FLOPS, 2.4, Table 3
    vi) Communication systems throughout the nuclear power plant areas including the reactor control spaces and emergency control areas. ABS.FLOPS, 2.4, Table 3
    vii) Process radiation monitoring systems. ABS.FLOPS, 2.4, Table 3
    viii) Fire protection systems for NPP and nuclear power service vessel. ABS.FLOPS, 2.4, Table 3
    ix) Containment cooling systems. ABS.FLOPS, 2.4, Table 3
    x) NPP security systems. ABS.FLOPS, 2.4, Table 3
    xi) Survival craft protection systems, including external drenching systems for decontamination, if fitted. [A.491(XII) 3.8.2]. ABS.FLOPS, 2.4, Table 3
    xii) Systems and components provided for security measures, including security doors and monitoring arrangements, including emergency lighting for security control spaces, if fitted. ABS.FLOPS, 2.4, Table 3

f) The ship’s electrical services necessary for maintaining the vessel in normal operational and habitable conditions are to be available through emergency power sources. (SOLAS II-1 Reg 3-7 and SOLAS II-1 Reg 40-1.1). ABS.FLOPS, 5.1.2, AUTO-FR7

    - i) All electrical services required for safety are to be available during emergency conditions. (SOLAS II-1 Reg 40-1.2) ABS.FLOPS, 7.1.1
- g) Ship must allow supply/power for essential services to be restored after malfunction. ABS.FLOPS, 7.1.1
- h) Ship must be provided with means to enable the safe conduct of towing, mooring and anchoring operations. (SOLAS II-1 Reg 3-8.2). ABS.FLOPS, 7.1.1
    - i) Ship must be provided with the means to enable shore power for distributing safe shutdown equipment power.
- i) Consideration will be given to the omission of duplicate components if the plant can be operated with the purification system secured and without hazard, for sufficient time to permit the ship to reach a port where repairs can be effected. ABS.Nuclear Ships.8.2
- j) Emergency electrical systems and generators can be started automatically or manually. MARAD, 8-24, 8-28, 8-36, 12-2
- k) Fuel systems for emergency generators shall minimize risk of failure
    - i) Fuel system shall be designed so as similar-type failure shall not cause failure of all generator sets. RMRS, PART VII, 6
    - ii) Daily service fuel tanks shall be placed as close to diesel generators as possible. RMRS, PART VII, 6
    - iii) Stand-by and emergency diesel generators shall use the same fuel. Fuel storage tanks shall allow its mutual transfer. RMRS, PART VII, 6
    - iv) Stand-by diesel generators shall have enough fuel to provide operation at lull load considering expected length of ship/floating facility voyages. RMRS, PART VII, 6
    - v) Fuel in emergency diesel generators shall provide operation for at least 30 days after any emergency state. RMRS, PART VII, 6
- l) Communication
    - i) At least one system of communication, which is to be available in the event of complete loss of electrical power, is to be provided between each of the locations [A.491(XII) 5.3.1]: ABS.FLOPS, 9.2.1, Communications
        - (1) Navigating bridge;
        - (2) Reactor control room;
        - (3) Emergency control position;
        - (4) Machinery space containing main propulsion machinery, main service generating sets, standby generating sets and emergency generating sets;
        - (5) The main and emergency machinery control rooms, if any
        - (6) Accessible spaces of the reactor compartment.

2) **Emergency Propulsion and Take Home Motor. Backup propulsion system that can bring ship to safety in case of reactor propulsion failure.**

- a) All nuclear ships shall be fitted with two fully independent propulsion systems. IMO A2.6, 3.12, page 145
    - i) In case of nuclear ships fitted with a single reactor,
        - (1) It shall be possible to power the propulsion systems by means of an auxiliary back-up power source. IMO A2.6, 3.12, page 145
        - (2) It shall be provided with an auxiliary power source capable of driving the propulsion plant, which shall:

        - (a) have sufficient power to permit the ship to operate safely in port or harbour and to maintain steerageway in sea conditions corresponding to a wind force of Beaufort 6 approaching the ship on the beam, with the ship in any normal condition of loading. IMO A2.8, 5.7, page 189
        - (b) be in a state of readiness when the ship is under way in narrow or congested waters. IMO A2.8, 5.7, page 189

b) Cold start of emergency propulsion must occur in a 2 minute time frame. MARAD, 8-21,8-22,8-23; Kramer, 141,

c) Take home motor must successfully dock and undock the ship. MARAD, 8-21,8-22,8-23

d) Take home motor must successfully navigate in reasonable sea conditions, such that power is sufficient to allow for turning ship away from wind and running with the sea if operation is desirable. Kramer, 150

**3) Reactor Control Room**

a) Reactor Control
  - i) The control system shall be designed to control reactor power, in response to operational demand, under all anticipated ship maneuvers and sea states during normal operation, abnormal operational occurrences and, where possible, in accident conditions. IMO A2.7, 4.4.4.5, page 158
  - ii) Reactivity control for the reactor system shall take account of the motion of the ship during normal operation and in accident conditions. IMO A 2.7, 4.2 Page 148
    - (1) The means of reactivity control should be capable of rendering the core subcritical by a sufficient margin during and after the service life of the core, including periods of maintenance, refuelling, reactor accident conditions and ship accident conditions including capsizing and sinking; IMO A2.7, 4.3.2.5, page 154; ABS.FLOPS, 5.1.2, SAFE-FR2 (AUTO)
  - iii) Systems for reactor controls are to be operable such that the reactor can be placed in a subcritical state without exceeding any of the specified fuel or other design limits [A.491(XII) 2.1.2.3.2]. ABS.FLOPS, 5.1.2, AUTO-FR11
  - iv) All control and safety shutdown systems are to be designed for safe operation of the equipment during start-up, shutdown and normal operational conditions. ABS.FLOPS, 9.1.4, III; ABS.FLOPS, 5.1.2, SAFE-FR2 (AUTO)
  - v) Failure of any control component shall not prevent the safe shutdown of the reactor [A.491(XII) 4.4.1] ABS.FLOPS, 5.1.2, AUTO-FR6
  - vi) Protection and safety systems are to start or operate automatically during the initial period of an emergency situation, and to keep reactor plant in a safe condition for at least 30 minutes without crew assistance. ABS.FLOPS, 5.1.2, AUTO-FR2; IMO A2.7, 4.8.1, page 167; ABS.FLOPS, 9.1.1, AUTO 5; ABS.FLOPS, 5.5.1, 5.5.1

**4) Emergency Control Systems: Secondary room for controlled shutdown**

a) Ship must have, as separate and remote from the reactor control room, an emergency control position shall be provided. IMO A2.6, 3.1.13.6, page 124

b) The secondary control room shall be possible for an operator to bring the reactor to a safe stable shutdown condition while maintaining residual heat removal. IMO A2.6, 3.1.13.6, page 124
    i) The emergency control position may be functionally connected with the navigating bridge so that, in case of emergency, a scram procedure could be performed under the control of the navigating bridge. IMO A2.6, 3.1.13.7, page 124
    ii) The emergency control position shall not affect the ability to control the reactor at the main control room. ABS.FLOPS, 8.2.3, 2.3;
c) The use of an emergency control position shall enable the reactor to be brought to a long term safe stable state where all the fundamental safety functions are being maintained, in the event of a fire in the main control room. Conversely, a fire at the emergency control position is not to affect the ability to control the reactor at the main control room. IMO A2.6, 3.9.7, page 143; ABS.FLOPS, 8.2, Requirements for Fire Safety
d) The emergency control room shall:
    i) Have the capability to initiate and monitor the operation of the reactor shutdown systems. IMO A2.7, 4.3.2.7, page 155; ABS.FLOPS, 5.1.2, AUTO-FR5
    ii) Have the capability to bring the reactor to a long term safe stable state where all the fundamental safety functions are being maintained, even in event of fire in main control room. IMO A2.6, 3.9.8, page 143
    iii) Be physically separate and remote from the primary control room. ABS.FLOPS, 4.1.2; ABS.FLOPS, 5.1.2, AUTO-FR5; RMRS, PART VII, 5.2
    iv) May be functionally connected with the navigating bridge so that, in case of emergency, an emergency shutdown procedure could be performed under the control of the navigating bridge [A.491(XII) 3.1.13.7] ABS.FLOPS, 4.1.2
    v) Provide the equivalent degree of safety and operability as those provided by local controls. ABS.FLOPS, 5.1.1, AUTO 4
    vi) Have the capability to operate residual heat removal from reactor. [A.491(XII) 4.4.4.4]. ABS.FLOPS, 5.4.2, 4.2
e) For emergency operation the instrumentation and controls should be designed with due consideration to the consequences of nuclear steam generator operation with defects in the plant and the consequence of loss of propulsion to the ship. ABS.Nuclear Ships.7.1

5) **Maximum Credible Accident (MCA) Scenario**

a) Special consideration should be given to the time that passengers and crew remain on board a nuclear ship at sea following a maximum credible accident. ABS.Nuclear Ships.3.12
b) Special consideration should be given to entering the port. Likely MCA would be when entering port. The most likely substantial releases of fission products would be caused by collision, which would be most likely around 100 miles from land, where ships often travel in heavy traffic and relatively high speeds. Closer to land, ships travel slowly, and further from land, ships are more spread out. MARAD, 12-4, 12-5, 12-6

**Ocean Exposures and Needs: Conditions or needs created by being at sea.**

1) **Movement from Sea: Ship needs caused by ship movement due to ocean conditions.**
    a) Ship design must account for sea conditions
        i) The ship and its nuclear power plant shall consider the effects of natural phenomena, such as extraordinary seaways, tornadoes, tsunamis, hurricanes, winds, snow and ice, applicable to the ship's service. IMO A2.5, 2.3.2, page 88; IMO A2.5, 2.7.9, page 109; RMRS, PART III, 8.1
        ii) Maximum roll 30 degrees from the vertical, with periods of 13 and 23 seconds (center of roll 20 to 30 feet above the baseline) in light and loaded conditions. MARAD, 12-8
        iii) Pitch and heave - maximum pitch amplitude of 7 degrees combined pitch and heave accelerations, 0.25 to 0.30 g at the reactor. MARAD, 12-8
        iv) Accelerations of .5g without damage to vessel or reactor system. Kramer, 259
        v) The inclination angles at which main and auxiliary machinery shall be capable of operation are shown on Table 1. IMO A2.8, 5.2.5, page 183
        vi) Inertial forces acting on the ship in a seaway shall be taken into account in the design for each of the critical nuclear components according to their Safety Class. This analysis carried out shall examine the motion of the ship in six degrees of freedom, utilizing the wave spectrum for the intended area of operation. IMO A2.5, 2.3.3, page 88; RMRS, PART III, 8.2
    b) Reactor system shall be designed to withstand seagoing conditions. ABS.Nuclear Ships.7.1
        i) Particular attention should be accorded to the redistribution of coolant flow and effects on heat transfer and coolant properties under the influence of ship motions. IMO A2.7, 4.2.2, page 150
        ii) Containment, as well as components, structure and systems inside the containment should be able to withstand accelerations due to ship's motion. See 1.4. ABS.Nuclear Ships.3.9
        iii) The performance of reactor heat removal shall take account of the motion of the ship during normal operation and in accident conditions. IMO A2.7, 4.2, page 148
        iv) Primary boundary should behave in ductile manner when stressed in sufficient margin. Reactivity control mechanisms should consider environmental factors, such as vibrations, shocks, and other movements when controlling reactivity. IMO A2.7, 4.2, page 148; Kramer 242-243; IMO A.4.6.2
        v) The reactivity control systems shall be fully operable within all design attitudes of the ship and capable of: IMO A2.7, 4.3.2.4, page 154; ABS.Nuclear Ships.7.1
            (1) Functional testing. IMO A2.7, 4.3.2.4, page 154
            (2) Periodic calibration of instruments throughout the entire range of reactor power. IMO A2.7, 4.3.2.4, page 154
            (3) Verification of proper functioning of instrumentation. IMO A2.7, 4.3.2.4, page 154

        (4) Reactor control should be provided to prevent an uncontrolled chain reaction under all reasonably foreseeable operational and accident conditions. ABS.Nuclear Ships.7.1
    vi) Reactor and reactor safety systems shall be designed to operate within limits including: IMO A2.5, 2.3.10, page 90; ABS.FLOPS, 5.3, Inclinations
        (1) Static list of up to 30 deg IMO A2.5, 2.3.10, page 90
        (2) Rolling angles of up to 45 deg IMO A2.5, 2.3.10, page 90
        (3) Or included angles of up to 10 deg either fore or aft direction IMO A2.5, 2.3.10, page 90
        (4) Or any combination of those angles within those limits, or a single motion, not exceeding 45 deg to one side IMO A2.5, 2.3.10, page 90
        (5) See 4-1-1/9 TABLE 7 of the Marine Vessel Rules for inclinations (Table 1 of the report contains equivalent information). ABS.FLOPS, 6.6, Inclinations
        (6) These angles may be reduced if it can be proven to the satisfaction of the Administration that the ship does not experience such attitudes, in which case the allowed reduction should be shown in the Safety Assessment IMO A2.5, 2.2.8.1.1.10, page 84
        (7) Reactor fast shutdown system is to be designed for, and be capable of shutting down the reactor at angles of up to 90° and be capable of maintaining the reactor in shutdown condition at all angles [A.491(XII) 4.3.1.4]. ABS.FLOPS, 6.6.2, 6.2
        (8) In addition, the reactor fast shutdown system is to operate automatically at smaller inclinations for safety reasons when: ABS.FLOPS, 6.6.2, 6.2
            (a) Flooding occurs within reactor containment [A.491(XII) 4.3.1.4.1]
            (b) The vessel becomes submerged [A.491(XII) 4.3.1.4.2]
            (c) The vessel heels to an angle of 45° or is trimmed to 10° inclination either way in the fore and aft direction or the vessel heels to the angle of vanishing intact stability, whichever is less [A.491(XII) 4.3.1.4.3].
    vii) Motions of the ship in a seaway shall be taken into account when evaluating the stability of the reactor control and when evaluating the dynamic behaviour of the reactor, assuming average as well as an extreme condition of seaway. IMO A2.5, 2.3.8, page 90
c) The inclination angles at which main and auxiliary machinery shall be capable of operation are: (see table) IMO A2.8, 5.2.5, page 183
d) Documentation is to be submitted that defines the environmental limits for all possible design or operational conditions, including the limiting inclination conditions for each. ABS.FLOPS, 5.3, Inclinations
e) Nuclear waste handling arrangements and their energy supplies, as applicable, are to be fully operable within all design attitudes of the vessel. ABS.FLOPS, 6.1.2, AUTO-FR1

2) **Vibration: The vibrations caused by the ship systems, movements, and being at sea**
    a) Reactor systems and containment systems must withstand and account for vibrations in design and testing. ABS.Nuclear Ships.3.9; ABS.Nuclear Ships.11.2

        - i) It is expected that vibration tests will be carried out to establish that no vibrations exist that would place the reactor in an unsafe condition. ABS.Nuclear Ships.3.9
        - ii) Reactor controls should operate satisfactorily under vibrations. ABS.Nuclear Ships.7.1
        - iii) The reactor shall be designed to limit mechanical and cyclical stresses under the effects of vibration and shock loading. IMO A2.5, 2.4.1, page 91
        - iv) It shall be demonstrated by analyses and/or tests that there are no flow-induced vibration in the core and no vibration- induced effects that would prejudice safe reactor operation. IMO A2.7, 4.2, page 148
    - b) Ship should account for effects of propeller and machinery, including vibrations, in the design and testing of monitoring devices and control systems and components. IMO A2.5, 2.3.14, page 91; USCG.46 cfr.55.10-5
- 3) **Ship Maneuverability: Ability of ship to change direction and speed and in what amount of time**
    - a) Ship should have maneuverability to use normal docks and maneuver similar to other ships. Kramer, 149; MARAD, 12-2
    - b) Steering
        - i) All nuclear ships shall be fitted with two fully independent steering systems. (comment: loss of steering is a major contributing factor in case of marine and navigation accidents). IMO A2.6, 3.7.3, page 141
            - (1) The steering gear control should be provided in duplicate from the principal steering station. An alarm system should be fitted to give warning at the principal steering station in the event of failure of one of the means of steering. An automatic change over should be provided. ABS.Nuclear Ships.2.5
        - ii) The main steering gear power units and their connections should be fitted in duplicate and each power unit should be capable of meeting the time requirements of the Marine Vessel Rules. ABS.Nuclear Ships.2.5
    - c) Stopping
        - i) The astern power and the load change rate of the reactor shall give the ship a reasonable short emergency stopping distance, that similar to a conventional ship (comment says: load change rate of the reactor would be different from the load change rate of a nuclear electric propulsion system) IMO A2.5, 2.4.4, page 93; RMRS, PART VII, 1.2
        - ii) Ship must maintain a reasonable short emergency stopping distance, similar to conventional ship, even with loss of reactor power. Kramer, 151
- 4) **Sea Water Corrosion: degradation of ship and reactor material due to sea water and other ocean exposures.**
    - a) Control and instrumentation systems for NPP systems, including alarm and indicator devices, are to be suitable for the intended application, designed for use in a marine environment, resistant to corrosion, and capable of operating under all anticipated environmental conditions. ABS.FLOPS, 9.1.4, II; IMO A2.7, 4.6.3, page 162

5) **Bilge: Bilge system requirements created by ship and NPP**
    a) Bilge pumping arrangements for all watertight compartments, except permanent ballast and cargo tanks, should comply with the most severe requirements of Regulation 35-1 of Chapter II-1 of the SOLAS Convention.* (comment: Updated to modern bilge pumping arrangements guidelines: SOLAS - International Convention for the Safety of Life at Sea - Chapter II-1 - Construction - Structure, subdivision and stability, machinery and electrical installations - Part C - Machinery installations - Regulation 35-1 - Bilge pumping arrangements.) IMO A2.8, 5.4.1, page 186
    b) Bilge, ballast and drainage systems are to be arranged to prevent the spread of radioactive liquids [A.491(XII) 5.4.2]. ABS.FLOPS, 4.1.2, SAFE-FR3
        i) Bilge pumping installations, serving compartments into which radioactive liquids may leak in normal service, are to be separate from and independent of the vessels' main bilge system [A.491(XII) 5.4.3]. ABS.FLOPS, 4.3.5, Bilge

**Reactor Operation Requirements.**

1) **Overall Criteria and Goals for Reactor: General duties and guidelines for NPP**
    a) Measures to contain radioactive materials and attenuate ionizing radiation are to be taken when the ship is being designed, constructed, commissioned, operated and decommissioned. [A.491(XII) 1.3.2]. ABS.FLOPS, 6.1.2, SAFE-FR11
    b) The NPP shall power the following primary essential marine services: ABS.FLOPS, 2.4, Table 1
        i) Services considered necessary to maintain hazardous spaces in a safe condition, including but not limited to (as identified in the Interface Document):
        ii) Control, monitoring and safety systems for nuclear power plant
        iii) Control, monitoring and safety systems for nuclear waste handling and storage systems
        iv) Ventilation and filtration systems necessary to maintain a safe atmosphere that controls the dose-equivalent limits in all normally manned areas
        v) Heating, ventilation and air conditioning systems in NPP-related areas
        vi) Heat transport systems
        vii) Lighting and emergency lighting systems
        viii) Process and post-accident sampling systems
        ix) Systems for treatment and control of radioactive waste and radioactive effluents
        x) Compressed and instrument air systems, as applicable
        xi) Demineralized water reserve and associated systems, as applicable
        xii) Containment cooling systems
        xiii) Chemical and volume control systems, as applicable
        xiv) Other services considered necessary to maintain radiation areas in a condition within dose-equivalent limits
        xv) Supporting system for emergency power supply and alternate power source
    c) The NPP shall power the follower secondary essential marine services: ABS.FLOPS, 2.4, Table 2
        i) Radiation detection and alarm systems
        ii) Plant gas system (e.g., hydrogen, carbon dioxide, nitrogen) as required
        iii) Auxiliary and radioactive waste area ventilation systems

        - iv) Demineralized water treatment, transfer and storage system
        - v) Turbine space close cooling systems
        - vi) Waste water systems, including equipment and floor drainage systems
        - vii) Radiologically controlled area ventilation systems
        - viii) Radioactive waste space HVAC systems
        - ix) Primary and secondary sampling systems
        - x) Electric equipment for security monitoring, security doors and other security closing appliances
        - xi) Security monitoring and security doors
        - xii) Overhead lifting equipment as required
    - d) Reactor must prevent against cold water injection. Kramer, 222 - 227
    - e) Reactor shall be capable of being started from a dead ship condition, without external aid. IMO A2.5, 2.4.3BIS, page 93; RMRS, PART VII, 1.3
- 2) **Waste Control: Requirements for effective storage and control of waste, especially radioactive waste.**
    - a) General requirements
        - i) The ship and NPP design shall envisage safety of crew and passengers and environmentally friendly collection, storage and treatment of radioactive waste before this radioactive waste is further discharged from the ship. RMRS, PART XII, 5.1; IMO A2.9, 6.5.1, page 221; IMO A2.9, 6.9.1, page 230; ABS.FLOPS, 5.1.1, ENV 10; ABS.FLOPS, 6.1.1, ENV 10; ABS.FLOPS, 8.1.1, ENV 10
            - (1) Ship shall manage and store radioactive waste streams to prevent any release into the sea or air. ABS.FLOPS, 6.1.2, ENV-FR1 (SAFE)
        - ii) The designs for the ship shall include appropriate arrangements for monitoring and handling of solid, liquid and gaseous radioactive waste being formed during normal operation to minimize its harmful effects on crew members, passengers, environment and ship. RMRS, PART XII, 5.3; IMO A2.9, 6.5.4, page 222
        - iii) The generation of radioactive waste shall be prevented where possible or minimized in terms of the quantity and activity of the waste generated. The accumulation of radioactive waste on the ship shall be minimized. IMO A2.9, 6.5, page 221
        - iv) When designing and operating the radioactive waste treatment and storage arrangements, the following shall be taken into account: RMRS, PART XII, 5.4
            - (1) permissible radioactive levels; RMRS, PART XII, 5.4
            - (2) requirement for biological shielding and usage of cooling system; RMRS, PART XII, 5.4
            - (3) possible corrosive effects of some radioactive gases and liquids on materials of containers, pipelines, equipment and fittings; RMRS, PART XII, 5.4
            - (4) requirement for radioactive leakage detection; RMRS, PART XII, 5.4
            - (5) possible formation of radioactive gases and measures to be taken to reduce effects and prevent combustible gas explosions. RMRS, PART XII, 5.4

   v) Facilities shall be provided on board the ship for the collection, treatment and storage of solid radioactive waste that has sufficient capacity for the volume and type of waste generated. IMO A2.9, 6.7, page 226; RMRS, PART XII, 5.5
   vi) Storage and transportation facilities as well as pipelines for radioactive waste discharge from the ship shall be designed to prevent any discharge of radioactive substances into the environment and other compartments of the ship/floating facility. RMRS, PART XII, 5.7
   vii) The ship shall be provided with at least two containers. RMRS, PART XII, 7.3.4
   viii)The capacity and operation of the radioactive waste management system shall be such as to prevent the necessity of discharging gaseous radioactive effluents when in port or harbor. If such discharges become necessary they shall conform to the requirements of the host Administration. (comment: This is an operating issue rather than a design issue. The overall requirement should be to ensure that there is no need to discharge radioactive gases to the environment when in port or harbor.) IMO A2.9, 6.6, page 225
   ix) The design, manufacture, operation, and testing of the handling, storage containment, and transfer systems for solid, liquid and gaseous radioactive wastes are to be in accordance with recognized standards approved by the Flag Administration and Port State Administration. ABS.FLOPS, 6.3.4, 3.4
   x) Gaseous radioactive waste discharge lines are to be equipped with isolation capability to prevent inadvertent or uncontrolled releases [A.491(XII) 6.9.5]. ABS.FLOPS, 6.3.7, 3.7.1

b) Waste management operations
   i) Handling and storage of radioactive waste, in quantities that could significantly contribute to personal doses received in the event of a collision, shall normally be confined to areas within the collision protective structure. Limited quantities of radioactive wastes may be carried outside these areas provided that they are properly packaged in containers approved by the Administration. IMO A2.9, 6.5.10, page 224
   ii) No radioactive waste other than the ship's own treated waste shall be carried on board the ship unless carried as cargo in accordance with accepted international agreements. IMO A2.9, 6.5.11, page 224

c) Waste monitoring
   i) Spaces which are likely to be contaminated with liquid radioactive substances shall be fitted with bilge wells and bilge alarms. RMRS, PART XII, 7.4
   ii) All escape routes for gaseous radioactive waste shall be monitored. RMRS, PART XII, 7.8.1
   iii) Means for remote measurements of liquid radioactive waste levels shall be provided. RMRS, PART XII, 7.3.4
   iv) Radioactive gases and aerosols shall be discharged into the environment through pipelines and vent ducts meeting tightness requirements and fitted with radioactivity filtering and monitoring equipment.
   v) The total volumes and radioactivity levels of aerosols and gases being discharged into the atmosphere shall be continuously and progressively

monitored. These parameters shall not exceed the standards as specified in the Sanitary Radiation Safety Rules. RMRS, PART XII, 8.4

  - vi) Gaseous radioactive waste discharge lines shall be fitted with automatic, remote and local shutdown means to prevent uncontrolled discharge. RMRS, PART XII, 8.5
  - vii) It is to be possible to monitor the activity or radiation level [...] in the storage container area [A.491(XII) 6.9.6]. ABS.FLOPS, 6.3.7, 3.7.2

- d) Prior to storage, solid radioactive wastes are to be segregated [...] according to their activity, types of radiation emitted, chemical activity, combustibility, etc. [A.491(XII) 6.7.3]. ABS.FLOPS, 6.3.5, 3.5.2; RMRS, PART XII, 7.8.2
  - i) Radioactive materials with major impact on individual radiation doses shall be arranged within the shielding barrier. RMRS, PART XII, 5.9; Kramer, 146
  - ii) Solid radioactive waste shall be stored and transported in special-purpose containers. Storage of solid radioactive waste shall provide for possible concentration/ formation of gases and liquids. RMRS, PART XII, 6.2
  - iii) The spent ion-exchange resins and filters as well as different parts (dirty tools, overalls, laboratory kits, etc.) shall be considered as typical solid radioactive waste. RMRS, PART XII, 6.1
  - iv) Gaseous radioactive waste may be compressed and stored provided that pressure vessels and appropriate pipelines meet the requirements of these Rules. Radioactivity risks shall be analyzed in the design in case of depressurization of the cylinder containing gaseous radioactive waste. RMRS, PART XII, 8.3
  - v) Provisions for the storage of liquid radioactive wastes include: ABS.FLOPS, 6.3.6, 3.6.3
    - (1) Liquid radioactive wastes are to be segregated on the basis of their physical and chemical nature and/or their radioactive characteristics, such as specific activity or isotope content [A.491(XII) 6.8.4.1]; ABS.FLOPS, 6.3.6, 3.6.3; RMRS, PART XII, 7.3.4
    - (2) Means of removing unwanted sludge from systems [A.491(XII) 6.8.4.2]; ABS.FLOPS, 6.3.6, 3.6.3
    - (3) A monitoring system and delay tanks [...], with arrangements for determining the volume and radioactivity of their contents as well as the rate at which these contents are released to the environment. Design is to account for further treatment of contents, if required [A.491(XII) 6.8.4.3]; ABS.FLOPS, 6.3.6, 3.6.3
    - (4) Each discharge and transfer line handling radioactive waste is to have automatic isolation capability, to prevent inadvertent or uncontrolled releases [A.491(XII) 6.8.4.4]; ABS.FLOPS, 6.3.6, 3.6.3
    - (5) The capacity of liquid radioactive waste storage tanks is to accommodate all bilge liquids produced in the reactor compartment and other controlled areas in design basis or design basis accident conditions [A.491(XII) 6.8.4.5]; ABS.FLOPS, 6.3.6, 3.6.3
    - (6) Cooling and shielding arrangements are to be provided as applicable for treatment and storage facilities according to the physical and chemical properties of the stored liquid [A.491(XII) 6.8.4.6] ABS.FLOPS, 6.3.6, 3.6.3

        - (7) Overflow of high-radioactivity liquid radioactive waste to containers for low radioactivity liquid radioactive waste is not allowed. RMRS, PART XII, 7.3.5
- e) Discharge and treatment: Release and treatment of radioactive waste from ship
    - i) Any programmed discharges of liquid or gaseous radioactive material from the ship shall be maintained within authorised limits and as low as reasonably achievable. IMO A2.9, 6.6, page 225; RMRS, PART XII, 5.11
    - ii) Radioactive waste discharge shall not affection radiological protection of people on board or in vicinity of ship RMRS, PART XII, 5.12
    - iii) Facilities shall be provided for the transfer of liquid radioactive wastes from the ship to a storage facility on the shore. IMO A2.9, 6.8.2, page 228
        - (1) Liquid radioactive waste treatment and storage facilities shall transfer this waste ashore or on board the special-purpose vessel through two separate pipelines. One pipeline shall be used for medium-radioactivity liquid radioactive waste, the other one for low radioactivity liquid radioactive waste. RMRS, PART XII, 7.2
        - (2) Liquid radioactive waste discharge pipelines shall be remotely isolated from the central control station and from the discharge station. RMRS, PART XII, 7.3.3
        - (3) Electric pumps for liquid radioactive waste transfer shall be corrosion resistant and leak tight. At least two pumps shall be provided on board the ship. Liquid radioactive waste discharge systems shall be provided with arrangements for preventing pressure increase above design values. RMRS, PART XII, 7.3.12
    - iv) The design shall ensure preventive measures for radioactive waste discharge from storage facilities into the environment and spaces of the ship. RMRS, PART XII, 5.6; ABS.FLOPS, 6.1.2, SAFE-FR8
    - v) Discharge of solid and liquid waste to appropriate dockside facilities shall be in accordance with regulations of local authorities, the host Administration, and by Flag and Port State Administrations. IMO A2.9, 6.6, page 225; ABS.FLOPS, 6.3.2, 3.2; ABS.FLOPS, 6.3.3, 3.3
    - vi) Radioactive liquids are to be collected and stored on board the vessel in closed containers or tanks, if their discharge would exceed the dose limits [A.491(XII) 6.8.3]. ABS.FLOPS, 6.3.6, 3.6.2
    - vii) Shielding design
        - (1) Pumps, pipelines and fittings shall have biological shielding, if necessary. RMRS, PART XII, 5.15
        - (2) Liquid radioactive waste pipelines and fittings shall have biological shielding (where control is provided from its location). RMRS, PART XII, 7.3.13
        - (3) Compartment bulkhead isolations, shielding and engineered protective measures are to be arranged to confine for treatment and controlled release to the environment by the off-gas ventilation system: [A.491(XII) 3.1.6] ABS.FLOPS, 6.2.1, 2.1.2

      - (a) radioactive material which may leak from the reactor, or from a small line rupture outside the containment structure [A.491(XII) 3.1.6.1] ABS.FLOPS, 6.2.1, 2.1.2
      - (b) radioactive material leaking from an open containment structure, or from high or medium level waste storage containers within the reactor compartment [A.491(XII) 3.1.6.2]. ABS.FLOPS, 6.2.1, 2.1.2
  - viii)Overall design
    - (1) Containers/tanks shall be protected against spontaneous emptying in case of damage to pipelines due to water ejection by siphon effect or by gravity. RMRS, PART XII, 7.3.2
    - (2) Liquid radioactive waste collection and storage containers shall be designed as free-standing, externally framed and inclined towards the drain hole. RMRS, PART XII, 7.3.2
    - (3) The distance between piping and systems shall be as such to ensure their proper maintenance and survey. RMRS, PART XII, 5.18
    - (4) Liquid radioactive waste containers shall allow for regular removal of contamination. RMRS, PART XII, 7.3.6
    - (5) Containers for storing liquid radioactive waste shall be equipped with air pipes made of corrosion resistant materials. Air pipes from liquid radioactive waste storage containers/tanks under hydrostatic pressure shall be led from the top of container/tanks to spaces where they are located. Air pipes from low level-radioactive liquid radioactive waste storage containers/tanks may be led to the ventilation mast through a special-purpose ventilation system. Water injection from liquid radioactive waste containers to vent ducts shall be excluded. Air pipes shall be connected to each other and to containers/tanks by welding. RMRS, PART XII, 7.3.8
    - (6) Liquid radioactive waste storage containers under hydrostatic pressure shall be made and tested as per the Marine Vessel Rules. In addition to air pipes, liquid radioactive waste storage containers under hydrostatic pressure only shall be fitted with overflow system for collection and discharge of liquid radioactive waste when the main containers/tanks are overfilled. RMRS, PART XII, 7.3.9
    - (7) Waste storage tanks and engineered safeguard systems may be permitted in the double bottom space. USCG.46 cfr.79.05-10

3) **Reactor Vessel and System Location: Requirements for location of reactor vessel and relevant systems**
  - a) Location of reactor and critical components must consider effects of grounding, collision, or other mishap resulting in holing of the vessel. USCG.46 cfr.79.05-10; ABS.Nuclear Ships.2.3; IMO A2.6, 3.1.2, page 117; ABS.Nuclear Ships.2.3; Kramer, 244 - 250
  - b) Systems containing radioactive material including high-level radioactive waste which require protection of their integrity in case of collision, shall be located inboard of the collision protection. IMO A2.6, 3.1.13.1, page 123

- c) Reactor installations, including all potentially vulnerable primary system components, shall be placed as far inboard from the shell as practicable. USCG.46 cfr.79.05-10; ABS.Nuclear Ships.2.3
- d) The vertical surface shall be located at a minimum distance (measured at right angles to the centerline at the deepest load line) inboard of the shell equal to one-fifth of the extreme breadth of the vessel. USCG.46 cfr.79.05-10; ABS.Nuclear Ships.2.3; IMO A2.6, 3.4.1, page 129; ABS.FLOPS, 4.3.1, 3.1.3
- e) Reactor installations shall be located a reasonable height above the ship's bottom, but in no case shall this height be less than the required double bottom height. USCG.46 cfr.79.05-10; ABS.Nuclear Ships.2.3
- f) Consideration shall be given to collision-analysis statistics with regard to the longitudinal (fore and aft) location of the reactor installation. USCG.46 cfr.79.05-10
- g) The preferred reactor location is aft of amidships, but not all the way aft. ABS.Nuclear Ships.2.3
- h) The longitudinal watertight, gastight bulkheads forming the sides of the safety enclosure shall be located at a distance inboard of the ship's side at least as great as the limits of penetration determined in subdivision and damage stability requirements. IMO A2.6, 3.1.10, page 119
- i) The main reactor control room shall be in the least vulnerable position (to fires, missiles resulting from explosions, toxic substances, radioactivity, etc.) but as near to the reactor and machinery as possible to keep service lines short. IMO A2.6, 3.1.13.4, page 124
- j) Location of reactor vessel should not negatively impact stability or trim. Kramer, 141

4) **Containment Vessel Design: Requirements for reactor containment vessel design created by reactor vessel exposures.**
   - a) General principals
     - i) Foundations for the reactor compartment and containment structures are to be designed with consideration given to: ABS.FLOPS, 4.3.3, Structures
       - (1) Loads under any inclination [A.491(XII) 3.3.8], see 6/6; ABS.FLOPS, 4.3.3, Structures
       - (2) Thermal stresses [A.491(XII) 3.3.8]; Kramer, 146; ABS.FLOPS, 4.3.3, Structures; MARAD, 4-3; RMRS, PART IV, 8.2
       - (3) Accessibility for inspection and maintenance activities [A.491(XII) 3.3.8]; ABS.FLOPS, 4.3.3, Structures
       - (4) Normal deformation of the unit, and deformations under extreme conditions [A.491(XII) 3.3.10]; ABS.FLOPS, 4.3.3, Structures
       - (5) Materials should be suitable for use in nuclear and marine environments, and be resistant to corrosion and erosion from the reactor coolant. IMO A2.7, 4.6.3, page 162
     - ii) Redundant systems and components essential to the safe operation of the ship and the NPP are to be physically separated [A.419(XII) 3.1.13.2]. ABS.FLOPS, 4.1.2; IMO A2.6, 3.1.13.5, page 124
     - iii) The safety enclosure shall be located entirely within the reactor compartment and within the structural boundaries designed to protect it and its contained

equipment from the external hazards of marine application. The enclosure may include penetrations and personnel access openings, which must be capable of maintaining the requisite gas tightness. IMO A2.6, 3.1.8, page 119; ABS.FLOPS, 6.2.1, 2.1.3

    iv) The containment structure shall be within the safety enclosure. IMO A2.6, 3.1.11, page 120
    v) The primary boundary shall be located within the containment structure. IMO A2.6, 3.1.11, page 120
    vi) All bulkheads and other boundaries forming the safety enclosure shall be gastight, of all-welded construction, and firetight as necessary to conform with Fire Protection Requirements. IMO A2.6, 3.1.7, page 119; ABS.FLOPS, 6.1.2, SAFE-FR9; RMRS, PART IV, 9
    vii) Double Bottom Requirement: Requirements for double bottom ship hull
        (1) A double bottom shall be provided under the reactor compartment, power conversion system spaces, the drive trains connected to it (for mechanical drive systems), sufficient for the protection of the reactor and safety related systems, including high level radioactive material storage areas. IMO A2.6, 3.6.1, page 139; IMO A2.6, 3.6.2, page 139; ABS.FLOPS, 4.3.1, 3.1.2
            (a) The depth of the double bottom under the reactor compartment shall provide protection against bottom damage of the extent given in 3.4.3 IMO A2.6, 3.6.1, page 139; ABS.FLOPS, 4.3.1, 3.1.2

b) Physical damage concerns
    i) Provide means to prevent penetration, rupture, cracking, leaks or damage of containment vessel in the case of collision, groundings, and hazards arising from cargoes, missiles and other sources specifically identified by the risk assessment to prevent the uncontrolled release of radioactive materials, as applicable according to the Interface Document, see 2/3.1.1 [A.491(XII) 3.1.2.1]. ABS.FLOPS, 4.1.2; Kramer, 146; MARAD, 1-6,1-7, 4-3
    ii) Physical damage to the NPP is not to affect the residual heat removal systems. ABS.FLOPS, 4.1.2
    iii) Missiles
        (1) The possibility of missiles being accidentally generated in the reactor compartment and machinery spaces shall be minimized. Arrangements shall be provided to protect systems and machinery from missiles, in particular for systems belonging to Safety classes 1 and 2. (comment: expanded to cover all systems). IMO A2.8, 5.2.3, page 183
        (2) Machinery having a potential for missile generation shall be oriented or shielded so as to minimize missile effects to ship and reactor safety equipment. IMO A2.6, 3.1.13.3, page 123
        (3) Missiles resulting from the malfunctioning of the components of the system should not cause the release of hazardous amounts of radioactivity to occupied spaces or the ship’s environment. ABS.Nuclear Ships.3.4
    iv) Pipes will not fail due to relative movement of the containment vessel and surrounding structure. ABS.Nuclear Ships.3.1

c) Structural integration of reactor compartment
    i) Foundational and protective structures for the reactor protection are to provide structural continuity of the hull in normal operating conditions. ABS.FLOPS, 4.1.2
    ii) Deformation to hull structures and the reactor compartment during conditions of the design environment are not to affect the structural integrity or result in the release of radioactive material.[A.491(XII) 3.1.11.14]. ABS.FLOPS, 4.1.2
    iii) The reactor compartment is to be bounded fore and aft and longitudinally by cofferdams or bulkheads extending from the double bottom to the bulkhead deck [A.491(XII) 3.1.2.2]. ABS.FLOPS, 4.3.1, NPP; IMO A2.6, 3.1.9, page 119
    iv) Structural members at the transition between ship and reactor compartment must be adequately sized and designed to transfer the weight and loads developed in the area of the reactor compartment and collision protective structure into the rest of the vessel. The transition area shall extend as far as necessary forward and aft of the reactor compartment to provide structural continuity of the hull. This structural continuity might be part of the protection provided against a glancing collision. IMO A2.6, 3.3.2, page 127
d) Containment Vessel Entry, Exit, and Maintenance
    i) Controlled area spaces where radioactive contaminants may occur shall be brightly arranged within the collision protection in a single block, if possible to facilitate maintenance of machinery and equipment inside as well as to provide the shortest possible routes for people and transportation of equipment, materials and radioactive waste. RMRS, PART XII, 3.18
    ii) Controlled area spaces on decks shall have an exit to cargo lift /trunk. Spaces where more fittings are located and lift/trunk is likely to be used shall have direct exit/entrance from lift/trunk, if possible. RMRS, PART XII, 3.17
    iii) Controlled area spaces shall have an emergency escape route to the open deck. RMRS, PART XII, 3.15
    iv) The controlled area spaces shall be free of equipment, machinery and devices which require continuous supervision and maintenance. RMRS, PART XII, 3.18
e) Containment Vessel Penetrations. ABS.FLOPS, 6.2.2, 2.2.1
    i) Penetrations of the boundaries of the reactor containment systems are to be limited to those required for nuclear safety. ABS.FLOPS, 6.2.2, 2.2.1; ABS.FLOPS, 6.1.2, SAFE-FR7; MARAD, 1-6,1-7, 4-3
    ii) Access openings in boundaries of the reactor compartment or in the boundaries of spaces within the reactor compartment which form watertight, gastight or fire protection divisions, are to be fitted with closures which will maintain the integrity of the division in which they are located. ABS.FLOPS, 6.2.2, 2.2.1
    iii) Where necessary for security or safety purposes, closures are to be provided with appropriate arrangements for local and remote operation. ABS.FLOPS, 6.2.2, 2.2.1
    iv) Provision is to also be made, by airlock arrangements if necessary, so that required air pressure differentials, where provided between adjacent

        compartments, are not rendered ineffective during operation of access closures [A.491(XII) 3.11]. ABS.FLOPS, 6.2.2, 2.2.1
        v) No high-pressure high-temperature piping containing primary water will be permitted to penetrate the containment vessel. Kramer, 185
    f) Radiation contamination concerns
        i) As far as reasonably practicable, radiation exposure of those on board, the public and the environment is to be minimized [A.491(XII) 2.1.1.1 Criterion A]. ABS.FLOPS, 4.1.2
        ii) All parts of the ship in which radioactive materials or contamination may exist should be identified and appropriate design measures taken to ensure that the spread of radioactive material or contamination into other parts will be minimized and that any necessary decontamination procedures can be carried out safely within the relevant dose-equivalent limit. [A.491(XII) 6.2.8]. ABS.FLOPS, 4.1.2
        iii) The use of cofferdams and double bottoms comprising the boundaries of the reactor compartment shall be restricted to the carriage if any of non-potable water. IMO A2.6, 3.1.3, page 117; ABS.FLOPS, 4.3.1, 3.1.1
    g) Decontamination
        i) Foundations, machinery and equipment attachments in the controlled area spaces where radioactive contaminations occur under SC1 and SC2 shall be designed to ensure access to all surfaces of foundations/their attachments for decontamination. Foundation spaces inaccessible for decontamination shall be sealed. RMRS, PART XII, 3.13
        ii) Machinery and equipment not suitable for decontamination shall be easily replaceable. Arrangement for covering these machinery and equipment during operation or general decontamination of spaces shall be envisaged. RMRS, PART XII, 3.14
        iii) The containment vessel shall be designed to enable decontamination. RMRS, PART XII, 3
5) **Shielding: Needs and requirements for adequate shielding**
    a) The nuclear propulsion plant should be provided with reliable biological shielding to protect persons on board ship, or within the immediate vicinity of the ship, against the hazardous effect of radiation. ABS.Nuclear Ships.11.2; IMO A2.6, 3.1.5.2, page 118; RMRS, PART III, 2.1; Kramer, 146
    b) The shielding materials should be selected so that their properties over long usage will not be damaged by radiation, normal operating temperature, vibration or marine atmosphere. ABS.Nuclear Ships.11.2
    c) The shielding shall ensure that there remains at least one physical barrier between irradiated fuel and the environment with the gas tightness and water tightness required for nuclear safety. IMO A2.6, 3.1.5.3, page 118
    d) Operation
        i) All controlled area spaces where radioactive contamination may occur under normal operation of the ship shall be located inside the shielding barrier. RMRS, PART XII, 3.8

        - ii) Shielding is to be arranged so that manning of essential control positions is possible without exceeding personnel limits for a reasonable period following any incident conditions [A.491(XII) 3.1.13.8]. ABS.FLOPS, 5.1.2, SAFE-FR41
    - e) Sequential shielding barriers are to be sufficient such that the vessel hull is not to be considered as a shielding barrier in any operating condition. ABS.FLOPS, 6.2.1, 2.1
        - i) Biological shielding directed towards the bottom of the nuclear ship shall prevent adverse effects on sea water when reactor plants are operating at a rated power. Radiation levels below the bottom of the ship shall allow for required docking operations with the reactor stopped. RMRS, PART XII, 3.5
    - f) Steam Supply shielding
        - i) The biological shielding design shall provide for repair works, reactor core handling, replacing steam supply system equipment with shielding dismantled to the minimum level as well a survey of steam supply system equipment. RMRS, PART XII, 3.6; MARAD, 5-11
    - g) The biological shielding design shall provide for repair works, reactor core handling, replacing steam supply system equipment with shielding dismantled to the minimum level as well a survey of steam supply system equipment. RMRS, PART XII, 3
- 6) **Radiation Exposures: Requirements for safety necessary due to radiation concerns.**
    - a) Emergency Radiation Exposure Systems
        - i) Survival Craft Needs
            - (1) The primary survival craft shall be fitted with an external drenching system for decontamination. IMO A2.6, 3.8.1, page 141
            - (2) Portable radiation monitoring devices are to be provided for use in all survival craft [A.491(XII) 3.8.1]. ABS.FLOPS, 9.4.1, 4.1
        - ii) The quantity of personal dosimeters, filter respirators, and air-supplied sets carried on board are to meet the needs of normal service and are to be sufficient for all passengers and crew in the event of an accident [A.491(XII) 6.4.8]. ABS.FLOPS, 9.1.2, SAFE-FR2; ABS.FLOPS, 6.2.3, 2.3.2
    - b) Laboratory Requirements
        - i) The vessel is to be provided with a laboratory and laboratory equipment, satisfactory to the Flag Administration, for the analysis of radioactive samples [A.491(XII) 6.4.9]. Kramer, 137; ABS.FLOPS, 9.3.2, 3.2.; IMO A2.9, 6.4.9, page 217
        - ii) Laboratory must provide facilities for proper waste assessments and ventilation. MARAD, 8-55, 8-56
    - c) Radiation Monitoring Requirements
        - i) Indications of radiation levels and of airborne contamination levels in controlled areas are to be presented at a central control point. If any significant increase in radiation level is detected within spaces, visual and audible alarms are to be arranged within each space [A.491(XII) 6.4.3]. ABS.FLOPS, 9.4.2, 4.2
        - ii) Sufficient fixed radiation checkpoints shall be established so that it is possible to compare radiation levels or contours within the ship periodically during the

life of the ship with the original surveys made when the ship was commissioned. IMO A2.9, 6.4.5, page 216

    iii) Ship must provide means to monitor and record environmental discharges. ABS.FLOPS, 9.1.1, ENV 13
    iv) As far as reasonably practicable, monitor radiation at all times and in every compartment or area or within all pipes, fittings or equipment where the possibility exists and under all plant process conditions. ABS.FLOPS, 9.1.2, AUTO-FR1 (ENV)
    v) Ship shall be equipped with sufficient portable monitors for routine and emergency radiation surveys; this equipment is to include beta, gamma, and neutron survey meters, air samplers, and alpha/beta contamination monitors [A.491(XII) 6.4.7]. ABS.FLOPS, 9.1.2, SAFE-FR1 (ENV)1
    vi) In addition to the base ABS Rule set, means are to be provided for detecting reactor coolant leakage for pressure vessels, pressure boundaries, pressure relief systems and penetrations to pressure boundaries [A.491(XII) 4.6.1]. See Section 9. ABS.FLOPS, 5.5.2, 5.2.1
    vii) Radioactive monitoring and recording systems outside of the NPP are to include: ABS.FLOPS, 9.4.3, 4.3
        (1) Fixed and portable equipment for assessing the concentrations and amounts of gaseous and airborne particulate radioactive material which may be released to the environment [A.491(XII) 6.4.10.1]; ABS.FLOPS, 9.4.3, 4.3
        (2) Installed equipment, including an alarm system, to monitor from the gaseous discharge lines the rate of release of radioactivity and the total activity released [A.491(XII) 6.4.10.3], as applicable; ABS.FLOPS, 9.4.3, 4.3
        (3) Equipment to assess to a specified accuracy the activity concentration and total amount of liquid wastes in the collection, treatment and storage facilities [A.491(XII) 6.4.10.4], as applicable; ABS.FLOPS, 9.4.3, 4.3
        (4) Equipment to determine the levels of specific radioactivity isotopes in liquid wastes prior to their discharge to the marine environment [A.491(XII) 6.4.10.5], as applicable; ABS.FLOPS, 9.4.3, 4.3;
        (5) Installed equipment, linked to a suitable alarm system and having the capability of automatically isolating the liquid waste discharge lines, to measure and record the activity concentration and the discharge flow rate where liquid waste discharge to the sea is permitted [A.491(XII) 6.4.10.6], as applicable. ABS.FLOPS, 9.4.3, 4.3
        (6) Equipment for assessing the levels and types of radiation emitted by solid radioactive wastes, prior to segregation and treatment [A.491(XII) 6.4.10.7]; ABS.FLOPS, 9.4.3, 4.3
        (7) Procedures and testing and monitoring equipment to verify the correct operational condition of the waste management equipment [A.491(XII) 6.4.10.8]. ABS.FLOPS, 9.4.3, 4.3
        (8) It is to be possible to monitor the activity or radiation level in the storage container area [A.491(XII) 6.9.6]. ABS.FLOPS, 6.3.7, 3.7.2

d) Acceptable Radiation Exposure and Health Requirements

i) Ship shall eliminate unreasonable radiation or other nuclear hazards, at sea or in port to the waterways or food or water resources. (SOLAS VIII/Reg 6). ABS.FLOPS, 5.1.1, SAFE 5; ABS.FLOPS, 5.1.2, SAFE-FR1

ii) Reactor design shall minimize radiation exposures and ensure radiation doses to workers at the plant and members of the public do not exceed dose limits. IMO A2.4, 1.3.8, page 53; ABS.FLOPS, 4.1.2, SAFE-FR2; ABS.FLOPS, 5.1.1, SAFE 5; ABS.FLOPS, 5.1.2, SAFE-FR1
   (1) The design shall be such as to ensure that, when the reactor is operating normally or is shut down, no persons on board or in the vicinity of the ship will, as a result of the ship's operation, be subjected to radiation or contamination levels in excess of the defined dose- equivalent limits. IMO A2.9, 6.2, page 207
   (2) The design of the ship and the reactor shall be such that there is no significant increase in the background radiation level of a port, due to the operation of the ship in startup and shutdown. IMO A2.9, 6.2, page 207
   (3) The ship shall be divided into zones that are related to their expected occupancy, and to radiation levels and contamination levels in operational states (including maintenance and inspection) and to potential radiation levels and contamination levels in accident conditions. IMO A2.9, 6.2, page 207
   (4) Those parts of the ship which would be required to be occupied by either passengers or crew during any Plant State 4 event shall be so located and/or shielded as to ensure that doses to personnel staying in such spaces for the whole course of the event would not exceed the applicable dose-equivalent limits. IMO A2.9, 6.2, page 207

iii) Protection against the effects of irradiation is to be provided by applying, either singly or in combination: 1. shielding arrangements; 2. controlled areas of the ship; 3. limited exposure times; and 4. limiting the distances from and the prevention of the unnecessary approach of persons to sources of radiation ABS.FLOPS, 6.2, Shielding and Radiological Safety

iv) Areas of ship with radiological hazard must be controlled and labeled
   (1) All parts of the ship in which radioactive materials or contamination may exist should be identified and appropriate design measures taken to ensure that the spread of radioactive material or contamination into other parts will be minimized and that any necessary decontamination procedures can be carried out safely within the relevant dose-equivalent limit. [A.491(XII) 6.2.8]. ABS.FLOPS, 4.1.2, SAFE-FR4
   (2) Access to a controlled area is to be limited to authorized persons and their entrance and exit is to be registered [A.491(XII) 6.2.5]. Depending on radiological or hazardous conditions, boundaries may be required to be locked or guarded. ABS.FLOPS, 6.2.3, 2.3.1
   (3) Taking into account the nature of the radiological hazard in controlled and supervised areas, access barriers, protective clothing, personnel monitors, washing facilities and changing rooms shall be located, as needed, between controlled or supervised areas and adjacent uncontrolled areas,

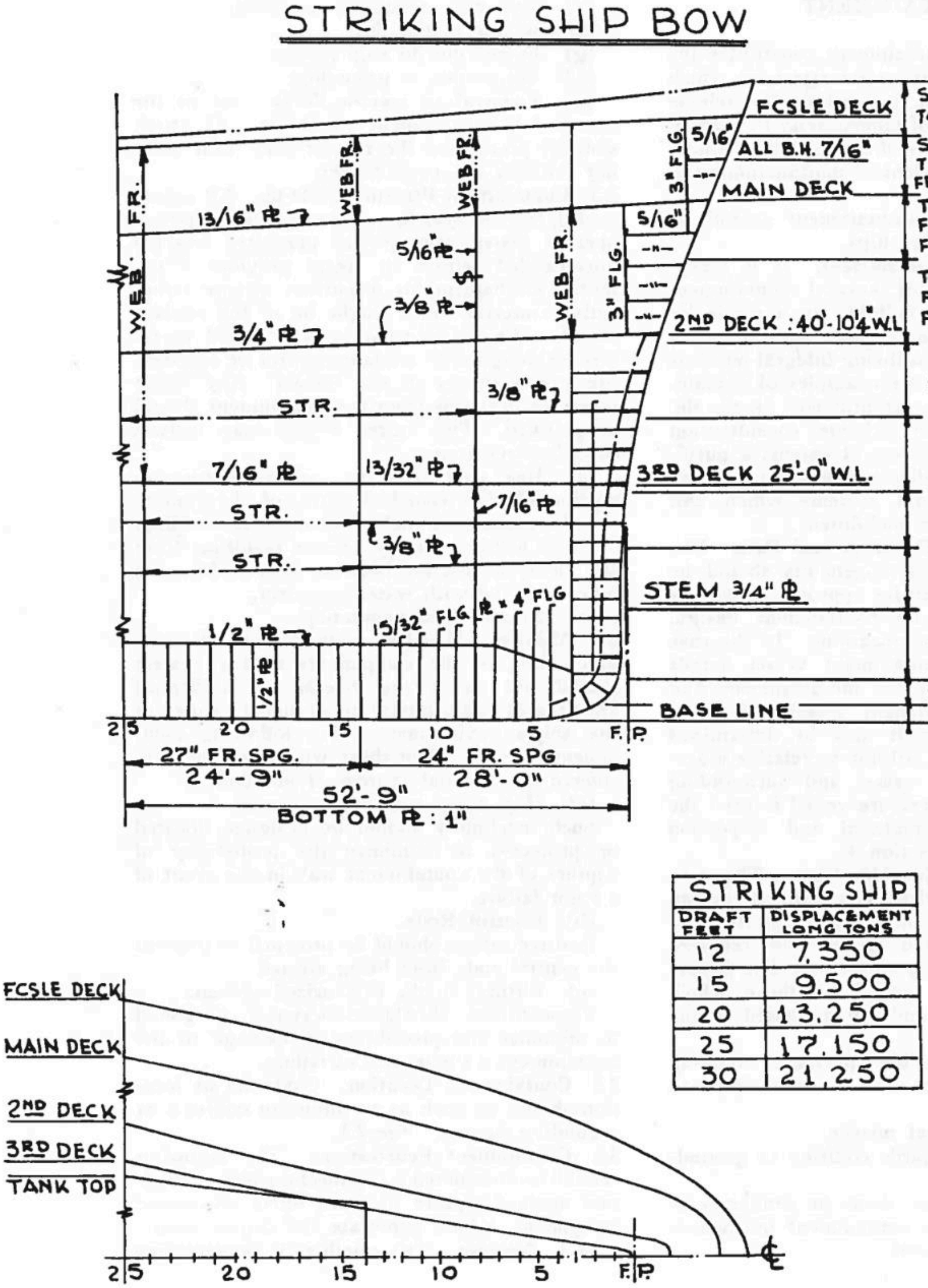
        to prevent the transfer of contamination from one area to another. IMO A2.9, 6.2, page 207; ABS.FLOPS, 6.2.3, 2.3.1
    v) General Health
        (1) Ship shall promote the occupational health and safety of personnel onboard. ABS.FLOPS, 6.1.1, SAFE 1.1
        (2) Ship shall provide for health protection and prompt access to medical care onboard vessel and ashore. ABS.FLOPS, 6.1.1, SAFE 4
        (3) Ship shall minimize danger to persons on board, the vessel, and surrounding equipment/installations from hazards associated with machinery and systems. ABS.FLOPS, 6.1.1, SAFE 1.1
    vi) Radiation exposure measurements should assume full ship occupancy for 365 days per year at maximum radiation from the reactor. Kramer, 149
    vii) Maximum credible dosage from a gross water leak should not approach a once-in-a-lifetime accident limit. MARAD, 13-35
    viii) Design should ensure that major ruptures are restricted to keep integrated dose below 5 rem for the crew for several days. [Kramer, 230 - 237]

7) **Controls and Primary Control Room: Requirements for effective and safe reactor controls and primary control room**
  a) Safety in Control Room
    i) At least two means of escape shall be provided from the main reactor control room and from the compartment in which the emergency reactor control position is located. Each escape route shall provide effective fire shelter from the compartment to the weatherdeck. IMO A2.6, 3.9.5, page 142; RMRS, PART VII, 5.1
    ii) The main reactor control room is to be in the least vulnerable position (to fires, missiles resulting from explosions, toxic substances, radioactivity, etc.) but as near to the reactor and machinery as possible to keep service lines short [A.491(XII) 3.1.13.4]. ABS.FLOPS, 4.3.2, Control rooms; RMRS, PART VII, 5.1
  b) Control Mechanisms
    i) All systems essential to operation or safety of the reactor shall be capable of being manually controlled, in addition to any automation provided. IMO A2.7, 4.1.3, page 147; ABS.FLOPS, 5.4.1, 4.1; ABS.FLOPS, 9.1.2, AUTO-FR2 (ENV)1
        (a) Automatic initiation of safety systems shall be provided where fast safety system action is required. IMO A2.7, 4.1.4, page 147
        (b) No human actions shall be required in the short term in any accident situation IMO A2.5, 2.6.3.4, page 104
      (2) All systems essential to operation or safety of the primary heat transfer system are to be capable of being manually controlled, in addition to any automation provided [A.491(XII) 4.1.3]. ABS.FLOPS, 5.5.1, 5.5.1
      (3) The design is to be such that an operator can resume control of safety protection system functions but cannot override correct safety system action except as allowed by specific, approved operating procedures consistent with qualified operating procedures [A.491(XII) 4.1.4]. ABS.FLOPS, 5.1.2, AUTO-FR41

    - ii) Facilities shall be provided to initiate and monitor the operation of the reactor shutdown systems from the main control room or from the emergency control room if the main control room is not available. IMO A2.7, 4.3.2.7, page 155

8) **Station Infrastructure: Infrastructure necessary for nuclear ship support from land**
  - a) Control Zones
    - i) Safety assessment shall address the safety of the nuclear merchant ship when it is in port. Needs to account for local meteorological conditions, population density and land usage factors. IMO A2.5, 2.3.1, page 88
    - ii) All ports ship enters shall be surveyed and establish controlled zone, low-population zone, and remote anchorage in case of nuclear emergency. MARAD, 13-71
      - (1) Controlled zone shall be an area defined by barriers such that all persons inside are under direct control of ship's personnel and local authorities, such that in the event of the MCA, evacuation could occur within two hours before any member of the public inside the zone would exceed acceptable dosage limit. MARAD, 13-71
      - (2) Low-population zone shall be an area in which it is reasonable to expect that in the event of an occurrence of the MCA total evacuation or protective measures could be carried out in a graded fashion within 24 hours so that no person in the zone would review more than acceptable dosage. MARAD, 13-71; MARAD, 13-71
      - (3) Dense population zone shall be an area which is immediately adjacent to the outer boundary of the low-population zone and cannot be evacuated, controlled, or protected. In the event of occurrence of the MCA, the total integrated population exposure to all persons in this zone plus the controlled zone and the low-population zone will not exceed acceptable dose. MARAD, 3-4
      - (4) Remote anchorage shall be area which the ship may be moved to after the MCA occurrence. It must allow stricken vessels to be anchored for 30 days and allow for the following 3 zones to be established. MARAD, 3-4
        - (a) An uninhabited controllable exclusion zone through which no ship or member of the general public must pass except under the strict control. MARAD, 13-71
        - (b) A zone that encompasses an area that can be evacuated within 24 hours. This zone has a sufficient radius so that a person on the perimeter· for 30 days would not receive more than an acceptable dose. MARAD, 13-71
        - (c) To ensure appropriate limitations to long term effects on the population as·a whole, a surrounding zone that has an acceptable dose limit to total population assuming the duration of the radioactive release to continue for 30 days. MARAD, 13-71
  - b) Shore power connection
    - i) Vessels equipped with a high voltage shore power connection designed to power the vessel with the shore power alone, enabling the shipboard

    generators to be shut down while in port, are to comply with the requirements given in the ABS Guide for High Voltage Shore Connection. ABS.FLOPS, 7.2.1, 2.1
  - ii) If the nuclear power service vessel provides power to shore, which may also augment other shore power generation sources as a parallel power source, the connection from the nuclear power service vessel to the shore distribution system is to be protected from shore power faults, frequency, and voltage variations in accordance with the applicable recognized codes/standards in the country where it is providing power. ABS.FLOPS, 7.2.1, 2.1
- c) Shore supplies of cooling medium may be used, two independent connections shall be provided. IMO A2.8, 5.5.3, page 188
- d) The ship must submit a port operating plan before entering, which has fission product limitations. MARAD, 3-2, 3-3
- e) Mooring
  - i) Ship to be provided with means to enable the safe conduct of towing, mooring and anchoring operations. (SOLAS II-1 Reg 3-8.2) ABS.FLOPS, 7.1.1, PROP 6
  - ii) Anchoring and mooring equipment, as applicable, are to have sufficient holding power to maintain the vessel in position based on the environmental conditions. ABS.FLOPS, 7.1.2, PROP-FR1
  - iii) Ship may not moor unless calculated that could evacuate ship with no person receiving radiation dose beyond acceptable limit if there is MCA while moored at location.



STRIKING SHIP

| DRAFT FEET | DISPLACEMENT LONG TONS |
|---|---|
| 12 | 7,350 |
| 15 | 9,500 |
| 20 | 13,250 |
| 25 | 17,150 |
| 30 | 21,250 |

Figure 9: Striking Ship Bow