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Radiation protection plan for a PC1 class nuclear-powered icebreaker

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For PC1 class icebreakers, nuclear power offers the opportunity to achieve higher propulsion power with reduced space compared to conventional marine power generation methods. The aim of this thesis is to develop a first version of a radiation protection plan for a PC1 class icebreaker powered by three SEALER-55 lead-cooled fast reactors. The methods include a descriptive literature review on the use of nuclear power in the marine sector, calculations on the effects of radiation and the measures required for protection, and AutoCAD drawings illustrating an arrangement of a nuclear vessel. The initial version of the GA was reviewed and commented on from a radiation protection perspective. A possible reactor shielding configuration was sketched based on radiation calculations, and the required dimensions of the reactor rooms were estimated.

The most penetrating types of ionizing radiation are gamma and neutron radiation. Both are produced inside a nuclear reactor, which is why reactors must be heavily shielded to reduce radiation doses to acceptable levels. The effective radiation dose rate, calculated for the SEALER-55 reactor, describes how quickly a person exposed to radiation accumulates radiation dose while accounting for radiation type and biological hazard. Dose limits are set by international and national regulatory bodies.

The marine sector is heavily regulated, as is the land-based nuclear sector. However, regulations for marine nuclear applications are limited and often outdated. The few existing regulations, the IMO Code of Safety for Nuclear Merchant Ships, ABS the Requirements for Nuclear Power Systems for Marine and Offshore Applications, and the RINA Guide for Nuclear Installation on Board of Marine Units, were reviewed, and the most essential rules for this radiation protection plan were highlighted. Additional regulations related primarily to dose limits were also reviewed.

Calculations were done for the gamma and neutron radiation fluxes and the resulting dose rates, along with attenuation caused by shielding materials. Calculations for the SEALER-55 reactor show that the reactor itself attenuates gamma radiation to acceptable levels, but neutron radiation requires additional shielding. As a result, approximately 250 cm of sequential shielding materials, primarily suited for neutron attenuation, is required. The materials recommended for the shielding configuration are water, concrete, lead, and steel. Polyethylene was considered due to its excellent neutron-attenuation properties but was excluded because of its flammability.

The estimated width of each square-shaped reactor room is 13.8 meters, including shielding and reserved space for auxiliary equipment and maintenance access. With these dimensions, the reactors should be placed along the ship’s centerline. The reactor compartment should also accommodate spaces for radioactive waste treatment and storage, radiation laboratories, decontamination facilities and reactor control rooms. A division of spaces into controlled and supervised areas was established: the reactor rooms and adjacent spaces on the port and starboard sides are classified as controlled areas, while the uppermost deck of the reactor compartment and the spaces adjacent spaces on both ends of the reactor compartment are considered supervised areas. Access to the reactor compartment should be carefully monitored. The results indicate that a new arrangement of the reactor compartment within the GA is required to comply with regulations and incorporate the necessary shielding estimates.

Key words: radiation shielding, radiation attenuation, nuclear merchant ship, maritime nuclear regulations, dose limits, lead-cooled fast reactor

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PC1-luokan jäänmurtajassa ydinvoiman käyttäminen perinteisten merenkulussa käytettävien energiantuotantotapojen sijaan tarjoaa mahdollisuuden saavuttaa suurempi propulsioteho pienemmillä tilavaatimuksilla. Tämän työn tavoitteena on kehittää säteilyturvallisuussuunnitelman ensimmäinen versio PC1-luokan jäänmurtajalle, joka saa tehonsa kolmesta SEALER-55-lyijyjäähdytteisestä nopeasta reaktorista. Metodeihin kuuluvat kuvaileva kirjallisuuskatsaus ydinenergian käytöstä ja sääntelystä merenkulussa, laskelmia säteilyn vaikutuksista ja siltä suojautumisesta, sekä AutoCAD-piirrustuksia ydinkäyttöisen aluksen järjestelystä. Ensimmäinen versio laivan yleisjärjestelystä tarkistettiin säteilyturvallisuuden näkökulmasta. Mahdollinen säteilysuojarakenne piirrettiin säteilylaskujen perusteella, ja tarvittavat reaktorihuoneen mitat arvioitiin.

Läpitunkevimmat ionisoivan säteilyn lajit ovat gamma- ja neutronisäteily. Ydinreaktorissa tuotetaan molempia, minkä takia reaktorit on suojattava hyvin saavuttaakseen hyväksyttävät säteilyannokset. SEALER-55-reaktorille laskettu vaikuttava annosnopeus kuvailee, kuinka nopeasti säteilylle altistunut henkilö kerryttää säteilyannosta, ottaen samalla huomioon säteilyn lajin sekä biologisen vaarallisuuden. Kansainväliset ja valtiolliset säännöstöt asettavat säteilyn annosrajat.

Merenkulun ala on tarkasti säänneltyä, samoin kuin ydinala maalla, mutta säännöt ydinvoimalle merenkulussa ovat harvassa ja usein vanhentuneita. Työssä tutustuttiin voimassa oleviin sääntöihin, kuten IMO:n Code of Safety for Nuclear Merchant Ships, ABS:n Requirements for Nuclear Power Systems for Marine and Offshore Applications ja RINA:n Guide for Nuclear Installation on Board of Marine Units, säteilyturvallisuuden kannalta tärkeimpiä sääntöjä korostettiin. Lisäksi työssä tutustuttiin muuhun olemassa olevaan sääntelyyn, kuten annosrajoja käsitteleviin sääntöihin.

Työssä laskettiin gamma- ja neutronisäteilyvuot, ja niistä aiheutuvat annosnopeudet sekä suojamateriaalien tuoma vaimeneminen. SEALER-55-reaktorille tehdyt laskut osoittavat, että reaktori itsessään heikentää gammasäteilyn hyväksyttävälle tasolle, mutta neutronisäteily vaatii lisäsuojan. Tulosten perusteella vaadittava rakenne on noin 250 cm paksu, kerroksittainen kokonaisuus, joka muodostuu pääosin neutronivuota vaimentavista materiaaleista. Suositellut materiaalit ovat vesi, betoni, lyijy ja teräs. Polyetyleeniä harkittiin sen erinomaisen neutronienheikennyskyvyn ansiosta, mutta jätettiin pois suunnitelmasta sen paloherkkyyden takia.

Neliön muotoisen reaktorihuoneen arvioitu leveys on 13,8 metriä, johon sisältyy säteilysuoja sekä tilavaraus apulaitteille ja huollon mahdollistamiselle. Tällä huoneen leveydellä reaktorit tulisi asettaa peräkkäin laivan keskiviivaa pitkin. Reaktoriosastoon tulisi kuulua tilat ydinjätteen käsittelylle ja varastoinnille, säteilylaboratorioille, dekontaminaatiotiloille ja reaktorivalvomoille. Tilat jaettiin valvonta- ja tarkkailualueiksi: reaktorihuoneet ja näiden paapuurin ja tyyrpuurin puolella olevat viereiset huoneet luokitellaan valvonta-alueiksi, kun taas reaktoriosaston ylin kansi sekä reaktoriosaston molempien päätyjen viereiset tilat luokitellaan tarkkailualueiksi. Pääsy reaktoriosastolle tulisi olla huolellisesti valvottua. Tulokset osoittavat, että yleisjärjestely täytyy päivittää reaktoriosaston osalta niin, että se vastaa sääntöjä ja ottaa huomioon tarvittavan säteilysuoja-arvion.

Avainsanat: säteilysuoja, säteilyn heikentäminen, ydinkäyttöinen kaupallinen laiva, merenkulun ydinvoiman säännöt, annosrajat, lyijyjäähdytteinen nopea reaktori

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Abbreviations

ABS	American Bureau of Shipping
DNV	Det Norske Veritas
GA	General arrangement
IACS	International Association of Classification Societies
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IMO	International Maritime Organization
IBELO	IceBreaker ELO
LBE	Lead-bismuth eutectic alloy
LBFR	Lead-bismuth fast reactor
LFR	Lead fast reactor
NRC	Nuclear Regulatory Commission
NS	Nuclear ship
PWR	Pressurised water reactor
RINA	Registro Italiano Navale
SEALER	Swedish Advanced Lead Reactor
SMR	Small modular reactor
SOLAS	International Convention for the Safety of Life at Sea
U.S.	United States
WNTI	World Nuclear Transport Institute

1 Introduction

The aim of this work is to identify the key considerations when integrating nuclear reactors into a merchant icebreaker and to protect people from radiation. This work was commissioned by Elomatic Consulting and Engineering Oy as a part of their internal development project called IBELO. The project's goal is to develop a concept design for a nuclear-powered PC1 class icebreaker intended for research operations in polar waters. The use of nuclear reactors as the power source is motivated by the elimination of the extensive fuel-tank capacity that would be required for traditional marine engines to supply a PC1 class vessel with fuel year-round. In addition, nuclear reactors enable a higher power output than conventionally fueled icebreakers, and they do so with a more compact volume. Integrating nuclear reactors into a merchant icebreaker introduces significant design challenges, ranging from the placement and protection of the reactors to ensuring the radiological safety of people and the environment. This thesis provides an initial overview of the radiation safety measures required for the ship.

1.1 History of nuclear ships

The majority of shipping worldwide is currently powered by diesel engines that use heavy fuel oil, marine gas oil or marine diesel oil [1]. Throughout history, most nuclear-powered marine vessels have been military ships and submarines, with only four civil nuclear-powered ships ever built: NS *Savannah*, NS *Otto Hahn*, NS *Mutsu*, and NS *Sevmorput* [2]. These vessels operated with pressurised water reactors (PWRs), the most commonly used small modular reactor (SMR) technology [2,3]. NS *Savannah* sailed under the United States flag, entered service in 1962, and retired in 1971. It served as both a passenger and bulk cargo vessel. West Germany launched NS *Otto Hahn*, an experimental ore cargo carrier, in 1968. Although designed as a cargo ship, it operated primarily as a research ship, and was also considered a passenger ship due to the large number of research personnel on board. After ten years of operation, its PWR propulsion system was replaced with a diesel engine. NS *Mutsu*, a Japanese nuclear-powered cargo ship, encountered difficulties during its initial testing in 1974, when increased fast neutron leakage through the radiation shielding was detected. The ship underwent repairs for four years and ultimately operated only during 1991-1992 [2]. Finally, NS *Sevmorput*, a Russian icebreaking freighter, entered service in 1988 with a reactor capable of producing 135 MW_{th} [2]. As of 2025, *Sevmorput* is reportedly no longer in operation and has been laid up in Murmansk since 2024 [4], leaving the world with zero nuclear-powered merchant ships currently in service [2]. Today, the only nuclear-powered ships in operation are those used by various militaries around the world.

Icebreakers are generally not categorized as merchant ships, even though they are in the civilian sector. Therefore, the icebreakers built in Soviet Union and Russia are not classified as merchant ships. The first Soviet nuclear icebreaker, NS *Lenin*, entered service in 1959 and operated until 1989. It was initially powered by three OK-150 PWRs, each having a thermal output of 90 MW_{th}. One of the reactors was kept in reserve in case of an emergency. In 1970, the OK-150 reactors were replaced with two 159 MW_{th} OK-900 reactors [2]. *Lenin* used nuclear-electric propulsion, but the Soviet-Russian nuclear icebreakers have since primarily used nuclear-mechanical propulsion [3]. Today, Russia operates several nuclear icebreakers, including the fourth-generation Arktika II class vessels *Arktika (II)*, *Sibir (II)* and *Ural*, all of which have been in service since 2020. Another Arktika II class icebreaker, *Yakutiya*, is currently under construction. Each of these icebreakers is equipped with two 175 MW_{th} RITM-200 PWRs [2].

In addition to PWRs, only one other reactor technology has been fully implemented for ship propulsion: heavy liquid metal-cooled reactors [5]. The first nuclear reactor using lead technology was a lead-bismuth fast reactor (LBFR), a type of reactor cooled with a lead-bismuth eutectic alloy, implemented by the Soviet Union in the 1950s for submarine propulsion [5,6]. The Soviet Union also used LBFRs in their *Alfa* class submarines from 1970 until the early 1990s [5]. In total, 15 LBFR cores were used for submarine propulsion [7]. Currently, no LBFRs or lead fast reactors (LFRs) are in operation worldwide, although several commercial LFR projects are under development. One LFR project in Russia is already under construction as a pilot demonstration prototype [7,8].

1.2 IBELO concept

IceBreaker ELO (IBELO) is the name of a concept design icebreaker which is the subject of this thesis. The icebreaker is planned to be powered with nuclear energy, having nuclear-electric propulsion, and it is being designed according to the Polar Class 1 rules. The ship will be designed for research purposes in polar waters and environments. Due to the Polar Class 1 requirements, the ship should be able to go through any ice conditions, and it should be operable year-around.

The overall length of the ship is to be 210 m, with a breadth of 40 m and a draught of 13 m. The displacement of the ship is estimated at 65 986 MT. The icebreaker will be able to accommodate a total of 130 persons onboard, 50 persons belonging to the crew and 80 to program personnel. Due to the high number of people on board, the ice breaker is considered a passenger ship. The icebreaker is to be powered by three lead-cooled fast small modular nuclear reactors. The reactors planned to be implemented are SEALER-55 reactors, a reactor designed by the Swedish Blykalla. The total electric output of these three reactors is 165 MW_e, which allows the ship to travel 3 knots in ice thickness of 4 meters. Below, on Figure 1, is the midship section of IBELO, and on Figure 2, is the view from the side. In the current design stage, the reactors are located in the center of the ship below the superstructure.

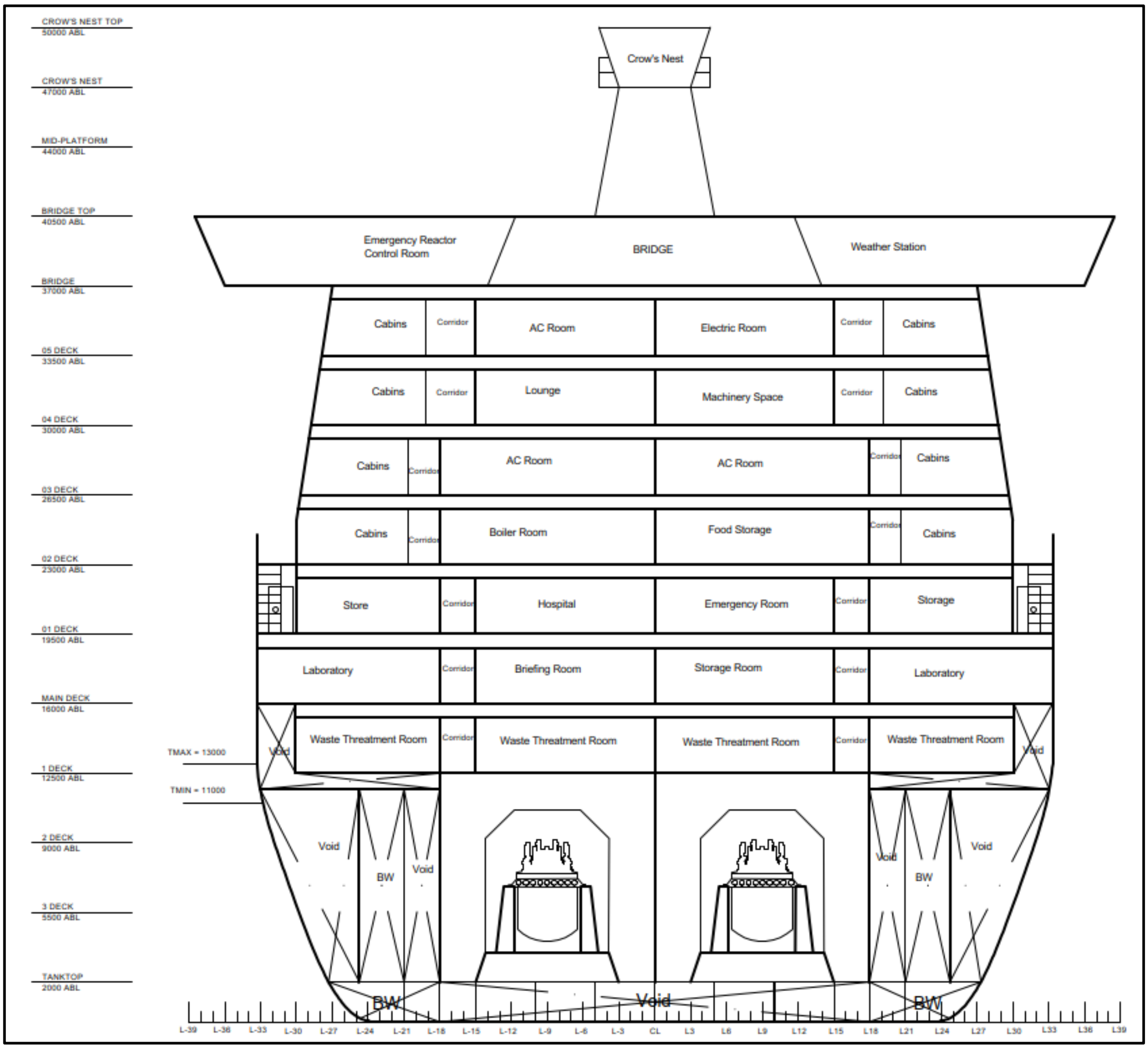

Figure 1. Midship section

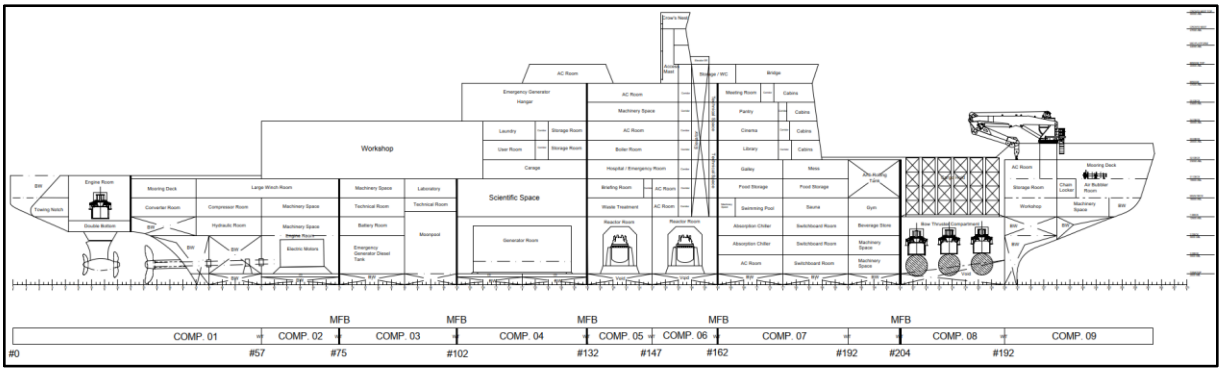

Figure 2. Side view.

1.3 Thesis scope and research plan

The scope of the thesis covers nuclear propulsion in merchant or commercial shipping, the regulations governing nuclear propulsion in merchant ships, selected international nuclear regulations, and U.S. nuclear regulations. The nuclear reactor chosen for the ship concept is the SEALER-55, a small modular reactor that uses fast neutron technology and is cooled by liquid lead. The radiation types addressed in this thesis are gamma and neutron radiation. The research questions are

(1) How does the reactor affect the structure and general arrangement of the ship? and

(2) What needs to be considered to ensure the radiological safety of people on board?

These will be answered through a qualitative literature review, calculations, and modelling. Gamma and neutron radiation fluxes and resulting radiation doses will be calculated. The aim is to develop a preliminary plan for the radiation shielding of the reactor and to determine what is required for a ship to safely host a nuclear reactor. The model will include the ship's general arrangement (GA) with a hazardous zone plan, along with comments on the requirements for accommodating a nuclear reactor.

First, the basics of fission reactions and neutron and gamma radiation are explained in Chapter 2. The formulas needed for radiation dose and shielding calculations are also presented in the same chapter. Chapter 3 describes the structure of the regulatory bodies in the marine and nuclear fields and summarizes the most important guidelines relevant to nuclear reactors on ships for the purposes of this thesis. The dose limits set by international bodies are also presented. Chapter 4 focuses on lead-cooled fast reactor technology, the SEALER-55 reactor design, and the dose and shielding calculations. Discussion on possible shielding materials and designs is also provided. Chapter 5 addresses the ship design, including the presentation of the GA. Chapter 6 concludes the thesis.

Artificial intelligence (AI) has been used to correct grammar and improve the readability of the text. AI has not been used to generate new content or analyze information, but solely to refine text already written by the author. All AI-assisted changes have been reviewed by the author. AI assistance was also used to search for sources.

2 Basics of radiation and dose calculation

In this chapter, the basics of radiation physics and fission reactions are introduced. The focus is on gamma and neutron radiation, and the mechanisms of their interactions with matter are explained. Formulas for radiation flux, doses, and attenuation are also presented.

2.1 Nuclear fission and radiation

Nuclear reactors generate thermal energy from nuclear fission occurring in fissile fuel rods. This thermal energy turns water into steam, which subsequently drives a turbine to produce electricity [3]. In spontaneous fission, a heavy fissile nucleus splits into two fragments called fission fragments while simultaneously releasing energy, neutrons, and photons. Fission can also occur when a nucleus absorbs a neutron and becomes unstable [9]. In a nuclear reactor, the fission process is induced, and uranium atoms are bombarded with neutrons [10]. Within a fraction of a picosecond after the fission event, the fission fragments emit multiple neutrons and gamma rays (photons), known as prompt neutrons and gammas [9]. The energy released in a single fission is approximately 200 MeV [11], of which about 170 MeV (85 %) appears as the kinetic energy of the fission fragments, while the remaining ~15 % is carried by photons and neutrons. Additionally, the fission products formed in the primary fission event can further emit neutrons and gamma rays, known as delayed neutrons and delayed gammas [9]. There are many possible fission reactions, one of which is illustrated by the formula

$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U$$

$${}^{236}_{92}U \rightarrow {}^{137}_{55}Cs + {}^{97}_{37}Rb + 2n. \text{ [11]}$$

Because a single neutron can induce the fission of a uranium nucleus – producing two to three neutrons that can trigger additional fission events – the overall process forms a self-sustaining chain reaction. The number of neutrons released in a fission event depends on both the isotope undergoing fission and the energy of the inducing neutron, but it averages about 2.5 [10]. Naturally occurring uranium ore consists of approximately 0.7 % ^{235}U and 99.3 % ^{238}U [3,10]. Since only ^{235}U can undergo fission with neutrons of any energy, its relative proportion in reactor fuel is typically increased through enrichment to sustain the fission process more effectively. Fuel is permitted to be enriched only up to 20 %, because material above this level can be used for nuclear weapons and therefore poses an unacceptable proliferation risk [3].

Alpha, beta, gamma and neutron radiation are present in a nuclear reactor. Alpha radiation consists of alpha particles, which are composed of two protons and two neutrons, similar to a helium nucleus. Because alpha particles have a substantial mass and a positive charge, they interact strongly with matter and therefore have a low penetration depth. Even a few centimetres of air or a sheet of paper is sufficient to stop an alpha particle. Beta particles, on the other hand, are high-velocity electrons or positrons and are therefore considerably less massive than alpha particles. They are more penetrating than alpha particles, but a few millimeters of material is enough to stop them. Both alpha and beta radiation can cause serious harm to living tissue [12]. Since their penetrating power is low and they are stopped by the inner walls of the nuclear reactor, people on board do not require specific protected from these particles. For this reason, they will not be the focused of this thesis.

Gamma radiation is a form of ionising electromagnetic radiation composed of highly energetic photons. Gamma rays have energies of about 10 keV and above [11], placing them in the highest-energy, shortest-wavelength region of the electromagnetic spectrum. For example, a 1 MeV photon has a wavelength of less than 10^{-11} m. Gamma radiation is produced by radioactive elements or by subatomic processes [12]. For instance, gamma radiation is emitted during fission, as previously mentioned, and during radioactive decay, when a nucleus releases excess energy to transition from an excited state to a lower-energy state or to the ground state [11,12]. The excited, unstable state of a nucleus is often the result of alpha or beta decay. Since photons have neither mass nor charge, the emission of gamma photons does not change the mass or charge of the nucleus.

Neutron radiation consists of neutrons, which are uncharged particles normally present in atomic nuclei. They can be released from nuclei through nuclear reactions such as fission and fusion. Neutrons interact with materials primarily through collisions with atomic nuclei, and before doing so they can travel long distances through matter. More about neutron interactions with matter is explained in Chapter 2.3. [12]

2.2 Gamma radiation interactions with matter

Gamma radiation can interact with matter in three different ways: the photoelectric effect, Compton scattering, and pair production [13]. In the photoelectric effect, electromagnetic radiation is absorbed by an electron, which is then emitted from the atom to which it was bound, leaving the atom ionised [12,13]. Part of the photon’s energy is used to release the electron, and the remainder is converted into the kinetic energy of the emitted electron [12,13]. If a photon has less energy than the amount required to detach an electron, the photoelectric effect does not occur [13].

Compton scattering occurs when a photon interacts with a free or loosely bound electron [13]. If the photon has substantially greater energy than the electron's binding energy, it can scatter as a result of the interaction [12]. During the interaction, the photon transfers part of its energy to the recoil electron's kinetic energy and changes direction [13]. Compton scattering depends only minimally on the atomic number of the material [12].

Pair production is an absorption process in which a photon transforms into an electron–positron pair. This process can occur only in the presence of a heavy nucleus or an atomic electron field, which is required to conserve the momentum of the incident photon. For pair production to take place, the photon's energy must exceed the combined rest-mass energies of the electron and positron, which is 1.022 MeV. The photon transfers its energy to the masses of the electron–positron pair, and any energy above 1.022 MeV is shared as kinetic energy between the two particles [14]. The produced particles gradually lose their energy through interactions with matter. Eventually, the electron loses all of its energy and becomes absorbed into an atom [12]. The positron, however, will ultimately encounter an electron and undergo annihilation, producing two 511 keV photons as the positron itself degrades [12,13].

The interaction of gamma radiation with matter depends on the energy of the radiation and the atomic number of the target material [13]. In tissue, the predominant photon interaction mechanism below an initial photon energy of 30 keV is the photoelectric effect. Then, between 30 keV and 30 MeV, most photon interactions with tissue occur via Compton scattering. Finally, above initial photon energies of 30 MeV, the primary interaction mechanism is pair production [12]. Through these interactions with matter, the intensity of gamma radiation gradually decreases [13].

Gamma radiation can penetrate materials extremely easily. The most effective materials for attenuating gamma radiation are those with high atomic numbers, such as lead. Sources emitting gamma radiation require heavy shielding because gamma radiation can have lethal effects on living cells. It is ionising radiation, meaning that it can remove electrons from atoms. As a result, high doses of gamma radiation can severely damage DNA and living cells. Acute radiation syndrome is an immediate effect that occurs when a person is exposed to high doses of radiation over a short period of time. Symptoms include nausea, vomiting, and organ damage, and in the most severe cases it can lead to a life-threatening condition. Long-term exposure to radiation, on the other hand, increases the risk of cancer through mutations in DNA. Other biological effects of radiation include skin burns, genetic mutations, and long-term damage to organs and tissues. [12]

2.3 Neutron radiation interactions with matter

There are two major ways in which a neutron can interact with matter: scattering and absorption. Scattering can be further divided into elastic and inelastic scattering. In an elastic interaction, a neutron transfers part of its kinetic energy to a nucleus and changes its direction and speed, while the nucleus is left with the same number of protons and neutrons as before the interaction. The total kinetic energy of the neutron and the nucleus remains the same. To slow down neutrons with the fewest number of elastic collisions, target nuclei with small atomic masses should be used. Elastic scattering is the most likely interaction mechanism for neutrons at low energies. [15]

Inelastic scattering, on the other hand, leaves the target nucleus in an excited state, from which it eventually releases radiation. Part of the kinetic energy of the incoming neutron is used to place the nucleus into this excited state, resulting in the total kinetic energy of the outgoing neutron and nucleus being lower than that of the incoming neutron. The excited nucleus may release gamma rays as it returns to a lower-energy state or to its ground state. The neutron behaves similarly to elastic scattering in that it only changes its speed and direction. Inelastic scattering is possible only when the available energy of the incoming neutron exceeds at least one of the excited states of the nucleus. Because the hydrogen nucleus has no excited states, inelastic scattering is impossible, and scattering occurs only elastically. [15]

The other interaction mechanism for neutrons is neutron absorption, or capture. This can lead to four different types of emissions from the nucleus: gamma rays, charged particles, neutrons, and fission. One or more gamma rays may be released when the nucleus rearranges its internal structure following neutron absorption. The nucleus can also emit charged particles – commonly protons, deuterons, or alpha particles – or it may release surplus neutrons. Neutron absorption can also induce fission, in which the nucleus splits into at least two smaller nuclei, called fission fragments, and additional neutrons are released. When absorption triggers the emission of gamma rays, charged particles, or neutrons, the resulting emission from a single neutron is indistinguishable from a scattering interaction, making their radiological impact effectively equivalent. [15]

Neutron radiation sources must also be sufficiently shielded. Neutrons can pass through materials – especially those with high atomic numbers – very easily. Particulate radiation, including neutron radiation, is also highly harmful to living tissue because of its ionising nature. The consequences of high neutron-radiation doses are similar to the risks of ionising radiation described previously in Chapter 2.2 and can even be fatal. Therefore, proper shielding must be provided. Materials containing hydrogen are the most effective for neutron shielding because neutrons lose energy most efficiently when colliding with hydrogen nucleus, which consists of a single proton, approximately the same size as a neutron. For this reason, water, polymers, and concrete are among the most effective neutron-shielding materials, along with neutron-absorbing compounds such as boron or cadmium. [12]

2.4 Radiation dose

As explained in the previous chapters, radiation damages the materials it interacts with, and in case of living organisms, it can destroy DNA. Therefore, it is important to monitor and minimize radiation exposure. The following formulas are used in this thesis to determine radiation dose.

To calculate the radiation flux at a distance *r* from a point-like radiation source, the number of fissions and the number of emitted particles must first be determined. The number of fissions occurring inside a reactor can be calculated when the thermal output power of the reactor and the energy released by a single fission reaction are known. The formula is

$$dN_f = \frac{P_{th}}{\varepsilon_f}, \quad (1)$$

where dN_f is the number of fission reactions occurring in a given time interval, P_{th} is the thermal output power of the nuclear reactor, and ε_f is the average energy released in one fission reaction.

Let υ be the average number of gamma rays or neutrons emitted per fission. Then the number of particles emitted per second is

$$N_r = dN_f \upsilon, \quad (2)$$

where N_r is the number of gamma rays or neutrons emitted per second.

The inverse square law is applied to calculate the radiation flux (ϕ), which represents the number of particles passing through a surface at a distance r from a point source emitting N_r gamma rays or neutrons per second [16]. The distance r is the radius of a sphere centred around the source. Since the surface area of a sphere is $4\pi r^2$, the flux ϕ at distance r is expressed as

$$\phi = \frac{N_r}{4\pi r^2}. \tag{3}$$

The radiation dose at a given distance from the point source, once the radiation flux is known, is calculated using the absorbed dose, equivalent dose, and effective dose formulas. The absorbed dose accounts for the energy transferred from radiation to a mass. The equivalent dose then accounts for the type of radiation and its relative biological effectiveness, allowing different radiation types to be compared. Finally, the effective dose describes the severity of radiation exposure to specific tissues. The different dose types and their formulas are explained in more detail below.

The absorbed dose D is denoted as

$$D = \frac{d\varepsilon}{dm}, \tag{4}$$

where $d\varepsilon$ is the mean energy imparted to a mass dm of matter by ionising radiation. Absorbed dose is expressed in grays (Gy), which are equivalent to joules per kilogram ($\frac{J}{kg}$). [17]

The equivalent dose, H_T, which defines the dose in a tissue or organ T, is given by

$$H_T = \sum_R w_R D_{T,R} , \tag{5}$$

where w_R is the radiation weighting factor and $D_{T,R}$ is the mean absorbed dose from radiation type R in a tissue or organ T. The weighting factor w_R is dimensionless, so the unit of equivalent dose is also $\frac{\mathrm{J}}{\mathrm{kg}}$. However, equivalent and effective doses are conventionally expressed in sieverts (Sv), not grays. [17]

The effective dose E takes the tissue weighting factor w_T into account and is the sum of the equivalent doses in all specified tissues and organs of the body. It is expressed as

$$E = \sum_T w_T \sum_R w_R D_{T,R} , \tag{6}$$

or

$$E = \sum_T w_T H_T \, , \tag{7}$$

where $w_R D_{T,R}$ or H_T is the equivalent dose in tissue or organ *T*, and w_T is the tissue weighting factor [17]. Some tissues are more sensitive to radiation, which is reflected in the tissue weighting factor. In summary, the absorbed dose considers only the energy transferred to a mass, whereas the effective dose also accounts for the biological severity of radiation in different tissues or organs.

For this thesis, we want to calculate the dose rate $\frac{dD}{dt} = \dot{D}$ for the whole body at a certain distance from a point source. When the tissue weighting factors are summed, the weighting factor for the whole body is $w_T = 1$ [17]. Using the radiation flux ϕ at a certain distance, together with the effective dose *E*, the average human body area a_h, and time *t*, we obtain the equation

$$\dot{D} = \phi E a_H t. \tag{8}$$

Dose rate is commonly reported in units of Sv/h, where t = 3600 s.

2.5 Radiation attenuation

When radiation penetrates a material, its intensity decreases [8]. This phenomenon is described by the Beer–Lambert's law:

$$I = I_0 e^{-\mu x}, \tag{9}$$

where I is the radiation beam intensity, I_0 is the incident beam intensity, μ is the linear attenuation coefficient, and x is the shield thickness. The linear attenuation coefficient is expressed in units of cm^{-1}, and this concept is used for X-rays and gamma rays [12]. Beer–Lambert's law can also be applied to other types of radiation, but we first focus on photon radiation using the linear attenuation coefficient.

A higher value of μ causes the beam intensity to decrease more rapidly. The coefficient depends on both the material type and the radiation energy. At higher radiation energies, the total attenuation of a material decreases. Attenuation can also be described using the mass attenuation coefficient, μ/ρ, where ρ is the density of the material. This is possible because μ depends on material density, and the attenuation caused by a thickness x is determined by the number of electrons present in that thickness. In general, the mass attenuation coefficient is more important than the linear attenuation coefficient because it depends solely on the atomic composition of the material [12].

The ratio I/I_0 derived from the Beer–Lambert's law is called the transmission [18]. It expresses the relationship between the incident beam and the resulting beam after passing through a given material thickness:

$$\frac{I}{I_0} = e^{-\mu x}. \tag{10}$$

Whereas the linear attenuation coefficient μ is used for gamma-radiation shielding calculations, the total macroscopic cross section Σ_t is the analogous quantity for neutron shielding [15]. Σ_t can be expressed as $\Sigma_t = N\sigma_t$, where N is the number of nuclei per unit volume and σ_t is the total microscopic cross section [12,15]. Since Σ_t is analogous to μ, Beer–Lambert's law can be written for neutron radiation as

$$I = I_0 e^{-\Sigma t x}, \tag{11}$$

where I_0 is the intensity of the uncollided neutron beam [15].

However, an effective removal cross section Σ_R is often used to describe neutron attenuation. According to Hila *et al.*, the removal cross section "quantifies a material's potential to effectively remove fast neutrons from their starting fast energies by elastic and nonelastic collisions" [19]. In other words, it represents the probability that a faster neutron undergoes its first collision [12]. Between neutron energies of 6 and 8 MeV, Σ_R is approximately two-thirds of Σ_t. Historically, elemental mass removal cross sections (Σ_R/ρ) have been used to estimate the removal cross sections of materials [19]. Σ_R is roughly constant for neutrons with energies between 2 and 12 MeV. Verma and Srivastava describe Σ_R as being "like an absorption or attenuation coefficient of material for neutron interaction" [12].

Because of this resemblance, and because Swinhoe *et al.* defined I_0 in Equation (11) as the intensity of the uncollided neutron beam while Σ_R represents the probability of a neutron experiencing at least one collision, we rewrite Equation (11) as

$$I = I_0 e^{-\Sigma_R x}. \tag{12}$$

It is important to note that the actual number of neutrons after passing through thickness x can be much larger due to multiple scattering and multiplication within the material. However, their energy levels decrease and their directions change [15]. The transmission expression in Equation (10) can also be applied to neutron radiation by replacing μ with Σ_R to describe the fraction of neutrons transmitted without collisions.

The mean free path λ is the average distance a neutron travels before undergoing a collision. In practice, it represents the typical thickness of material a neutron can transverse without interacting. It is the reciprocal of the total macroscopic cross section and is expressed as

$$\lambda = \frac{1}{\Sigma_t}. \text{ [15]} \tag{13}$$

3 Regulatory framework

This chapter provides an overview of the current status of the regulatory framework governing ships with nuclear propulsion. The basic structure of maritime regulatory organisations is introduced, followed by an overview of the nuclear regulatory framework in both the international and United States contexts. There is a lack of up-to-date regulations for nuclear-powered ships. In this thesis, certain laws and regulations originally intended for land-based applications are adapted to the marine environment to address some of these gaps. Additionally, rules and regulations relevant to this work and essential for radiation safety are presented in this chapter.

3.1 Basics of the marine and nuclear regulatory bodies

Nuclear energy has matured greatly since its inception, and correspondingly many countries, regulators, and international organisations have developed regulations, standards and guidelines for its safe and responsible use [5]. For land-based applications, the nuclear sector is heavily regulated, particularly at the national levels [3]. However, for merchant-marine applications of nuclear propulsion, the regulatory framework is limited and largely outdated. The existing regulations do not cover all reactor technologies, which is an understandable gap given the rapid development of, and increased interest in, Generation IV SMR technologies in the past decade.

3.1.1 Maritime regulatory bodies

Outside of nuclear-marine applications, the marine sector is heavily regulated, with well-defined roles among the various parties involved. International organizations, classification societies, and national governments – including flag states, coastal states, and port states – establish international and national regulations [3]. Shipowners and shipyards must comply with the regulations set by these entities and collaborate with them accordingly.

As the most fundamental international treaty in the maritime sector, the United Nations Convention on the Law of the Sea (UNCLOS) defines the essential rules governing the use of the oceans, ocean resources, and the movement of ships [20]. The International Maritime Organization (IMO) is a specialised agency of the United Nations responsible for ensuring safe and secure shipping and for preventing pollution from ships [2]. The IMO and the International Labor Organization (ILO), also a United Nations agency, are the highest international regulatory bodies in the shipping sector. The International Convention for the Safety of Life at

Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL), both established by the IMO [20], provide safety standards and environmental protection guidelines applicable to merchant ships, including nuclear-powered vessels [3].

The International Association of Classification Societies (IACS) is an organisation under the IMO that establishes and maintains requirements and technical standards for the design, construction, and operation of ships. The members of the IACS are non-governmental, third-party organisations [3,5]. Examples of IACS members include the American Bureau of Shipping (ABS), Det Norske Veritas (DNV), Registro Italiano Navale (RINA) and Lloyd's Register (LR). The primary task of IACS is to develop Unified Requirements (URs), which help harmonise specific rule requirements across its member societies [5].

On the national level, a flag state is the country whose flag a ship flies, and it ensures that the laws of that country are obeyed on board the vessel. It is the ship's most essential regulatory body. A port state, on the other hand, is a nation that exercises Port State Control (PSC) to inspect ships calling at its ports. PSC ensures that ships comply with international codes and standards [21]. Coastal states are responsible for traffic monitoring and intervention within their maritime zones [22]. According to ABS [23], "the Port Authority/Port State or Coastal State Administration is the appropriate authority of the country in which the vessel is operating, stationed, or laid up" [23]. All of these governmental bodies complement one another within the maritime regulatory and control system [22].

3.1.2 Nuclear regulatory bodies

Nuclear technologies are regulated primarily through national frameworks, where the sector is heavily controlled, while international bodies play a comparatively smaller, though still important, role [3]. The International Atomic Energy Agency (IAEA) is an intergovernmental regulatory body under the United Nations. It facilitates cooperation in the nuclear field and monitors the use of nuclear technologies [24], thereby promoting the peaceful application of nuclear energy [5,24]. Another global organisation is the World Nuclear Transport Institute (WNTI), a non-governmental membership organisation [25] that develops standards primarily for the safe transport of radioactive materials [26]. It also influences shipping regulations through its role as a consultant to the IAEA [5]. In the field of protection against ionising radiation, the International Commission on Radiological Protection (ICRP) operates as an independent international organisation that provides recommendations and guidance. ICRP's recommendations are closely followed in most national regulations and by the IAEA [27].

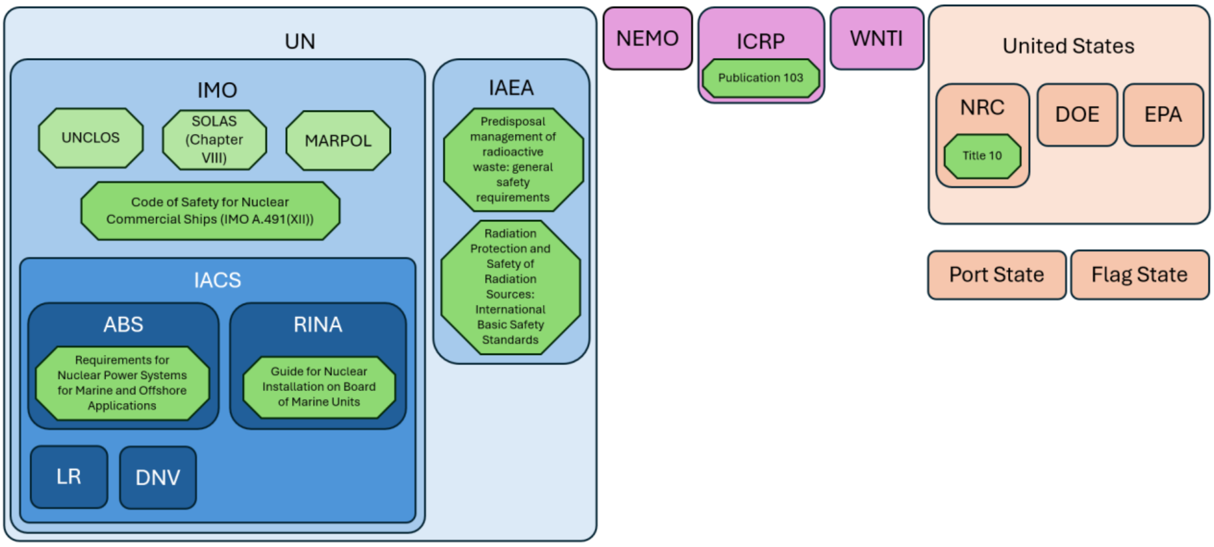

Figure 3. Illustration of the essential regulatory parties and regulations for this thesis.

In the United States, several national regulatory bodies oversee the nuclear sector. These include the Nuclear Regulatory Commission (NRC), the Department of Energy (DOE), and the Environmental Protection Agency (EPA) [5]. The NRC is responsible for developing policies and regulations, issuing orders to licensees, and addressing legal matters related to nuclear safety [28]. The DOE, among its many functions, manages naval reactor and energy development programs. The EPA, in contrast, focuses on regulating and protecting the environment – specifically the lands, air, and waters of the United States. All U.S. regulations are recorded in the Code of Federal Regulations (CFR) or other U.S. legal codes [5].

An organisation connecting the nuclear and marine fields is the recently established Nuclear Energy Maritime Organization (NEMO), founded in 2024. Its mission is to bring stakeholders from both the nuclear and maritime sectors together and to support the development of forward-looking standards and rules. The organization focuses on the development, operation, and decommissioning of floating nuclear power systems [5]. After introducing the many regulatory organisations within the marine and nuclear industries, Figure 3 illustrates the organisations in relation to one another. Their publications, which are relevant for this thesis, are also included in the illustration.

3.2 Regulations for nuclear ships

Nuclear ships, like all ship types, must comply with the requirements of the International Convention for the Safety of Life at Sea (SOLAS), an international treaty established by the IMO that sets minimum safety standards for ships. SOLAS also includes a dedicated section for nuclear vessels – Chapter VII: *Nuclear Ships* – which outlines the fundamental safety regulations for all nuclear-powered ships other than ships of war. According to this chapter, nuclear ships must follow all other SOLAS requirements except those specifically modified within Chapter VII. Under Chapter VII, Regulation 4 assigns responsibility for approving the reactor installation to the Administration, meaning the ship's flag state [29]. This requirement is reiterated in later regulations concerning nuclear ships. Regarding radiation safety, the treaty states: "The Administration shall take measures to ensure that there are no unreasonable radiation or other nuclear hazards, at sea or in port, to the crew, passengers or public, or to the waterways or food or water resources" [29]. The treaty places strong emphasis on safety, setting requirements for safety assessments, surveys, and certification. Some of the regulations issued by some organsations introduced earlier will be reviewed in this chapter, with focus on ship structure, reactor spaces and radiation protection.

The International Maritime Organization (IMO) created the Code of Safety for Nuclear Merchant Ships in 1981 to supplement the regulations in SOLAS [30]. The Code, also known as Resolution A.491(XII), defines structural requirements for nuclear-powered ships and sets goals for ensuring the structural integrity of the vessel in order to protect the reactor compartment, with a strong emphasis on radiation protection. The Code applies only to nuclear ships that operate with pressurised light water reactors (PWRs) [30].

IMO has not updated the document since its publication in 1981. A growing interest in ships using nuclear propulsion requires updated regulations that also account for reactor technologies other than PWRs. According to WNTI, the organisation has submitted a gap analysis on the Code of Safety for Nuclear Merchant Ships, providing recommendations for a revised code. Among WNTI's requests are technology neutrality to incorporate all types of advanced marine reactor technologies, a goal-setting rather than a prescriptive approach [31].

While an updated version of the Code is still pending, some classification societies have published their own recommendations for nuclear marine applications. For example, ABS released the Requirements for Nuclear Power Systems for Marine and Offshore Applications in October 2024. Although ABS acknowledges that the Code is outdated, it still refers to it frequently. The requirements issued by ABS do not apply to nuclear power used for propulsion but rather to other marine and offshore applications [23]. However, due to the limited regulatory framework in this area, these requirements are reviewed for the purposes of this thesis. The ABS requirements apply to all reactor technologies, and ABS also recognises the possibility of having multiple nuclear power plants on board [23]. Another classification society that has published guidance for nuclear ships is RINA, which released the Guide for Nuclear Installation on Board of Marine Units, effective January 2026 [32]. The guide is intended for nuclear ships using nuclear energy for propulsion and applies to all reactor types [32].

It is worth noting that, for the most part, the regulations are prescriptive and do not provide highly specific instructions. It is also emphasised that all designs must be accepted by a flag administration and/or a classification society. ABS requires that the licensee of the reactor, as well as the applicable nuclear safety structures, systems, and components, be approved by the nuclear regulator of the flag administration [23].

3.2.1 Hull and Structure

The hull and the structure of the ship should be designed to protect the reactor from any external hazards such as collisions, groundings, and missiles, while also minimizing the effects of ionizing radiation emitted by the reactor to the ship and its personnel. Regulations strongly emphasize the structural safety of both the ship and the reactor compartment, stating that the reactor should be located in the least vulnerable position relative to potential hazards [23,30]. The optimal placement for reactors is at the center of the ship, as hazards like collisions and groundings are statistically more prone to occur at the bow or stern of the ship. Additionally, the central location experiences less movement, and the ship's stability is better maintained when heavy reactors and their shielding are positioned amidships [2]. Acceptable irradiation levels can be achieved through proper structural design. The Code lists possible measures that should be implemented to protect against the effects of irradiation. These measures are "(1) interposing adequate shielding, (2) establishing controlled areas of the ship, (3) limiting exposure times, (4) preventing the unnecessary approach of persons to sources of radiation, and (5) actions by the personnel in emergencies in accordance with plans and instructions" [30].

Establishing controlled areas of the ship is achieved by dividing the vessel into zones based on actual or potential radiation hazards [23,30]. Interposing adequate shielding is accomplished by using sequential shielding barriers around sources of radioactivity [23,32]. The vessel's shell should not be considered a radiation shield under any operating condition [23]. This means that the radiation shielding must be designed to reduce the radiation to acceptable limits on its own, even though, in practice, all ship structures contribute to attenuation. IMO's Code states that there should be four physical barriers between the fuel and the environment to ensure sufficient attenuation and compliance with dose-equivalent limits. These barriers are (1) fuel cladding,

(2) primary pressure boundary, (3) containment structure and (4) safety enclosure [30]. All four barriers should be located within the reactor compartment [30].

In contrast, ABS requirements and the RINA Guide do not specify the physical barriers in the same manner as IMO. However, all three organizations require the containment structure to adequately limit radiation emissions to acceptable levels [23,30,32]. The safety enclosure is not mentioned in the RINA Guide or ABS requirements. Instead, both organizations use the term "shielding barrier" for a structure similar in function to the safety enclosure [23,32]. Additionally, RINA frequently uses the term "biological shielding" to describe structures designed to protect living organisms from radiation [32]. Fuel cladding is not mentioned in ABS requirements [23], but it is defined as the first shielding barrier between nuclear fuel and the environment in the RINA Guide [32]. RINA also defines the primary heat transfer medium circuit as the secondary shielding barrier rather than the primary pressure boundary [32]. This terminology takes all reactor technologies into account, since the primary pressure boundary is only applicable to pressurized systems. Going forward with this thesis, we will discuss the containment structure, safety enclosure, and reactor compartment.

The definition of a reactor compartment is: "The onboard space containing the nuclear reactor that is bounded by the hull, the bulkhead deck and fore and aft by athwartship cofferdams or bulkheads" [23]. Inside the reactor compartment the safety enclosure, which serves as the fourth barrier of the reactor. To protect the reactor compartment from groundings, a double bottom must be provided beneath it. The distance between the safety enclosure and the bottom of the ship must be at least B/15 or 2 meters (whichever is greater), where B represents the ship's breadth [30]. According to the IMO, the damage extent region "inboard from the ship's side at right-angles to the centerline at the level of the summer load line" to the safety enclosure should be at least B/5 or 11 m (whichever is less) [23,30]. RINA, however, states that "The longitudinal bulkheads designed to be the side walls of the shielding barrier are to be at least $B/5$ or 11.5 m (whichever is less) apart from outer shell side […]" [32]. In this context, shielding barrier and safety enclosure are considered equivalent. The damage extent region can also be used for functional spaces and rooms, and must not be considered a double hull [23]. The safety enclosure formed by bulkheads or other boundaries must be gastight, firetight and watertight including all piping and electrical penetrations as well as personnel access openings [30,32]. The forward and aft boundaries of the safety enclosure may be integrated with the cofferdams or suitable bulkheads forming the reactor compartment.

The cofferdams separating the reactor compartment from the adjacent spaces should be at least 900 mm in width [32]. It is also permitted to fill the cofferdams and double bottoms forming the boundaries of the reactor compartment with non-potable water [27]. If cofferdams are not used in the fore and aft to form the reactor compartment, the bulkheads defining the compartment must be suitable for protecting it from external fires or explosions [30].

Within the safety enclosure, there should be a containment structure acting as the primary radiation shield outside of the reactor [30]. In this thesis, the containment structure can also be referred to as a biological shield or shielding barrier. The containment system should be equipped with overpressure protection to ensure that no contaminated radioactive material exceeding acceptable exposure limits is released into the environment or other onboard spaces [23]. Access through the containment structure must be provided, along with sufficient accessibility for inspection and maintenance activities [30]. According to the IMO, "Reactor and containment structure foundations should be adequately designed for proper support […]" and "they should be adequate to retain the primary pressure boundaries and containment structure in position under any inclination" [30]. Thermal stresses must also be considered, and the hull structure is required to absorb all final loads. Therefore, the foundation structures may be integrated with the hull structure [30]. RINA additionally states that "biological shielding is to be provided, directed towards the bottom of the Unit, to prevent adverse effects on sea water when reactor plants is operating at a rated power" [32].

The reactor compartment, including all systems that contain radioactive material – such as high-level radioactive waste storage – must also be protected by a collision protective structure [23,30]. The protective structure should be arranged in way of the reactor compartment so that there is "an additional reasonable area forward and aft of reactor compartment transverse bulkheads" [30]. The structure must prevent "penetration of the longitudinal watertight, gastight boundaries of the safety enclosure" [30]. A collision-protective structure designed to limit penetration may allow the Administration to accept a reduced extent of the damage-extent regions on the side or bottom of the ship [23]. However, all nuclear safety systems must remain operable even if the nuclear power plant experiences physical damage [23].

A shielding barrier is to be provided around all spaces within controlled areas where radioactive contamination may occur during normal operation [32]. According to RINA, there should be sufficient biological shielding for the heat transfer system, radioactive waste storage, and other radioactive sources to ensure radiation safety from normal operation to severe accident conditions [32]. All materials that are expected to be in contact with or potentially exposed to ionizing radiation, like containment structures, piping, and radiation shielding barriers, must be suitable for their intended purpose [23].

3.2.2 Radioactive waste

According to the IAEA's general safety requirements on predisposal management of radioactive waste, which apply to all nuclear reactors, national governments must provide a legal and regulatory framework for the safe management of radioactive waste, including requirements for protecting human health and the environment. The volume and activity of generated radioactive waste must be controlled, and these factors must be considered already during the design phase of the facility [33]. The design of the nuclear power plant should aim to keep waste production at a minimal level, as far as practicable [30,33]. The safety of the facility throughout its expected operating lifetime, including normal operation, potential accident conditions, and eventual decommissioning, must also be addressed during the design stage. The IAEA requires radioactive waste to be "characterized in terms of its physical, mechanical, chemical, radiological and biological properties". Furthermore, "waste shall be stored in such a manner that it can be inspected, monitored, retrieved and preserved in a condition suitable for its subsequent management" [33].

According to ABS, a vessel must "have provisions in place for the safe handling, storage, and disposal of radioactive waste" and must "provide means to monitor and record environmental discharges". Therefore, radioactive waste streams are to be managed and stored in a manner that prevents the release of unreasonable levels of radiation into the sea or air. Radioactive waste treatment and storage facilities must remain fully operable under all design and operation conditions [23]. These facilities are also required to be provided with biological shielding [32].

Regulations for nuclear ships classify radioactive waste into solid, liquid and gaseous categories [23,30,32]. There should be special-purpose containers for the storage and transport of solid radioactive waste [32], and such waste must never be discharged into the environment under any circumstances [23,30]. Liquid radioactive waste must be stored in enclosed containers or tanks [23,32], with medium- and low-activity liquids kept in separate spaces. RINA specifies that a minimum of two containers must be carried on board [32]. According to the IMO, the storage capacity for liquid radioactive waste must account for all bilge liquids generated in controlled areas under normal operating conditions [30]. Two separate pipelines must also be provided to connect treatment and storage facilities for transferring liquid radioactive waste ashore or to a special-purpose ship. RINA further states that “Gaseous radioactive waste are to be compressed and stored in pressure vessels (cylinders) and appropriate pipelines […]” [32]. The release of liquid and gaseous radioactive waste into the environment is permitted, but it must be carefully monitored, and uncontrolled releases must be prevented [23,30,32]. The volume and radioactivity levels of any discharges must not exceed limits established by national or international radiation safety standards [32]. According to the IAEA, any portion of the waste that cannot be discharged, “has to be processed in such a way that the resulting waste form can be safely stored and retrieved from the storage facility up until its ultimate disposal” [33].

3.2.3 Dose limits and controlled and supervised areas

According to the ICRP, occupational exposure refers to all exposure incurred by workers in the course of their work, with certain exceptions. The ICRP defines workers in Publication 103, part 5.4.1.183, as follows: “A worker is defined by the Commission as any person who is employed, whether full time, part time, or temporarily, by an employer and who has recognised rights and duties in relation to occupational radiological protection”. The ICRP does not recommend classifying workers themselves but instead classifies areas of work into controlled areas and supervised areas. ICRP requires workers in controlled areas to be well informed, specially trained, and to form a readily identifiable group. [17]

Radiation dose limits are established to protect human health from high doses of radiation, and they are typically set separately for occupational workers and members of the public. The ICRP provides recommended annual effective and equivalent dose limits for occupational and public exposure in Publication 103 [17]. The updated values were published in 2007 [17]. The dose limits are presented in Table 1. In contrast, the IMO has established limitations on dose-equivalent rates for different areas and spaces of the ship [30]. These limits are presented in Table 2. The limits apply specifically to ionizing radiation and do not account for natural background radiation; therefore, they apply only to ship-generated sources [30].

At the national level, the NRC has established regulations for occupational and public dose limits for adults. According to annual occupational dose limits set in §20.1201 [34], the more restrictive of the following must be applied: the total effective dose equivalent must not exceed 5 rems (50 mSv), or the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye must not exceed 50 rems (500 mSv) [34]. When comparing the total effective dose equivalent to the ICRP’s recommended occupational effective dose limit of 20 mSv, ICRP’s recommendation is clearly stricter.

Table 1. Radiation dose limit recommendations by the ICRP. [17]

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years	1 mSv in a year
Annual equivalent dose in:		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	-

Table 2. Limiting dose-equivalent rates for different areas and spaces. [30]

Area or Space	Dose-Equivalent Rate
1. In the navigating bridge	0.75 µSv/h (0.075 mrem/h)
2. In accommodation spaces	0.15 µSv/h (0.015 mrem/h)
3. On upper deck and in cargo spaces	0.50 µSv/h (0.050 mrem/h)
4. On ship's sides above the waterline	0.50 µSv/h (0.050 mrem/h)
5. On ship's bottom where "in water" maintenance or survey is contemplated with the reactor at 10% power	7.5 µSv/h (0.75 mrem/h)

NRC Part § 20.1301, on the other hand, defines radiation dose limits for individual members of the public [34]. It states that "The total effective dose equivalent to individual members of the public from the licensed operation does not exceed 0.1 rem (1 mSv) in a year […] ". This limit excludes, for example, doses from natural background radiation, medical treatments, exposure to treated patients, voluntary medical research, and permitted sewer disposal by the licensee [34]. The ICRP's recommended annual dose limit for the public aligns with the NRC's regulation.

ABS does not specify dose limits in its document, but it states that dose limits must not exceed those set by a competent authority [23]. ABS also recommends referring to ICRP Publication 103 [23]. The RINA Guide likewise does not specify numerical dose limits, but it requires the nuclear power plant to be designed so that, even in a severe accident, the radiation dose received by people on board and by a limited portion of the population would be no more than twice the maximum dose limit established by national or international radiation safety standards [32].

The IAEA requires, in its Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, that registrants and licensees designate as a controlled area "any area in which specific measures for protection and safety are or could be required for: (a) Controlling exposures or preventing the spread of contamination in normal operation; (b) Preventing or limiting the likelihood and magnitude of exposures in anticipated operational occurrences and accident conditions" [35]. Supervised areas are defined as "any area not already designated as a controlled area but for which occupational exposure conditions need to be kept under review, even though specific measures for protection and safety are not normally needed" [35].

The IMO defines controlled areas, supervised areas and uncontrolled areas differently. In controlled areas, personnel access is restricted, and the dose-equivalent levels are likely to exceed 3/10 of the dose-equivalent limits recommended by ICRP for occupationally exposed persons. For supervised areas, the corresponding threshold is 1/10. The IMO defines uncontrolled areas as any spaces on the ship that are not controlled or supervised for radiation protection and where the dose is not likely to exceed the ICRP's recommended dose-equivalent limits for members of the public [30]. NRC, on the other hand, sets the limit for a person within the controlled area under normal conditions at 0.25 mSv for the annual whole-body dose [34].

At the access points to the controlled area, personal protective equipment, individual-monitoring devices, workplace-monitoring equipment, and storage for personal clothing must be provided [35]. Additionally, the IMO and RINA require access barriers or physical security barriers at entry points, where the entry and exit of authorized personnel must be recorded [30,32]. Exit points from the controlled areas must be equipped with decontamination facilities, including provisions for contamination monitoring of skin, clothing, and any objects or materials leaving the area, as well as washing and showering facilities and storage for contaminated personal protective equipment [32,35]. Workers in supervised areas must also be provided with suitable and adequate personal protective equipment [35]. According to RINA, an emergency escape route to the open deck must be provided from spaces located within the controlled area [32].

In the case of IBELO, it is appropriate to classify all crew members who are granted access to any controlled or supervised area as occupational workers. Therefore, the annual dose limits for occupational workers set by the ICRP or NRC should apply to them – meaning annual limits of 20 mSv or 50 mSv, respectively. In this thesis, the lower of the two limits is used. All other people on board should be classified as members of the public, limiting their annual dose to 1 mSv. For comparison, 1 mSv is a very small amount: the average annual dose received by a person in the United States is about 620 mrem (6.2 mSv), roughly half of which comes from natural background radiation [36]. These limits can also be considered quite safe, as they are well below 100 mSv. Rühm *et al.* reported that there is substantial evidence that doses above 100 mGy can cause cancer – taken here as approximately 100 mSv for comparison – and also found evidence that smaller doses may increase cancer risk [37].

3.2.4 Ventilation and bilge

According to the RINA Sec. 5 part 11.1, "the ventilation systems of controlled and supervised areas are to be independent, separated and isolated from each other and the rest of ventilation systems installed on board" [32]. Ventilation airflow must also be designed to move from spaces with lower potential airborne contamination toward spaces with higher potential airborne contamination [30,32]. Controlled areas must always be maintained in under pressure, even when one entrance is open [32]. RINA Sec. 5 part 11.9 further states that "air from the controlled area spaces are to be discharged through a dedicated mast" [32]. Additionally, ventilation for the controlled area is to be redundant, meaning a standby fan must automatically activate in the event of a failure in the primary system [32].

The bilge system within the controlled area must also be independent from the ship's other bilge systems [32]. RINA states that "compartments in controlled area are to be drained into special containers" which aligns with the IMO's earlier-mentioned rule [32]. Within controlled areas, biological shielding must also be provided for pumps and pipelines where necessary [32]. According to the IMO, interconnections between the ship's normal piping systems and piping in areas that contain or may contain radioactive material should be minimized. Interconnections between radioactive fluid systems and potable water systems are strictly prohibited [30].

3.2.5 Reactor control rooms and openings in watertight bulkheads

A reactor should have two distinct reactor control positions: the main reactor control room and an emergency control position. The main reactor control room should be located in the least vulnerable area with respect to hazards such as fires and radioactivity, while remaining as close to the reactor and associated machinery as practicable. The emergency control room, by contrast, should be separate from and remote to the reactor control room, and it may be functionally connected to the navigating bridge. The operator should be able to maintain the reactor in a safe state from the emergency control position whenever the main reactor control room is not accessible. A connection to the navigating bridge would allow a scram procedure to be carried out under the control of the navigating bridge. Both control positions should be sufficiently shielded to allow essential control functions to be manned for a reasonable period under any circumstances [30]. ABS suggests that, in cases where multiple nuclear power plant units are installed onboard, more than one main reactor control room may be fitted [23]. According to IMO regulation 3.9.5, “At least two means of escape should be provided from the main reactor control room and from the compartment in which the emergency reactor control position is located. Each escape route should provide effective fire shelter from the compartment to the weatherdeck” [30]. In other words, each control room should have at least two exit doors.

ABS sets the following requirements in their Section 6, Part 2.2.1(ii), based on IMO rules: “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 watertight, gastight or fire protection division in which they are located. Where necessary for security or safety purposes, closures are to be provided with appropriate arrangements for local and remote operation. 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]” [23]. In other words, watertight, gastight, and firetight doors are to be used in boundaries that form watertight, gastight or fire protection divisions. Airlocks may also be installed in spaces where access between a lower and a higher pressure area is needed. According to SOLAS Chapter II-1, Regulation 13 [29], openings for pipes, scuppers, electric cables, and similar penetrations in watertight bulkheads must also maintain the watertight integrity of those bulkheads. The overall number of openings in watertight bulkheads should be kept to the minimum possible [29].

In passenger ships below the bulkhead deck, there must be two means of escape from each watertight compartment or similarly restricted space or group of spaces. At least one of these escape routes must be independent of watertight doors. The Administration may also accept a single means of escape from crew spaces that are used only occasionally, provided that the escape route is independent of watertight doors. If the construction of only one escape is approved, it must still provide a safe means of escape. It is also specified that stairways should have a minimum clear width of 800 mm. [29]

To conclude this regulation-focused chapter, it appears that such specialized vessels as nuclear ships are not explicitly recommended by any regulatory body, but they are permitted to be constructed and operated. In other words, regulations do not prohibit a nuclear icebreaker, for example. Some of the greatest challenges facing nuclear merchant ships are liability and indemnification, port entry, and regulations [2]. Administrations and ports may deny entry of a nuclear-powered ship to a port. For instance, NS *Savannah* was excluded from port visits to Australia, Japan, and New Zealand, and the launch of NS *Otto Hahn* triggered protests against nuclear power, which reduced the number of ports willing to receive the ship. NS *Sevmorput* was even denied entry into four major Soviet ports in 1988 due to protests and fears following the Chernobyl accident. Although some countries and ports refused entry to these vessels, many others accepted them: *Savannah* visited 32 domestic and 45 international ports in 26 countries, and *Otto Hahn* visited 46 ports in 22 countries [2]. It should therefore be assessed early in the nuclear ship design process which ports would allow the vessel to enter. Liability and indemnification arrangements should likewise be planned at an early stage to determine who would be the responsible party in the event of a nuclear incident. For example, *Savannah* was indemnified against nuclear accidents by the U.S. government up to USD 500 million [2]. Overall, issues related to liability, indemnification, and port entry should be addressed early in the ship design process.

4 Nuclear reactor and radiation shielding

In this chapter, lead fast reactor (LFR) technology, breeder reactor technology, and the SEALER-55 reactor are introduced. A closer look is taken at the reactions occurring inside an LFR, and calculations for the gamma and neutron fluxes, along with the corresponding dose rates, are performed. Suggested radiation shielding structures and materials for the concept ship design are presented based on radiation attenuation calculations, with comparisons drawn to existing shielding designs in commercial vessels. A discussion of the proposed radiation shielding plan is also included in this chapter.

4.1 Lead-cooled fast reactor characteristics

Lead-cooled fast reactors are Generation IV small modular reactors that use lead or lead-bismuth eutectic alloy (LBE) as the coolant. Because lead has a high melting point (327 °C) and an even higher boiling point (1737 °C), the reactor can operate at atmospheric pressure and high temperature. Lead fast reactors (LFRs) use fast neutrons in their operation [6,7], in contrast to thermal neutrons used in more traditional reactors such as pressurised water reactors [2].

Compared to water, there are many advantages to using lead as the reactor-core coolant. Lead helps the reactor maintain criticality by preserving the fast neutron population in the core [38]. This occurs because neutrons lose relatively little energy when scattering elastically with lead, owning to lead's high atomic mass. At the same time, lead reduces neutron leakage from the inner region of the core while providing strong neutron reflection for those that do escape [6]. Lead is also chemically relatively inert, meaning it has low reactivity with water and air. In addition, its high atomic mass allows it to attenuate gamma radiation effectively, making it a strong shielding material against gamma radiation [6,7].

Despite lead's low reactivity with water and air, it can cause corrosion in structural materials such as steel, especially at high temperatures [6,7]. The type of corrosion in this context is known as liquid metal corrosion, which may manifest as dissolution, oxidation, erosion corrosion, or fretting corrosion [39]. Structural materials and any corrosion preventive coatings must therefore be selected carefully, and both the coolant purity and dissolved oxygen levels must be continuously controlled [6,7]. Oxygen is used to protect steel and other metal components from lead-induced corrosion by forming a protective oxide layer on the surface of stainless steel, although this layer may reduce heat transfer. Protecting thin-walled components, such as fuel cladding and heat exchanger tubes, is particularly important [39]. The high melting point of lead also presents challenges in preventing unintentional freezing of the coolant. If unintentional freezing and remelting occur, components inside the reactor may experience mechanical failures due to volumetric contraction and expansion [6].

The term *fast reactor* means that the reactor uses fast neutrons rather than thermal (slow) neutrons. Fast neutrons have energies above roughly 1 MeV, whereas thermal neutrons have energies of about 0.025 eV [40]. ^{235}U is a fissile material, meaning that neutrons of any energy – including thermal neutrons – can induce fission when they strike a ^{235}U nucleus. In a fast reactor, ^{238}U can also undergo fission, but only when neutron energies exceed approximately 1.5 MeV. Even then, neutron capture of inelastic scattering in ^{238}U remains more likely than fission [10].

In nuclear reactors, neutrons produced in fission must induce further fission events in other uranium atoms to sustain a self-supporting chain reaction. The average energy of neutrons emitted in a fission event is about 2 MeV [10]. In a thermal reactor, neutrons are slowed down through scattering interactions, losing energy until they reach thermal energies. With these slow neutrons, fission in ^{235}U can be induced creating a sustaining chain reaction, but fission in ^{238}U is not possible. Neutron capture in ^{238}U becomes less likely below 1 eV compared to fission in ^{235}U. To sustain a chain reaction in a fast reactor, the relative proportion of ^{235}U must therefore be significantly increased. As noted earlier, fast neutrons can also induce fission and capture reactions in ^{238}U [10], which provides a major advantage for fast reactor systems.

When ^{238}U captures a neutron, it becomes ^{239}U. ^{239}U then decays as following, with the corresponding half-lives:

$$^{239}U \frac{\beta -}{23.5\ min} \rightarrow {}^{239}Np \frac{\beta -}{2.35\ d} \rightarrow {}^{239}Pu \frac{\alpha -}{24360\ y} \rightarrow {}^{235}U\ etc.$$

Cover a reactor's operational lifetime, ^{239}Pu is effectively the end-product of this decay chain. ^{239}Pu has nuclear properties similar to ^{235}U and can undergo fission with neutrons of all energies. This process makes ^{238}U a fertile isotope, as it can be converted into a fissile material through neutron capture [10].

If enough neutrons are available in a reactor to both sustain the fission chain reactions and convert a sufficient number of fertile isotopes into fissile isotopes, the reactor is considered a breeder reactor. For a nuclear chain reaction to be self-sustaining, the average number of neutrons released per fission must exceed 1. For breeding to occur, the number of neutrons released must exceed 2. In that case, one neutron on average sustains the chain reaction, while one or more of the remaining neutrons can be captured by fertile isotopes to create new fissile material. When the total number of fissile nuclei increases during operation, the reactor is said to be breeding [10].

4.2 SEALER-55

In this study, a lead-cooled small modular reactor (SMR) called SEALER-55 (Swedish Advanced Lead Reactor) has been chosen as the reference reactor. The LFR technology is promising, and the reactor has characteristics that make it compatible with icebreaker designs due to its inherent safety and functional size. SEALER-55 is currently still in concept phase, but an electrical prototype, SEALER-E, is under construction at an Advanced Reactor Testing Site in Oskarshamn [41]. In 2018, Wallenius *et al.* [42] studied a smaller version of the reactor, known simply as SEALER, designed for remote Arctic regions with a nominal electrical output of 3 MW_e [42]. In this thesis, the basic characteristics and operating principles of SEALER-55 are described based on Wallenius *et al*. and current information provided by Blykalla [42,43].

SEALER-55 has an electrical output of 55 MW_e and a thermal output of 140 MW_{th}, and its fuel residence time is estimated at 25 years [7,43]. The reactor has a height of 5.5 meters and a diameter of 4.8 meters [8]. In this thesis, these dimensions are used together with a 5-meter diameter and height reported by Blykalla on their website [43]. The design strategy is to seal the inner vessel of the reactor and dismantle the reactor as a single unit when it is taken out of operation [42,44]. The basic characteristics of the reactor are summarised in Table 3. Although SEALER-55 has not been specifically designed for marine applications, it has attracted interest in the marine sector. Emblemsvåg *et al.* [44] conducted a study evaluating and comparing promising reactor designs for merchant vessels, in which SEALER-55 ranked second. Its cradle-to-grave approach was highlighted as its greatest advantage, while the risk of coolant solidification was noted as a concern [44]. In this thesis, it is assumed that the reactor is suitable for an icebreaker and capable of withstanding the marine environment, including vibrations and tilting.

Wallenius *et al.* [42] reported that the first-generation SEALER design uses 19.75 % enriched uranium oxide (UO_2) fuel, but uranium nitride (UN) fuel was expected to be considered in the future [42]. Blykalla now confirms that SEALER-55 uses UN as its fuel [7,43]. Duarte *et al.* [45] conducted a neutronic analysis of SEALER, comparing UO_2, UN and U_3Si_2 (uranium silicide). One of the advantages of UN over UO_2 identified in the study was its more efficient

Table 3. Basic characteristics of the SEALER-55 reactor. [8,42,43]

Parameter	Value	Unit
Height	5.5	m
Diameter	4.8	m
Output power (electric)	55	MW_e
Output power (thermal)	140	MW_{th}
Fuel	UN	-
Fuel residence time	25	years
Operational pressure	non-pressurized	-

use of fissile material and its higher conversion ratio [45]. Blykalla suggests that using UN increases the fuel lifetime by approximately 40%, as UN contains about 40% more uranium per unit volume than standard UO_2 [43]. The UN fuel will be enriched to 12 % ^{235}U. After the reactor's 25-year lifespan, the fuel is planned to be reprocessed [46].

The SEALER-55 core consists of 84 fuel assemblies, 2 control-rod assemblies, 10 shutdown-rod assemblies, and 66 reflector assemblies. Each of the 84 fuel assemblies contains 169 fuel rods made of either UN or (U,Hf)N, the latter being uranium nitride doped with hafnium. The control-rod assemblies are made of boron carbide (B_4C) and are used to regulate core reactivity, together with the shutdown-rod assemblies, which use tungsten diboride/boron carbide (WB_2/B_4C) absorbers. The WB_2 shutdown-rods are designed to insert passively by gravity. The reflector assemblies are made of zirconium dioxide (ZrO_2), and their primary function is to reflect escaping neutrons back into the core [8]. A schematic reactor core map of SEALER is shown in Figure 4 [42]. Although the core map does not represent SEALER-55 exactly, as the number of assemblies differs and shield assemblies are not mentioned as part of the SEALER-55 core, it can still be used as a reference. In the illustration, the shutdown assemblies are shown in the withdrawn position and appear as light-blue hexagonal spaces.

Blykalla reports that they have addressed the problem of corrosion in structural materials by developing three different aluminium-alloyed steels capable of withstanding long-term exposure to lead [43]. For cladding tube protection, they use 15-15Ti austenitic stainless steel [46]; for lead pump impellers, they use martensitic steel [43]; and finally, an austenitic steel, SS316L, is used for the core barrel and primary vessel [42]. A temperature of 820 K is considered as the highest allowable temperature of molten lead at which the steel structures can still resist corrosion [42]. Therefore, the operating temperature must remain below 820 K but

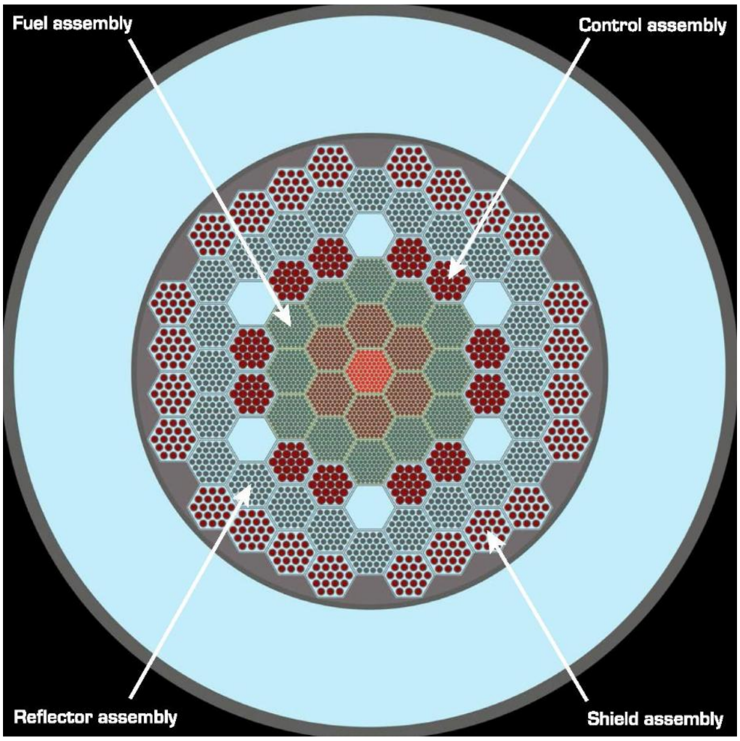

Figure 4. Core map of SEALER. Source: Wallenius *et al.* [42]

above the melting temperature of lead. SEALER-55 is designed with a core inlet coolant temperature of 663 K and a temperature rise of ΔT_{core} = 42 K, resulting to a core outlet coolant temperature of 705 K [38,42].

A schematic image of the primary system design is shown in Figure 5. The reactor core is located at the bottom of the hot pool, secured in the bottom grid plate. Surrounding the upper half of the hot pool are eight coolant pumps and steam generators, forming eight symmetrical flow paths. These components are situated in an annular plenum between the core barrel and the reactor vessel, referred to as the hot pool. The cold leg is the region between the core barrel and the reactor vessel below the hot pool, and it connects to the cold pool, which lies directly beneath the reactor core. Lead coolant circulated through the entire system: nuclear fission heats it in the core, the coolant pumps move it into the hot pool, it then flows downward through the steam generator tube bundles, continues into the cold leg and cold pool, and finally returns to the core inlet. [42]

Electrical energy is produced in a secondary system connected to the nuclear reactor. Hot lead heats water inside the steam generators, generating steam that drives a turbine connected to a generator, producing electricity. Steam exiting the turbine is directed to a condenser and then

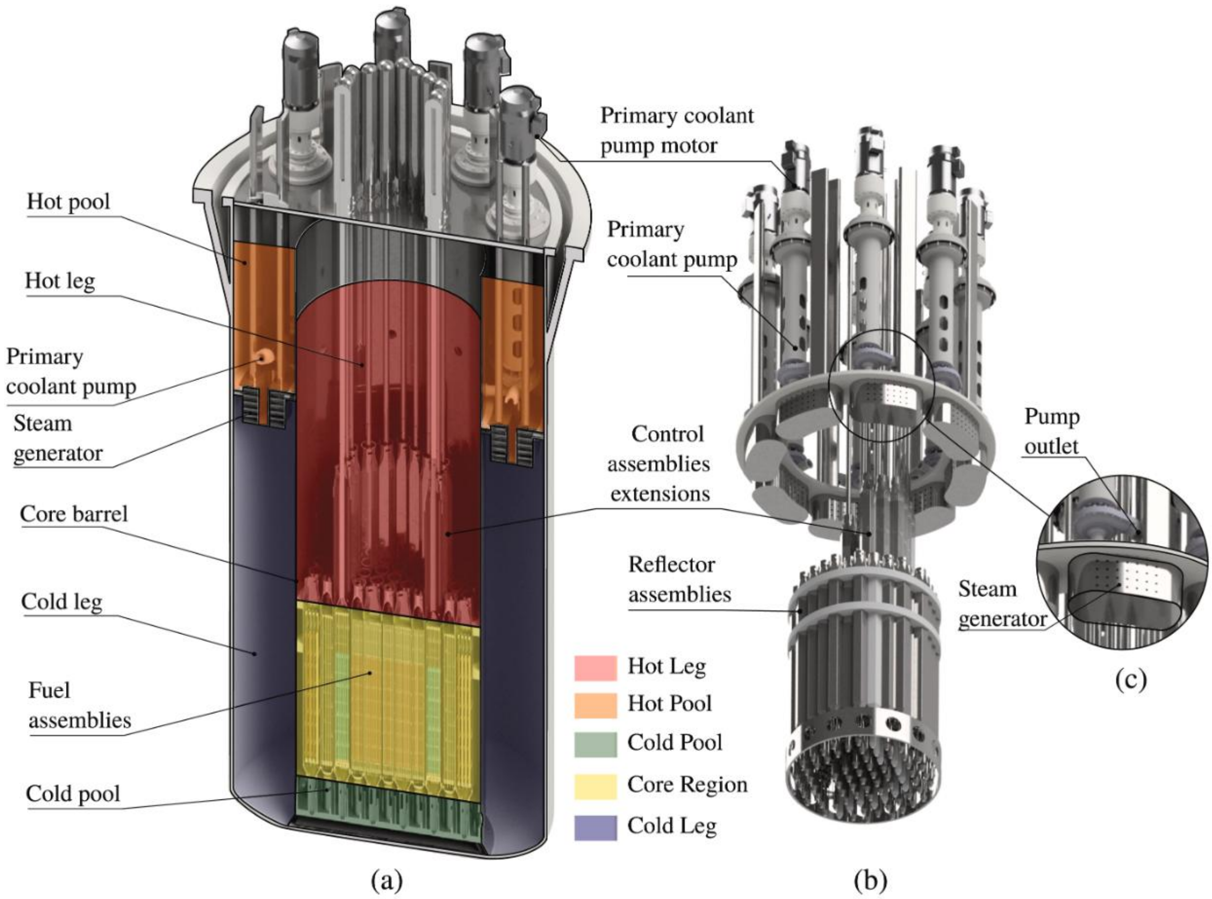

Figure 5. SEALER Reactor: (a) CAD rendering with highlighted regions, (b) Core and mechanical assemblies, and (c) Steam Generator (SG) and pump detail. Source: Umezu et al. (2024), adapted from Wallenius et al. (2018)

returned to the steam generators inside the reactor. The secondary system lies outside the scope of this thesis and will not be the focus of this work.

Blykalla promotes SEALER as a passively safe system. The basis of its passive safety is that decay heat is removed from the reactor core by natural convection of the lead coolant and by thermal radiation from the reactor vessel to the environment [42,43]. The reactor should be able to operate safely and ensure full heat removal even if six out of eight coolant pumps are out of operation [42]. Another safety advantage is that the reactor can be operated in low pressures [43]. The operating temperatures are also significantly below the coolant's boiling point and core's melting point. Additionally, the shutdown rods in the reactor core are designed to have a much higher density than lead, using $(W, Re)^{10}B_2$ as the absorber material. This allows the reactor to be shut down passively by gravity alone [42]. However, it remains uncertain how the marine environment, particularly vessel motion and tilting, would affect the functionality of the shutdown rods.

4.3 Gamma and neutron radiation calculations

There are many reactions occurring in the core of a fast reactor, with numerous possible fission-fragment scenarios. Calculating the exact neutron and gamma-radiation fluxes produced in the core – and the resulting fluxes outside the reactor after multiple interactions of neutrons and gamma rays of different energies with matter – is highly complex. In this thesis, certain assumptions and simplifications are made in order to determine a conservative upper-bound value. We assume that the reactor is operated at full power under normal conditions.

To estimate the required shielding materials for the reactor, the gamma and neutron fluxes must be calculated. Since the thermal power of SEALER-55 (140 MW_{th}) and the average energy released per fission reaction (200 MeV) are known, Equation (1) can be used to calculate the average number of fission reactions, giving $dN_f = 4.37 \cdot 10^{18}\,\frac{1}{s}$. Gamma and neutron radiation fluxes and doses must be calculated separately, but the value of dN_f can be used for both calculations.

First, we focus on gamma radiation. The most important reactions producing gamma radiation are the fission reactions of ^{235}U and ^{239}Pu, as well as the decay of ^{239}U to ^{239}Pu. Fission of ^{235}U is likely the dominant source, since fission of ^{238}U is relatively rare even at fast neutron energies. Fission of ^{239}Pu also contributes once it has been produced through neutron capture of ^{238}U and followed by the decay of ^{239}U. According to the ENDF/B-VIII.0 database reported by Stetcu *et al.* [47], the total prompt gamma energy released per fission is 7.28 MeV for ^{235}U, 5.61 MeV for ^{238}U, and 6.37 MeV for ^{239}Pu [47]. Because ^{235}U produces the most intense prompt gamma emissions, we assume that all reactions contributing to energy and gamma ray production are ^{235}U fissions in order to obtain the upper-bound value. The ENDF/B-VIII.0 database also reports that the average energy of a prompt gamma ray from ^{235}U fission is 0.85 MeV, with an average gamma multiplicity of 8.58 [47]. Delayed gamma rays have similar energies and multiplicities, typically 6–8 gamma rays with an average energy near 1 MeV [9]. For simplicity, we use the same energy for delayed gammas as for prompt gammas (0.85 MeV), and adopt a delayed gamma multiplicity of 7. Adding the prompt and delayed multiplicities yields a total gamma ray multiplicity of 15.58. Using this value in Equation (2) gives a gamma production rate of $N_r = 6.81 \cdot 10^{19}\,\frac{1}{s}$.

Next, the neutron flux must be calculated. As previously mentioned, one fission generates an average of 2.5 neutrons. We assume that this value applies to every fission occurring in the reactor. We also assume that one neutron from each fission induces another fission reaction, leaving an average of 1.5 free neutrons produced per fission. Because SEALER-55 is a fast reactor and therefore capable of breeding, some fraction of neutrons is absorbed in fertile material and cannot escape the core. Since this fraction is uncertain, it is not included in the calculation. Both breeding and neutron capture would reduce the number of neutrons leaving the core. Conversely, the contribution of delayed neutrons, which is also uncertain, would increase the neutron flux. Given these uncertainties, we neglect all such effects and use 1.5 neutrons per fission in the calculation. Using this value in Equation (2) yields a neutron production rate of $N_r = 6.55 \cdot 10^{18}\,\frac{1}{\mathrm{s}}$.

The gamma and neutron radiation fluxes can be calculated using Equation (3). The fluxes are evaluated at several distances relevant for radiation shielding calculations based on the general arrangement (GA) of IBELO. These distances, along with their descriptions and the corresponding dose limits, are presented in Table 4. The distances represent approximations from the centre of the reactor to the nearest point of each specified location. The annual dose limits are selected according to occupational and public exposure limits. We assume that some rooms within the reactor compartment may be accessible to non-occupational personnel; therefore, the public dose limit is applied to all areas other than the reactor rooms inside the reactor compartment.

After the radiation fluxes are determined for all relevant locations, Equation (4) is used to calculate the absorbed dose. We use the worldwide average adult body mass of dm = 62 kg [48]. For the gamma and neutron radiation energies, we use 0.85 MeV and 2 MeV, respectively. The radiation weighting factor is incorporated through Equation (5). For photons, the radiation weighting factor is $w_R = 1$, as defined in ICRP Publication 103 [17]. For neutrons, the weighting factor is expressed as a continuous function of neutron energy, also provided in ICRP Publication 103. The weighting factor peaks near 1 MeV, where it reaches approximately 21, and decreases at both lower and higher energies, approaching about 2.4 below 0.01 MeV and above 1 GeV. Using the formula given in Publication 103 (Equation 4.3), the neutron radiation weighting factor at 2 MeV is $w_R \approx 17.34$ [17]. The tissue weighting factor w_T is included in Equations (6–7). Because the factors are weighted such that the sum over all tissues equals 1, we use $w_T = 1$ for whole body exposure. Applying Equation (6) or (7) yields the effective doses for gamma and neutron radiations.

Table 4. Distances and their descriptions that were used in the dose rate calculations, and dose limits for the spaces.

Distance (m)	Space description	Dose-equivalent rate (µSv/h) (IMO)	Annual limit (mSv) (ICRP)
3	Between the reactor and its shielding	7.5	20
5	Inside reactor room after reactor shielding	7.5	20
6	Other than reactor rooms inside the reactor compartment	0.50	1
7	Above reactor compartment	0.50	1
17.5	Accommodation spaces	0.15	1
29	Bridge	0.75	1

Equation (8) is then used to determine the dose rate $\dot{D}$ at Sv/h. The average human body area is taken as $a_H = 1$ m^2. The time t is set to 3600 s to convert the result into the desired unit. The results from Equations (7) and (3) are used in Equation (8) to obtain the dose rate at the specified distances from the reactor. At this stage, the values correspond to a bare reactor core. To determine $\dot{D}$ outside the reactor vessel, and to assess the required shielding, we use Equation (9) for gamma rays and Equation (12) for neutrons to calculate the radiation flux after attenuation in matter. The resulting gamma and neutron fluxes from Equations (9) and (12) are then inserted into Equation (8) to determine the updated dose rates. Below is an example of the described calculations for neutron radiation.

Number of fission reactions per second:

$$dN_f = \frac{P_{th}}{\varepsilon_f} = \frac{140 \cdot 10^6\ W}{200 \cdot 10^6\ eV \cdot 1.602 \cdot 10^{-19}\ J} = 4.37 \cdot 10^{18}\ \frac{1}{s} \tag{1.1}$$

Number of neutrons released per second:

$$N_r = dN_f \upsilon = 4.37 \cdot 10^{18}\ \frac{1}{s} \cdot 1.5 = 6.55 \cdot 10^{18}\ \frac{1}{s} \tag{2.1}$$

Neutron flux at distance $r = 3$ m:

$$\phi = \frac{N_r}{4\pi r^2} = \frac{6.55 \cdot 10^{18}\ \frac{1}{s}}{4\pi \cdot (3\ m)^2} = 5.80 \cdot 10^{16}\ \frac{1}{s^2} \tag{3.1}$$

Absorbed dose:

$$D = \frac{d\varepsilon}{dm} = \frac{2 \cdot 10^6\ eV \cdot 1.602 \cdot 10^{-19}\ J}{62\ kg} = 5.17 \cdot 10^{-15}\ Gy \tag{4.1}$$

Effective dose:

$$E = \sum_T w_T \sum_R w_R D_{T,R} = 1 \cdot 17.34 \cdot 5.17 \cdot 10^{-15}\, Gy = 8.96 \cdot 10^{-14}\, Sv \tag{6.1}$$

Dose rate:

$$\dot{D} = \phi E a_H t = 5.80 \cdot 10^{16} \frac{1}{s^2} \cdot 8.96 \cdot 10^{-14}\, Sv \cdot 1\, m^2 \cdot 3600\, s = 18.7 \cdot 10^6\, Sv/h \tag{8.1}$$

Neutron flux after penetrating 50 cm of molten lead:

$$I = I_0 e^{-\Sigma_R x} = 5.80 \cdot 10^{16} \frac{1}{s^2} \cdot e^{-0.104 \frac{1}{cm} \cdot 50\, cm} = 4.36 \cdot 10^{14} \frac{1}{s^2} \tag{12.1}$$

Dose rate:

$$\dot{D} = \phi E a_H t = 4.36 \cdot 10^{14} \frac{1}{s^2} \cdot 8.96 \cdot 10^{-14}\, Sv \cdot 1\, m^2 \cdot 3600\, s = 0.141 \cdot 10^6\, Sv/h \tag{8.2}$$

Table 5 lists the linear attenuation coefficients and removal cross sections of the materials used for attenuating gamma and neutron radiation in this thesis. Some of the values were obtained by combining mass attenuation coefficients or mass removal cross sections with the density of the material. The table also includes the transmission, defined as the ratio of radiation fluxes after passing through 10 cm of a material. In other words, the fraction of radiation that penetrates a 10 cm layer of a material. The transmission for gamma radiation is calculated using Equation (10), and the transmission for neutron radiation is calculated using Equation (12). A smaller transmission value indicates that less radiation passes through the material.

There is more available data for removal cross sections than for total macroscopic cross sections. This, together with the definitions explained in Chapter 2.5, leads to the use of removal cross sections instead of total macroscopic cross sections for the neutron attenuation calculation. It is important to note, however, that the removal cross sections provided in the literature apply to fast neutrons but are not specified at a particular energy. The desired energy would be 2 MeV, since this value was used in the dose rate calculation. However, since the removal cross section remains approximately constant for neutron energies between 2 and 12 MeV, we can assume that using a generic fast neutron removal cross section is appropriate for the attenuation calculations.

It can be seen from Table 5 that gamma radiation is, on average, attenuated much more efficiently than neutron radiation. For gamma radiation, there are clear differences between materials with high atomic numbers and those with low atomic numbers. Because materials

Table 5. Gamma and neutron attenuation coefficients and transmissions for shielding materials.

Material	μ (cm^{-1})	Gamma transmission for x = 10 cm	Σ_R (cm^{-1})	Neutron transmission for x = 10 cm
lead (molten)	0.85 [49,50]*	$0.20 \cdot 10^{-3}$	0.098 [19,50]*	0.38
steel (SS316L)	0.476 [51]**	$0.86 \cdot 10^{-2}$	0.15 [19,51,52]*	0.21
concrete	0.17 [19,53,54]*,**	0.18	0.090 [19]	0.41
water	0.075 [49,55]**	0.47	0.103 [56]	0.36
polyethylene	0.0792 [53]*,**	0.48	0.12 [57]	0.31
lead (solid)	0.91 [49]*	$0.11 \cdot 10^{-3}$	0.10 [19,49]*	0.35

*Calculated using density and mass attenuation coefficient
**Interpolated for 0.85 MeV

with higher atomic numbers exhibit stronger attenuation, the results align well with the theoretical background. In contrast, removal cross sections show far less variation between materials than linear attenuation coefficients. Due to these small differences, a clear distinction between high- and low-atomic number materials is not apparent for neutron attenuation. For example, the values suggest that lead is slightly more effective at attenuating neutron radiation than concrete, even though hydrogen containing materials are generally better neutron moderators. The high density of lead may explain this behaviour, since the removal cross section reflects only the probability of the first neutron collision and does not account for the type of interaction between the neutron and the material. It is important to consider what fraction of penetrating neutrons is absorbed and what fraction undergoes elastic or inelastic scattering. Additionally, inelastic collisions can cause nuclei to emit gamma rays and, as described in Chapter 2.3, neutron absorption can lead to various secondary emissions. These effects should also be taken into account. A more comprehensive study of neutron attenuation properties would therefore be necessary.

Next, the dose rate after radiation has passed through the reactor materials is calculated. The gamma flux from a plane core without any shielding at distance of 3 m is $6.02 \cdot 10^{17} \frac{1}{m^2 s}$, whereas the neutron flux is $5.80 \cdot 10^{16} \frac{1}{m^2 s}$. Based on the known dimensions of SEALER-55, we assume that there is always a minimum of 50 cm of liquid lead surrounding the reactor core. We also assume that 20 cm of steel lies between the reactor core and the outer surface of the reactor vessel. It is likely that the amount of molten lead is underestimated, but this is acceptable, and more preferable, to avoid overestimating shielding performance. With these assumptions, the corresponding gamma and neutron fluxes at a distance of 3 m (i.e., almost immediately outside

Table 6. Calculated gamma and neutron dose rates outside the reactor without radiation shielding.

Distance	Gamma dose rate (Sv/h)	Neutron dose rate (Sv/h)
3	$9.85 \cdot 10^{-17}$	$6.39 \cdot 10^{3}$
5	$3.55 \cdot 10^{-17}$	$2.30 \cdot 10^{3}$
6	$2.46 \cdot 10^{-17}$	$1.60 \cdot 10^{3}$
7	$1.81 \cdot 10^{-17}$	$1.20 \cdot 10^{3}$
17.5	$5.19 \cdot 10^{-18}$	$1.90 \cdot 10^{2}$
29	$1.78 \cdot 10^{-18}$	$0.68 \cdot 10^{2}$

the reactor vessel) become $1.25 \cdot 10^{-5} \frac{1}{m^2 s}$ and $2.00 \cdot 10^{12} \frac{1}{m^2 s}$, respectively. Here, the difference between the gamma and neutron attenuation properties of lead and steel is evident: gamma radiation is attenuated far more strongly than neutron radiation. Equations (9) and (12) were used to calculate the fluxes after penetrating the reactor materials. Using these fluxes, the dose rates obtained through Equation (8) at various distances from the reactor core are presented in Table 6.

Table 6 illustrates how distance affects the radiation dose. However, this effect is due solely to geometric spreading, as the radiation flux is distributed over a larger area as distance increases. The magnitude of the radiation flux – and therefore also the dose rate – decreases in proportion to the inverse square of the distance. In reality, radiation would be attenuated even further as the distance from the reactor increases because of the ship's structure and the various materials between the reactor and the observation point. These effects are not included in the calculations because, according to ABS, the ship's structure should not be considered a radiation shield. From Table 6, we can see that even without any additional shielding, the gamma radiation dose rates are already well below the IMO dose limits listed in Table 2. In contrast, the neutron dose rate greatly exceeds the limits, despite the fact that the radiation fluxes generated inside the core are of similar magnitude for both radiation types. This highlights the need for additional shielding specifically to reduce the neutron radiation.

There are two major reasons for the large difference in dose rate compared to the radiation flux produced in the core: the attenuation properties of the reactor coolant and the radiation weighting factor. The dominant effect comes from the attenuation properties of molten lead. The gamma ray transmission through 10 cm of molten lead is only $0.20 \cdot 10^{-3}$, whereas the neutron transmission is 0.38. As the thickness of lead increases, this difference compounds, resulting in a substantial disparity in the radiation fluxes that penetrate the reactor materials. The second factor, although less significant, is the radiation weighting factor. For gamma radiation, the weighting factor is $w_R = 1$ at all energies, whereas for 2 MeV neutrons it is approximately 17.3. As demonstrated by the continuous neutron radiation weighting factor described earlier, the effective neutron dose decreases as neutrons lose energy through collisions in matter. Because the weighting factor becomes roughly constant at around 2.4 below approximately 0.01 MeV, the factor clearly shows that exposure to a single neutron at any energy is more hazardous than exposure to a single gamma ray.

4.4 Radiation shielding

4.4.1 Radiation shielding in past nuclear ships

It is worth reviewing past radiation shielding designs for nuclear marine applications. Unfortunately, there are no operational examples of LFR technology, and only limited information is available on the reactor shielding of the Soviet submarines that used lead-bismuth-cooled LBFR systems. The only information found is that the reactors had a single-walled shield, but the shielding material itself was not mentioned [58]. Using this information as a basis for the shielding design in this project would therefore be inappropriate.

Although the commercial nuclear-powered vessels were equipped with PWRs, their shielding designs can still be used for comparison in this project. It is important to note, however, that PWR technology differs significantly from LFR technology, for example, PWRs rely on thermal neutron fission and use water as the coolant. As a result, gamma radiation is likely a greater challenge and neutron radiation a lesser challenge in PWRs compared to LFRs.

At the beginning of its lifetime, the icebreaker *Lenin* housed three PWRs located at the center of the ship, arranged side by side in an isolated reactor compartment [2]. The PWRs were surrounded by a water-filled steel tank, and the tops of the reactors were covered with concrete and a heat-resistant composition of graphite and boron [2]. A surrounding water tank was also used in the shielding designs of *Savannah* and *Otto Hahn*. Specifically, the primary shielding of the PWR in *Savannah* consisted of a 33-inch (84 cm) thick annulus of water surrounding the reactor laterally. According to the safety analysis report of NS *Savannah*, “the water in the primary shield tank was cooled by intermediate cooling water through a coil within the shield tank” [59]. Additionally, water from the intermediate cooling system could be used to maintain the water level in the tank.

A 1–4 inch (2.5-10 cm) layer of lead outside the primary shield tank was also part of the primary shielding. The secondary shielding surrounded the containment vessel that enclosed the reactor, the primary shielding, and some auxiliary equipment. A vertical bulkhead of reinforced concrete encircled the lower half of the containment vessel, with space left between the concrete shield and vessel for auxiliary equipment. The maximum thickness of the concrete shield was 4 feet (122 cm). On the upper half of the containment vessel, the shielding consisted of approximately 6 inches (15 cm) of lead followed by about 8 inches (20 cm) of polyethylene on the vessel shell. Additional lower shielding could be added by filling the tanks within the inner bottom below the reactor compartment when the ship was in drydock. The concrete shield weighted approximately 1187 tons, and the combined lead and polyethylene shielding weighted around 616 tons. The pressure containment in *Savannah* was designed based on Maximum Credible Accident (MCA) conditions [59].

In *Otto Hahn*, 0.6 mSv/h was considered the maximum permissible dose rate inside the containment vessel. This was achieved with an annular water tank with two concentric layers of cast iron surrounding the reactor pressure vessel; however, primary coolant pumps interrupted the arrangement. The shielding reduced dose rates to 15–20 mrem/h (0.15–0.2 mSv/h), which allowed a short-term entry into the containment vessel even during full load conditions. Outside the containment vessel, 0.6 m of concrete served the secondary shield. Additionally, a 2.5 cm thick lead shielding in the hot well reduced the radiation dose to 0.06 mrem/h (0.6 µSv/h), which was the maximum permissible dose rate in the engine room [2]. While these shielding designs are reviewed, it should be remembered that both *Savannah* and *Otto Hahn* were constructed before the release of the Code of Safety for Nuclear Merchant Ships.

4.4.2 Discussion on shielding options in IBELO

As mentioned earlier, all radiation sources must be shielded. At this stage of the concept design, this primarily concerns the reactor and the radioactive waste rooms. The discussion here focuses on shielding of the reactors, as radiation dose calculations from the radioactive waste room have not yet been performed.

Using at least two radiation shielding materials is a necessity to protect against both neutron and gamma radiation. Although gamma radiation is already at acceptable levels due to the lead coolant, additional shielding should still be provided outside the reactor in case of a larger gamma release. As shown in Table 6, the absence of gamma shielding would result in a dose rate of $3.55 \cdot 10^{-17}$ Sv/h inside the reactor room. Adding 10 cm of lead reduces this dose rate to $5.0 \cdot 10^{-21}$ Sv/h. Materials primarily used for neutron shielding will also attenuate gamma radiation, but lead and steel are significantly more effective gamma shields than water, polyethylene or concrete.

Neutron radiation dose without shielding is extremely severe, as the neutron doses exceed acceptable limits by a magnitude of 10^{11}. It is therefore essential to select reactor shielding materials primarily for their neutron attenuation capability. To facilitate comparison between materials, Table 7 presents how much of each single material would be needed to achieve the acceptable level of neutron radiation at each location on the ship, based on the calculated neutron fluxes and the material's removal cross sections. All thickness values are rounded up to the nearest 10 cm.

The materials selected for radiation attenuation evaluation are based on the most common shielding materials for nuclear reactors. According to Holbert *et al.* [2], the typical primary biological shields are water and lead, while the typical secondary biological shields are concrete, polyethylene and lead [2]. Since decay heat is removed from the reactor by natural convection of the molten lead, it must be considered that the closest layer – or layers – of radiation shielding may be exposed to elevated temperatures. Assessing the structural strength of the shielding materials is beyond the scope of this thesis, but it should be examined further when developing the shielding solutions. Additionally, in land-based applications, space and weight are generally not limiting factors in radiation shielding design. On a ship, however, both variables must be minimized as much as possible.

When water is used as a radiation shield, it must be enclosed in a steel tank. Water has several advantages: it is much lighter than materials such as concrete, and it is a more effective neutron moderator due to its high hydrogen content. Additionally, the tanks can be emptied and refilled when necessary. However, using water as the primary shield – where it would be closest to the reactor – may pose challenges due to high temperatures. Because the coolant temperatures are significantly higher than the boiling point of water, heat transfer from the lead coolant to the surrounding water shielding must be managed to prevent boiling. This challenge could be addressed by continuously cooling the water, similar to the approach used in NS *Savannah*. However, introducing a new cooling system naturally increases complexity and introduces additional risks. One such risk is a malfunction in the water circulation or cooling system, which could lead to boiling of the water inside the tank.

Table 7. Required thicknesses to sufficiently attenuate neutron radiation using only one material.

Material	Thickness (cm)
steel (SS316L)	160
concrete	280
water	240
polyethylene	210
lead (solid)	240

An additional risk associated with using water as a radiation shield is the possibility of leakages. Although such an event is highly unlikely, it could occur in accident situations or if the tank or its penetrations are poorly constructed. If any water is lost from the tank, additional water must be supplied by a pump to keep the tank full. Water used in the reactor compartment cannot be discharged into the environment without monitoring its contamination and radiation levels. In the event of either a controlled or uncontrolled release of water from the shielding tank, it may be necessary to store the shielding water inside the ship before discharging it at a port or into the environment. No radioactive waste discharges to the environment are desired, even though releases below certain activation levels are permitted. The worst-case scenario involving a water-shielding tank would be an unintended emptying of the tank, after which the neutron flux outside the shielding would increase significantly, with neutrons still at high energies. Additionally, large quantities of radioactively contaminated water could be released into surrounding structures, creating further challenges for containment and cleanup. Even if safety systems ensure that sufficient water remains in the shielding tanks, there is still a theoretical possibility of the tanks becoming empty. Therefore, relying on water as the sole neutron shielding material would be risky.

The advantage of concrete as a radiation shield is that it is stable, remains in place, and can withstand high temperatures. It is also possible to mix other materials into concrete to improve its neutron shielding properties. Hydrogen in concrete and water performs very well at slowing down neutrons, but it is not an excellent neutron absorber. Materials such as boron, lithium, or cadmium are more effective for neutron absorption due to their high neutron-capture cross-sections [60]. For example, Gokul *et al.* reported that concrete mixed with boron carbide (B_4C) exhibits superior neutron attenuation properties compared to conventional concrete [60]. Using such mixtures, while ensuring that the structural integrity of the concrete is maintained, would be beneficial not only for slowing neutrons but also for absorbing them. However, when neutrons are absorbed, secondary radiations such as gamma rays or particle emissions may be produced by the shielding materials. The severity of these secondary emissions should be evaluated and accounted for in the shielding design.

Concrete also has some disadvantages. Although concrete is relatively lightweight (ρ = 2.39 g/cm^{-3}) [19], it is still heavier than water (ρ ≈ 1.00 g/cm^{-3}), and due to its lower hydrogen content, it is a less efficient neutron moderator than water. A further challenge is that concrete shielding is difficult to replace, meaning the same structure is desired to remain in place for the entire lifetime of the ship. Over such a long period, the concrete shield may experience structural damage or degradation. In addition, some stable isotopes in concrete can become radionuclides through neutron irradiation over time, causing the concrete itself to become radioactive. Once activated, it is classified as radioactive waste, which is extremely challenging to decontaminate after decommissioning [61]. Severe neutron activation of water can be avoided by periodically replacing the shielding water, which is an option that is far less practical for a concrete shield.

Polyethylene is a lightweight material (ρ ≈ 0.91–0.97 g/cm^{-3}), even lighter than water, and an excellent neutron radiation shield due to its high hydrogen content. It is also cost-efficient, easy to process and chemically non-reactive [62]. Its shielding performance can be further improved by doping it with materials such as bismuth oxide (Bi_2O_3), tungsten carbide (WC), or boron carbide (B_4C) [57]. The greatest challenge with polyethylene is its high flammability and rapid flame spread. A fire onboard a ship is one of the most severe accident scenarios, so the use of highly flammable materials should be avoided whenever possible. In addition, polyethylene cannot withstand high temperatures, as its melting point is around 130 °C [62]. Because of these drawbacks, polyethylene will not be used as a shielding material in the reactor rooms. However, its use as a shield in other areas such as the radioactive waste room or the main control room may still be considered.

The interactions between the shielding materials should also be considered. The water tank must remain corrosion-free, which can be ensured through the use of stainless steel. The interfaces between lead, steel, and concrete should be studied while accounting for the atmospheric conditions in which they operate. Since the reactor room is likely to have a higher temperature than normal ambient conditions, the temperature resistance and thermal expansion of the materials must be evaluated. The potential for corrosion and oxidation of all materials should also be taken into account.

4.4.3 Radiation shielding plans and discussion on results

Based on the calculations and discussion in this thesis, an option worth investigation would be to place water tanks around the reactor to moderate the fast neutrons leaking from the core. A lead wall would then be installed outside the water tank. Additional neutron moderation and absorption would still be required, for which concrete doped with an effective neutron absorber could be used. After this, a thin layer of lead could be added to account for any secondary gamma radiation. A steel wall would surround the shielding structure to contain the lead within the assembly. This configuration would surround the reactors on the sides. The water tank would extend from the sides to above and below the reactor, and the concrete shield would fully cover the water tank. Both water and concrete would be partially placed inside the double bottom of the ship. The top of the concrete shield would be followed by a thin layer of lead to capture any secondary gamma radiation. The reactor foundation could also be used as a radiation shield by filling it with water. The entire shielding structure would be enclosed within a safety enclosure made of steel which can be considered the outer limit of the reactor room.

The thickness of the entire shielding structure would need to be approximately 250 cm. One example of a configuration that provides sufficient neutron and gamma attenuation consists of 118 cm of water, a total of 15 cm of lead, a total of 10 cm of steel, and 105 cm of concrete, resulting in a combined thickness of 248 cm. Using this arrangement as an example, Table 8 and Table 9 present the neutron and gamma fluxes, dose rates, and annual doses, respectively. Additionally, Figure 6a and 6b illustrate the radiation shield configuration around a reactor.

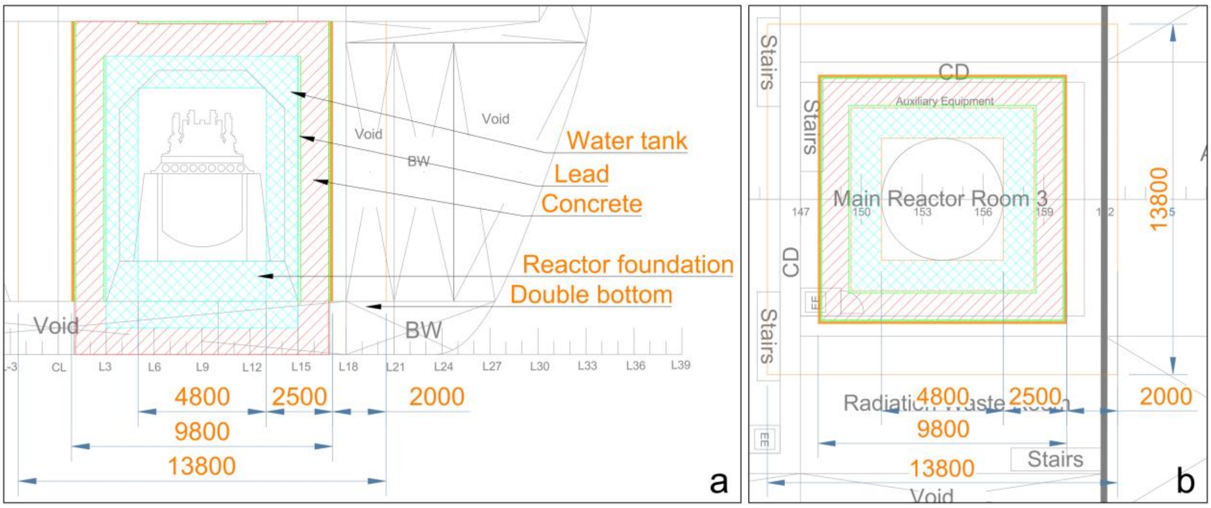

Figure 6a. Side view of a radiation shielding plan for one reactor, and Figure 6b. Top view of a radiation shielding plan for one reactor.

Table 8. Neutron flux, dose rate and annual dose after shielding example at different distances from reactor core.

Distance (m)	Flux ($1/m^2s$)	Dose rate (Sv/h)	Annual dose (mSv)
5	136	$1.32 \cdot 10^{-7}$	1.16
6	94.6	$9.16 \cdot 10^{-8}$	0.80
7	69.5	$6.73 \cdot 10^{-8}$	0.59
17.5	11.1	$1.08 \cdot 10^{-8}$	0.09
29	4.05	$3.92 \cdot 10^{-9}$	0.03

Table 9. Gamma flux, dose rate and annual dose after shielding example at different distances from reactor core.

Distance (m)	Flux ($1/m^2s$)	Dose rate (Sv/h)	Annual dose (mSv)
5	$9.00 \cdot 10^{-26}$	$2.14 \cdot 10^{-36}$	$1.87 \cdot 10^{-29}$
6	$6.26 \cdot 10^{-26}$	$1.48 \cdot 10^{-36}$	$1.30 \cdot 10^{-29}$
7	$4.60 \cdot 10^{-26}$	$1.09 \cdot 10^{-36}$	$9.55 \cdot 10^{-30}$
17.5	$7.35 \cdot 10^{-27}$	$1.74 \cdot 10^{-37}$	$1.53 \cdot 10^{-30}$
29	$2.68 \cdot 10^{-27}$	$6.35 \cdot 10^{-38}$	$5.57 \cdot 10^{-31}$

In the tables, the fluxes are calculated for one reactor only, whereas the dose rate and annual dose values are calculated for the combined radiation flux from three reactors. The dose rate and annual dose are simply multiplied by three, although the actual dose from three reactors would be somewhat lower and dependent on the viewing point. As shown in the Table 8 and Table 9, gamma doses are negligible and do not pose a threat with the chosen shielding configuration. Neutron doses, on the other hand, are significantly higher, though still within acceptable limits. Neutron radiation should therefore be monitored carefully to detect any increase in neutron leakage. Because the annual doses outside the reactor rooms remain within acceptable limits, exposure time restrictions are not required. However, time spent in controlled and supervised areas should still be limited to further enhance safety and to comply with regulations possibly requiring time restrictions. The factor that most strongly increases the required shielding thickness is the annual neutron dose at a distance of 6 meters from the reactor core. The design goal was to keep the annual dose below 1 mSv, enabling manned spaces located only 6 meters, or slightly less than 7 meters, from the reactor centerpoint to be used regularly and for extended periods.

In Figure 6a, a side view of the reactor, its radiation shield, and the reactor room is shown. It must be noted that the sketch of the reactor is not to scale, making it appear smaller than its actual dimensions. The shielding sketch, however, reflects the real size of the reactor. The primary shield, the water tank, is formed by steel bulkheads. The entire height of the tank must be filled with water to avoid unnecessary weight shifting caused by moving water. The width of the water tank should align with the bottom longitudinals to increase structural support from the ship's hull. Since the bottom longitudinals are placed every 600 mm, a water tank width of 1200 mm would be practical from structural, constructional, and radiation shielding perspective. The design requires further review from a regulatory perspective to determine what boundaries could be considered as the containment structure, and to ensure that the boundaries of the containment and the shielding barrier (same as safety enclosure) must be completely separate and independent, as stated in the RINA guide [32].

Figure 6b shows the reactor room and radiation shields from above, at the midpoint of the reactor. As shown, the radiation shield has a square shape. Although a circular shape would optimize the use of space, a square configuration with straight structural elements distributes loads more effectively into the hull structure. In other words, the hull can support straight structures better than curved ones because of its straight longitudinal and transverse members. This improved structural support is also the reason for aligning the boundaries of the water tank with the bottom longitudinals. Additionally, constructing straight components and fitting them into the ship is both easier and more cost-effective than constructing curved structures.

It is not yet known how much space will be required for the auxiliary equipment associated with the reactors and the shielding. This equipment may include oxygen pumps and coolant heating systems for the reactor [6,42], as well as pumps for the water circulation system of the shielding tank. Maintenance requirements for these systems must also be taken into account. Until the reactor supplier provides exact information on the auxiliary-equipment needs, it can only be speculated whether the equipment should be placed inside or outside the radiation shield. Placing the equipment outside the shield would provide easier access whenever maintenance is required. However, this would require penetrations through the radiation shield for the necessary connections to the reactors. This could be avoided by placing the auxiliary equipment inside the shield. The drawback of this option is that access to the equipment would be more difficult and would require shutting down the reactor in question. Additionally, increasing the protected area would increase the overall weight of the radiation shield.

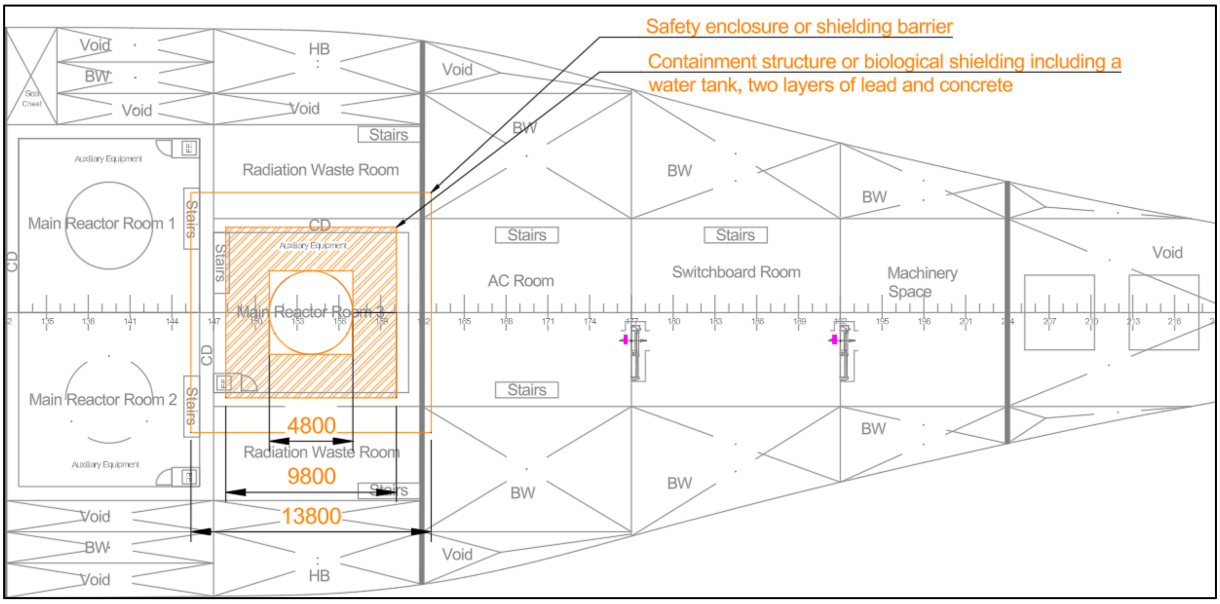

Figure 7. A rough sketch of the reactor room and biological shield with room left for auxiliaries and maintenance outside the shield.

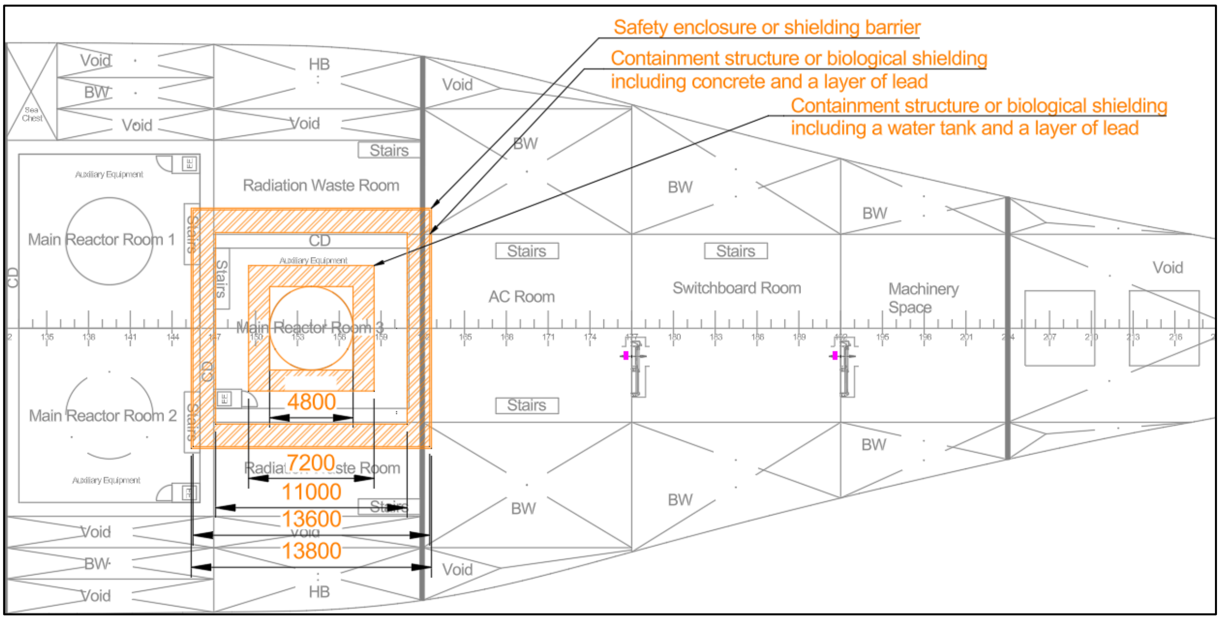

Figure 8. A rough sketch of the reactor room and biological shield with room left for auxiliaries and maintenance between the shield.

Another option is to divide the radiation shield into two sections, leaving space between them for auxiliary equipment. Figure 7 shows a rough sketch of the biological shielding and the reactor room, which is defined by the safety enclosure. Figure 8 shows a similar arrangement, but with space allocated between the shields for auxiliary equipment. Since the option of placing all auxiliary equipment inside the shield is less practical and results in a heavier structure than the other two configurations, no illustration of that option is provided.

Radioactive waste must also be provided with biological shielding. Since the reactors do not require refuelling during operation, the radioactive waste generated is likely to consist of medium- or low-activity waste. With appropriate gamma and neutron shielding materials, combined with limited access times in the waste rooms, radiation hazards can be effectively managed. Because radioactive waste rooms are classified as controlled areas, personnel entering them are equipped with personal protective equipment. Primary shielding can be applied directly to the containers holding the radioactive waste. A layer of lead and polyethylene would be straightforward to install as primary shields. If polyethylene is to be avoided due to fire safety concerns, concrete would also be suitable for radioactive waste storage. A secondary shield lining the radioactive waste room would enhance radiation safety in these spaces.

According to the rules and regulations, the main reactor control room must also be provided with radiation shielding to ensure its operability under all manageable conditions. Polyethylene or concrete can serve as neutron shields, and a thin layer of lead would be sufficient to further reduce gamma radiation levels in the control room. It may be even questioned whether a gamma shield is necessary at all. The regulations also require a radiation shield toward the bottom of the ship. Therefore, the shielding plan includes the reactor foundation and the double bottom as parts of the shielding by filling them with water and concrete. However, this approach should be further investigated since IMO specifies that the double bottom can be filled only with non-potable water, meaning that the use of concrete would be prohibited.

It is possible that the results of this thesis indicate a greater need for shielding than what will ultimately be required in practice. This is primarily because the assessed reactor has not yet been built, meaning no measured radiation data or published estimates of required radiation protection in a ship environment are available. As a result, rough calculations and assumptions were necessary, which most strongly affected the neutron flux and dose calculations. The assumptions regarding neutron flux and the neutron shielding properties of materials may lead to differences between the shielding thickness calculated here and the thickness actually required. For example, the lead coolant is expected to be effective at retaining fast neutrons within the core. This could result in a lower neutron flux in reality than the values used in this thesis. However, shielding thicknesses used in past nuclear ship projects were of the same order of magnitude as the calculated requirements presented here.

The calculations in this thesis assume normal operating conditions. When accident scenarios such as core melt, fuel cladding failure, unprotected transient overpower, or loss of flow are considered [6,42], the required shielding thickness could increase. Since the estimated shielding need in this thesis is likely already higher than what would be required under normal conditions, the actual shielding requirement when accident scenarios are included would likely be close to the current estimate.

As briefly mentioned earlier, the proposed design must be re-evaluated from a regulatory point of view. Things to look at are the use of the double bottom for radiation shielding, especially when using other materials than water, and the placement of the containment structure. In the current design proposal, the containment structure could be composed of the inner sides of the water tank and the reactor foundation. This would allow the structure to be completely separate from the safety enclosure, meaning the boundaries of the reactor room. How the regulations should be applied in practice is open to interpretation, which leaves room for alternative design approaches.

The current proposed shielding structure appears to mitigate radiation very effectively, and possibly more than necessary. In preliminary design stages, it is preferable to propose a solution that exceeds the actual shielding requirements. The ship-design process is iterative and follows a so-called design spiral, in which each iteration increases the level of detail. At following iterations, the shielding will be designed with greater precision, including a more thorough review of the regulations. Nevertheless, the current shielding plan was made with the best knowledge to date, prioritizing sufficient radiation shielding over regulatory compliance.

5 Nuclear reactors inside the ship

In this final discussion chapter, the integration of the reactors into the ship is examined. Controlled and supervised areas are defined based on the current layout of the reactors and their surroundings. Topics addressed include the proposed reactor layout, reactor installation and decommissioning, emergency preparedness, reactor operation related spaces, and access points.

5.1 Controlled and supervised areas

Although the reactor shielding is currently designed so that crew members outside the reactor compartment could comply with the dose limits for members of the public, it would be more prudent to classify some rooms near the reactors as supervised areas. Figure 9–12 show the controlled and supervised areas in the general arrangement (GA) from the fourth lowest deck, 1 DECK, down to the lowest deck, TANKTOP. A blue hatch pattern represents supervised areas, and a pink hatch pattern represents controlled areas. Every room within the reactor compartment is classified as controlled area. The reactor rooms and radioactive waste rooms contain radioactive sources, but the rooms currently named as radiation laboratories are also classified as controlled areas because they are in immediate proximity to the reactors and directly linked to reactor operations. The reactor control room is classified as a supervised area because, although it is associated with reactor operations, it is located farther from the reactors. Specific radiation protection measures are therefore not required in the control room, but personal protective equipment should be available, and access should be monitored. Specific radiation protection measures are also not required in the main generator room aft of the reactor compartment, nor in the machinery spaces and the AC room forward of the reactor compartment. These rooms are classified as supervised areas because they are adjacent to the reactor rooms, and it is appropriate to keep them under review for potential radiation exposure.

Classifying areas outside the reactor compartment as supervised areas would mean that personnel working fall under occupational radiation worker regulations rather than the regulations applied to members of the public. Further investigation would be required to determine which members of the ship’s crew fall into each category. With the current proposal for controlled and supervised areas, any workers who require access to rooms in either category should be considered occupationally exposed. This may increase the need for training among the affected personnel. The advantage of classifying some areas outside the reactor compartment as supervised areas is that it enhances worker safety by ensuring radiation exposure is monitored, even though these workers are not operating directly within the reactor compartment. The IAEA requires special training for personnel working in the controlled areas, but it does not specify additional training requirements for personnel working in supervised areas. Employers, registrants, and licensees are responsible for designating these areas [35].

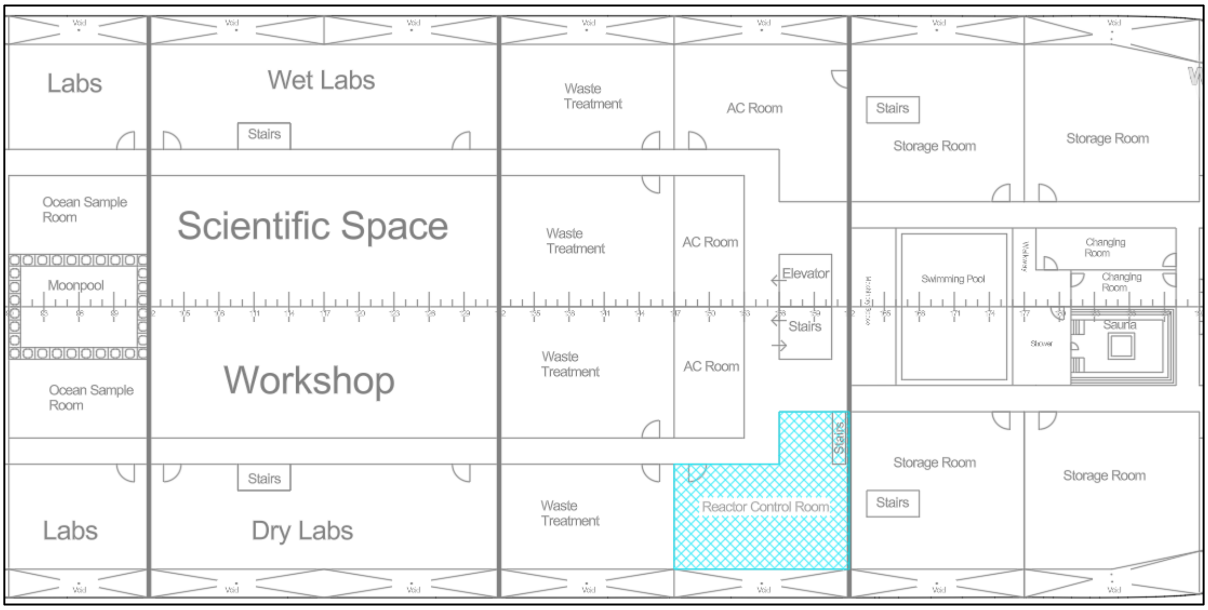

Figure 9. Supervised area on the fourth lowest deck, 1 DECK. The supervised area is marked with a blue hatch pattern.

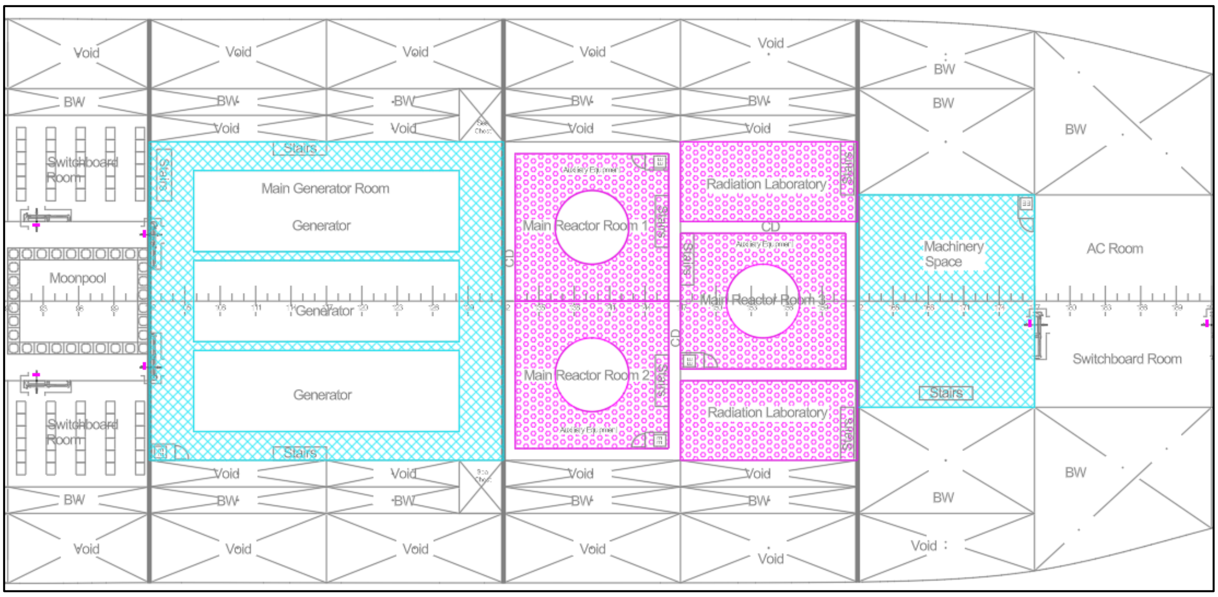

Figure 10. Controlled and supervised areas on the third lowest deck, 2 DECK. The controlled area is marked with a pink hatch pattern, and the supervised area is marked with a blue hatch pattern.

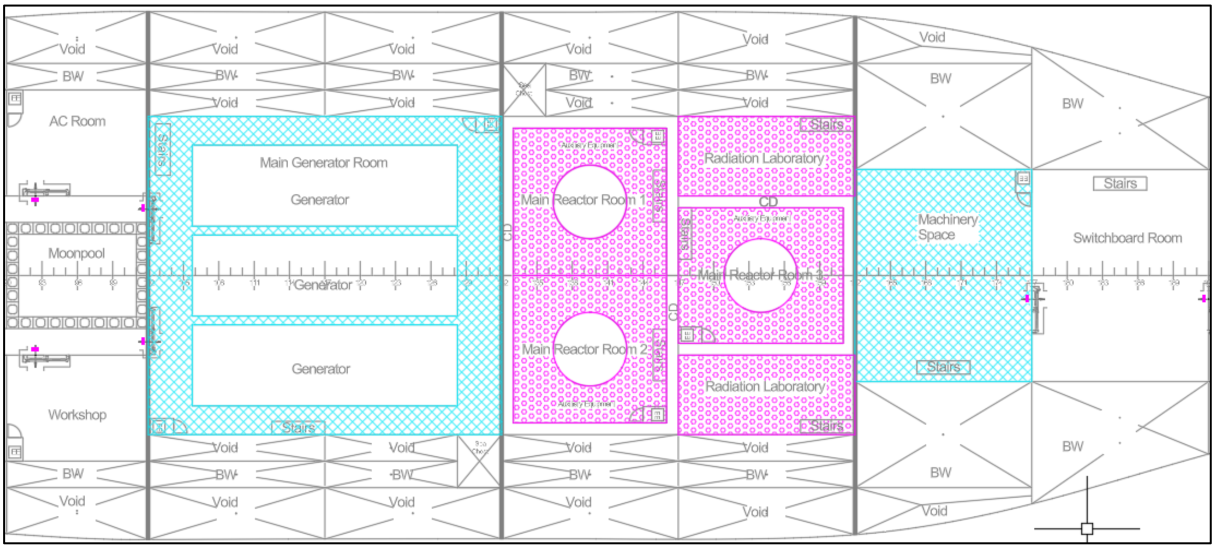

Figure 11. Controlled and supervised areas on the second lowest deck, 3 DECK. The controlled area is marked with a pink hatch pattern, and the supervised area is marked with a blue hatch pattern.

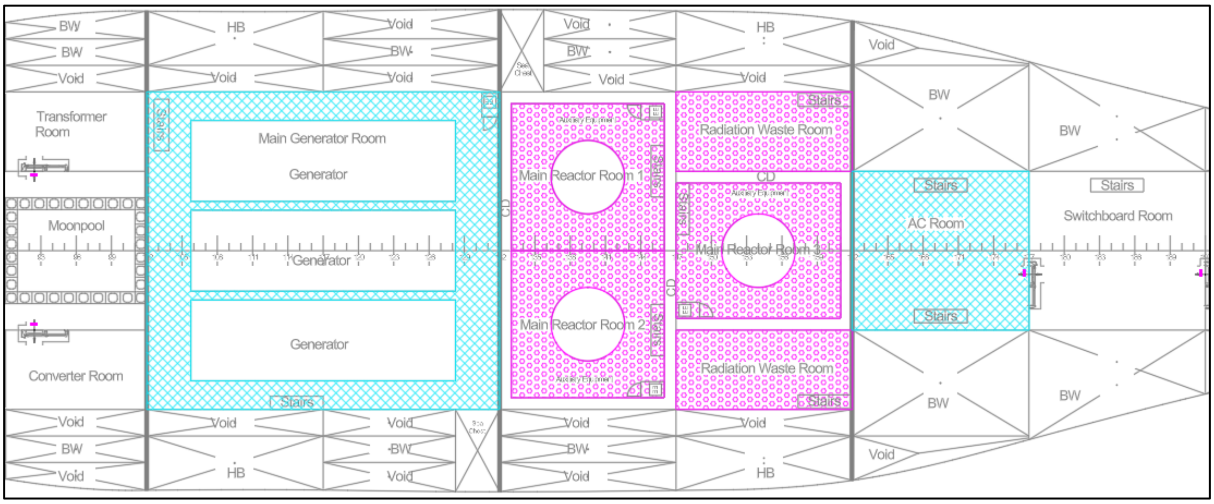

Figure 12. Controlled and supervised areas on lowest deck, TANKTOP. The controlled area is marked with a pink hatch pattern, and the supervised area is marked with a blue hatch pattern.

5.2 Reactor placement and installation in the ship

The three reactors inside IBELO will be placed in separate rooms formed by bulkheads. As mentioned earlier, the bulkheads forming the sides of the reactor rooms can be considered the safety enclosure. The containment structure, or biological shield is located inside this safety enclosure. The safety enclosure must be watertight to ensure improved reactor safety and to comply with regulatory requirements. Each reactor must have its own shielding and safety enclosure to ensure that the remaining reactors can remain operable if, for example, one reactor room floods, thereby increasing system redundancy. The drawback of this design choice is its greater space requirement.

In the current version of the GA, the reactors are placed in a watertight compartment in a triangular arrangement: one reactor in front and two behind. The forward reactor is located between the radioactive waste rooms on TANKTOP and the rooms related to reactor operations, currently named as radiation laboratories, on the upper decks. The reactor control room is located on 1 DECK above one of the radiation laboratories, and the emergency reactor control room is positioned next to the bridge. The current plans were developed using a reactor diameter of 5 m, but the diameter has since been specified more precisely as 4.8 meters, with a height of 5.5 meters. The reserved distance between each reactor and its safety enclosure is approximately 2.6 m in the current GA. In this version, each reactor room also includes one set of stairs and one emergency escape.

As shown in Figure 7 in Chapter 4.4.3, the space required per reactor is greater than what was planned in the first version. The reactor and its radiation shield nearly fill the entire room as originally drawn. Therefore, each reactor room must be larger than in the initial design, which introduces challenges for the overall reactor layout. A clearance of 2 meters is proposed to be reserved on all sides of the radiation shield for auxiliary equipment, other systems, and access. It is not yet known whether this distance will be sufficient or oversized for the equipment associated with the reactor and its shield.

RINA states that the distance between the shielding barrier and the outer shell of the vessel should be at least B/5, where B is the breadth of the ship. For IBELO, B/5 corresponds to 8 meters. Although the IMO allows a smaller damage-extent region, this thesis follows the requirements set by RINA in this matter, as it is more recent. In the current version of the IBELO concept, where the shielding barrier is considered as the edges of a reactor room, the distance to the outer shell is only 6.38 m on TANKTOP, 7.89 m on 3 DECK, and 9.11 m on 2 DECK for the two reactors placed side by side. According to the current shielding calculations, it appears that two reactors with their shields could theoretically fit next to each while still maintaining an 8 m distance to the outer shell on both sides. However, accommodating auxiliary equipment, corridors, or escape routes would become challenging. Although the triangular arrangement, – with two reactors side by side – offers a compact layout and preserves more longitudinal space for other ship functions, it does not appear feasible due to the limited transverse space and the damage-extent requirement set by RINA.

Currently, it appears that two reactors can fit next to each other only if (1) the required biological shielding thickness is reduced, (2) the need for auxiliary systems is very minimal or these systems are placed outside the safety enclosure, (3) the hull shape is widened from the bottom to the main deck, or (4) the rules regarding the damage-extent region change. With the current biological shielding requirements and hull shape, it is inevitable that the reactors must be arranged longitudinally in a line.

When the reactors are rearranged in the GA during the next iteration, the placement of watertight bulkheads should be reviewed. It should be considered whether all reactors could be placed within a single watertight compartment, whether each reactor should have its own watertight bulkhead, or whether they should be grouped, for example, two in one compartment and one in another. Having watertight bulkheads separating the reactors would improve safety in the event of flooding, but it would also make the design and construction more complex and costly. Since the safety enclosures themselves must be watertight, it does not appear necessary to have watertight bulkheads extending to the main deck between each reactor.

The placement of the reactors inside the ship should also be re-evaluated. They are currently in the center of the ship, below the superstructure, which is the most safe and secure place for the reactors. However, as the layout of the reactor compartment will be redesigned, it should also be considered, whether the reactors should be moved closer to the fore or aft of the ship, and how they would be installed to and removed from the ship. In *Otto Hahn* and *Savannah*, the reactors were placed in the middle of the ship, ahead of the superstructure, which was located aft. This arrangement allowed for an access point above the reactor. If a similar approach was adopted in IBELO, the shaft would need to be located either forward or aft of the superstructure. If the reactors were moved closer to the bow and the superstructure shifted slightly aft, a shaft could be positioned in front of the superstructure. However, this choice presents several challenges: limited space, increased vibrations from icebreaking, greater weight concentrated toward the bow, and reduced safety in the event of collisions. This design may also be infeasible simply due to the reduced breadth of the ship on the lowest decks toward the front. If the reactors – including their required damage extent regions – were placed as far forward as possible, there might not be sufficient lateral space for other reactor operation related rooms. The spaces would then need to be located on decks above the reactors or aft of them.

Another option for having a shaft for the reactors would be to place the reactors at the aft of the ship and position the shaft behind the superstructure. In this case, the generators would need to be located forward, and the placement of the moonpool might also need to be reconsidered. Positioning the reactors closer than the generators to the propulsion would complicate the machinery connections and result in a more complex design, construction and loss of efficiency. Nevertheless, having only one shaft for three reactors may not justify the complications associated with placing the reactors as far forward or aft as possible. Providing one shaft for each reactor would require so much space that the superstructure and other functional areas of the ship would need to be significantly compromised, making such a design impractical.

Not having a shaft for installing the reactors leaves the option of installing the reactors in place and building the ship around them. In that case, removing the reactors at the end of their service life would either require decommissioning the ship at the same time or cutting a hole in the side of the ship. This approach favors aligning the service life of the ship and the reactors so that decommissioning of both occurs simultaneously. If one or more reactors needed to be removed before the ship reached the end of its service life, cutting an opening in the ship's side would be the most convenient and cost-effective solution. It should, of course, be evaluated whether the risks associated with removing a reactor through a side opening are acceptable compared with a design that allows removal from above. Removing reactors through the top of the ship is also highly challenging, and if this were the intended method for possible mid-life reactor replacement, significant changes to the GA would be required, as a removal route for each reactor would need to be designed along with appropriate radiation protection along that route. For these reasons, removing reactors through the side of the ship appears to be the simplest solution. In the current IBELO concept, it seems most practical to keep the reactors in the middle of the ship, where they are best protected, and remove them through the side if replacement becomes necessary before the vessel is fully decommissioned.

5.3 Reactor compartment design aspects

With the current planned size of the reactor rooms, three reactors in a row would require 41.4 meters of the ship's length. This is almost a third of the current TANKTOP deck length, which is around 150 meters. Considering that there must be at least 8 meters between the outer hull shell and the reactor rooms – and that other space consuming machinery such as generators and a moonpool are also required – it appears very challenging to fit three reactors into the ship with the current reactor room space reservation and regulations. Adjustments to the reactor room dimensions or the hull shape will almost certainly be necessary. Additionally, the weight of the reactors and their shielding will need to be considered in the future. However, if the reactors are placed near the longitudinal center of the ship, weight is unlikely to be a major issue. Because IBELO is an icebreaker, weight constraints are less restrictive than they would be for, for example, a cruise ship.

Access to the reactors through radiation shields must be provided for maintenance and repair purposes. Although not yet confirmed, it is assumed that the reactors can be accessed from the top. Therefore, an access opening should be included above the reactor shielding, which is composed of lead, concrete and water, even if this access point is expected to be used rarely. The lead and concrete shields, as well as the water tank above the reactor should be cut open to allow access, during which the water level would need to be decreased enough to clear the top of the water tank. Access to the reactor rooms from the top also appears to be the most practical solution, as it minimizes the need for doors through the watertight bulkheads forming the lateral boundaries of the reactor rooms. If lateral access from the lower decks is desired, longitudinal corridors could be added along the sides of the reactors. In any case, further investigation is required to determine what types of access and escape routes are necessary for the reactor rooms. Currently, the goal is to enter these rooms only on special occasions, possibly as infrequently as once per year. All access points to controlled areas should pass through controlled access barriers to ensure security and safety of the personnel and the entire ship. All reactor-related operations should require entry through these access barriers.

As stated in the regulations, airflow should be directed from spaces with a lower likelihood of airborne contamination toward spaces with a higher likelihood. Airlocks can also be used where needed. For example, radioactive waste rooms and reactor rooms could have airlocks at their entrances. It remains to be determined what type of ventilation is required for the reactor rooms. Since human access to these rooms does not occur on a regular basis, continuous air circulation is not essential. Additionally, because the water shield can also cool the reactor, dedicated ventilation may not be required for residual heat removal. Although effective ventilation could support passive decay heat removal, the presence of radioactivity poses challenges. One option for the reactor rooms is to fill them with noble gas, which could improve radiation safety.

Figure 13–16 present the four lowest decks, from 1 DECK down to the TANKTOP. They include an option for the reactor compartment layout, creating space reservations on the GA, based on the regulations reviewed in Chapter 3.2. Appendix 1 further summarises relevant requirements for the reactor compartment, and Appendix 2 Colour codes on Figures 6 and 13–16provides a table of colours and their meanings used in the figures.

On 1 DECK, shown in Figure 13, the proposed layout covers the entire area reserved for reactors on the lower decks, and additionally extends both to the sides of the ship and towards the bow. On both sides, some room is left for corridors bypassing the reactor compartment. The area directly above the reactors, named as reactor access rooms, would be used as access points to the reactors through the biological shield, and to the reactor rooms along their sides. As the main reactor rooms are used only occasionally, providing only one means of escape could be enough. The access rooms should be provided with biological shielding for the radioactivity that might rise when access to the reactors or the reactor room is open. The reactor access rooms should be considered as part of the controlled areas. The reactor control room would be located forward from the reactors and at the center of the ship. This is a safe placement because it is close to the reactors, yet not directly above them, and far from the ship’s bow and sides. In the current plan, there is only one reactor control room. If separate rooms for each reactor are required, the control room area could be extended either towards the bow or the sides of the ship. The reactor control room is to be provided with two means of escape as shown in the figure. In addition to the reactor access rooms and the control room, decontamination facilities would be located on this deck. Those facilities should be used when exiting the reactor compartment. Access barriers used for monitoring access of personnel are also illustrated in the figure. Emergency exits, stairs and lifts are provided for the radiation laboratories and radioactive waste rooms which are on the lower decks. There is also a lot of space reserved for any functions needed inside the reactor compartment, like additional decontamination spaces, storage and office spaces.

The 2 DECK, shown in Figure 14, is the uppermost deck that contains the reactor rooms, which extend down to the TANKTOP. Reactor rooms including the shielding structure and other space requirements are sketched on top of the current GA. Additional longitudinal space compared to the current version is required for the reactor rooms, as all reactors are arranged along the centerline. This configuration leaves some space on both sides of the reactor rooms, which could be used as radiation laboratories or storage areas. Access points to the radiation laboratories from the 1 DECK can also be seen in the figure. Also, cofferdams forward and aft of the reactor operation related areas are present. They are further discussed shortly.

Figure 15 presents 3 DECK, which has a similar layout as 2 DECK. The spaces on both sides of the reactors could be used for further radiation laboratory spaces, storage or even for radioactive waste handling if needed. Finally, Figure 16 presents the TANKTOP, which is the lowest deck and has the same layout as the two decks above. It is preferable to locate the radioactive waste rooms to this deck, as this area is likely the second most radioactively hazardous space after the reactor rooms. Since low and medium activity waste must be treated and stored in separate spaces, placing them on opposite sides of the reactors could be convenient. The required capacity for waste treatment and storage must be carefully evaluated in the next stages of ship design to ensure sufficient space for these operations. If the available space on the TANKTOP is not enough, the waste treatment and storage facilities could extend to 3 DECK. Figure 14–16 present how the cofferdams have extended through the three lowest decks. The cofferdams should have a width of at least 900 mm, and they should separate reactor rooms and preferably the radioactive waste rooms from adjacent spaces. Additionally, the access through stairs and lifts, and the emergency exits have extended from the 1 DECK to the TANKTOP. The lifts would be used for moving larger equipment. As can be seen on Figure 16, the closest distance of the main reactor rooms to the side shell of the ship is 8 meters in this proposal. It means that the reactors cannot be moved forward or else the damage extent region is not sufficient. The total length of the reactor compartment from TANKTOP to 2 DECK would be 41.4 meters, and 43.2 meters including the cofferdams. In the proposed layout, the side rooms can only be accessed from 1 DECK, but a corridor between either of the cofferdams and main reactor rooms could be proposed to connect the side rooms to each other. However, this would slightly increase the length of the reactor compartment.

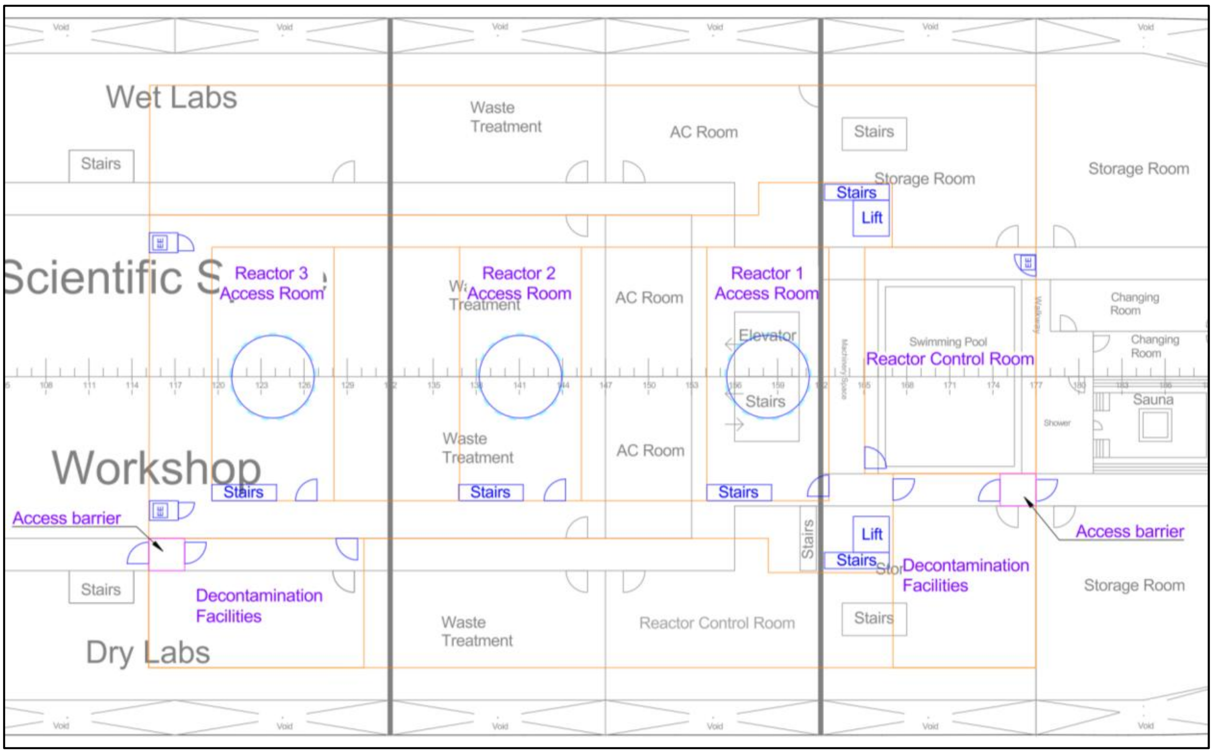

Figure 13. Proposed reactor compartment space reservations on 1 DECK.

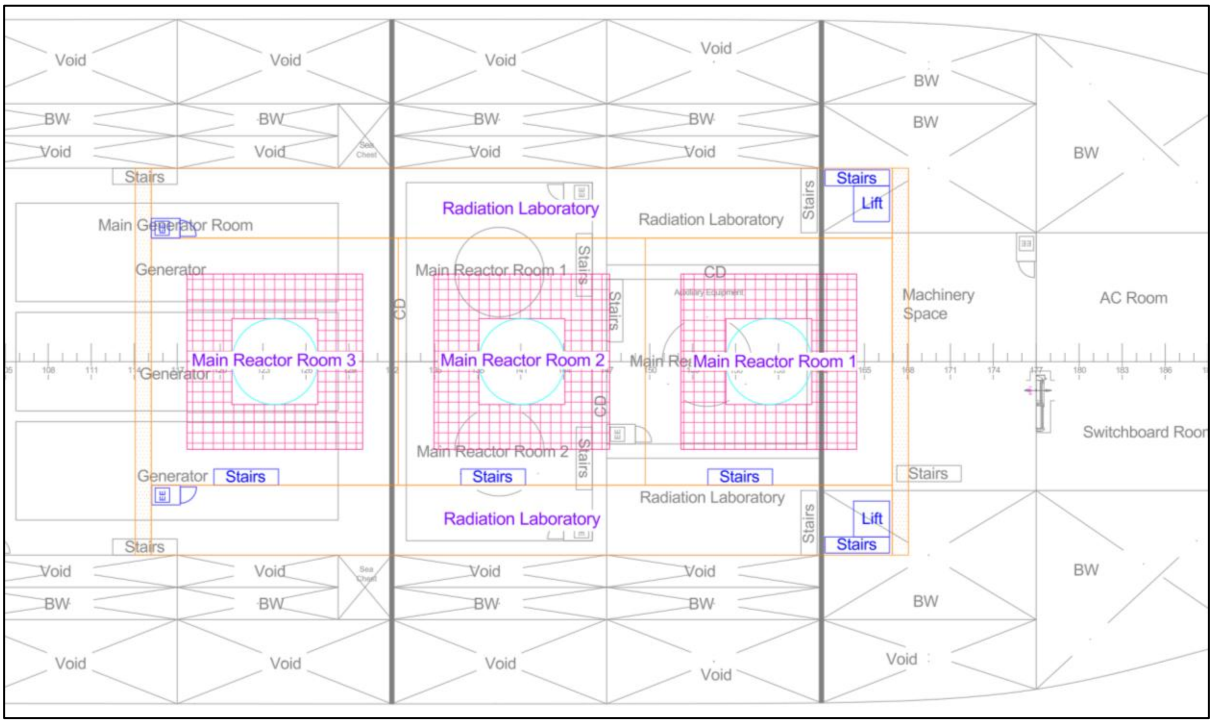

Figure 14. Proposed reactor compartment space reservations on 2 DECK.

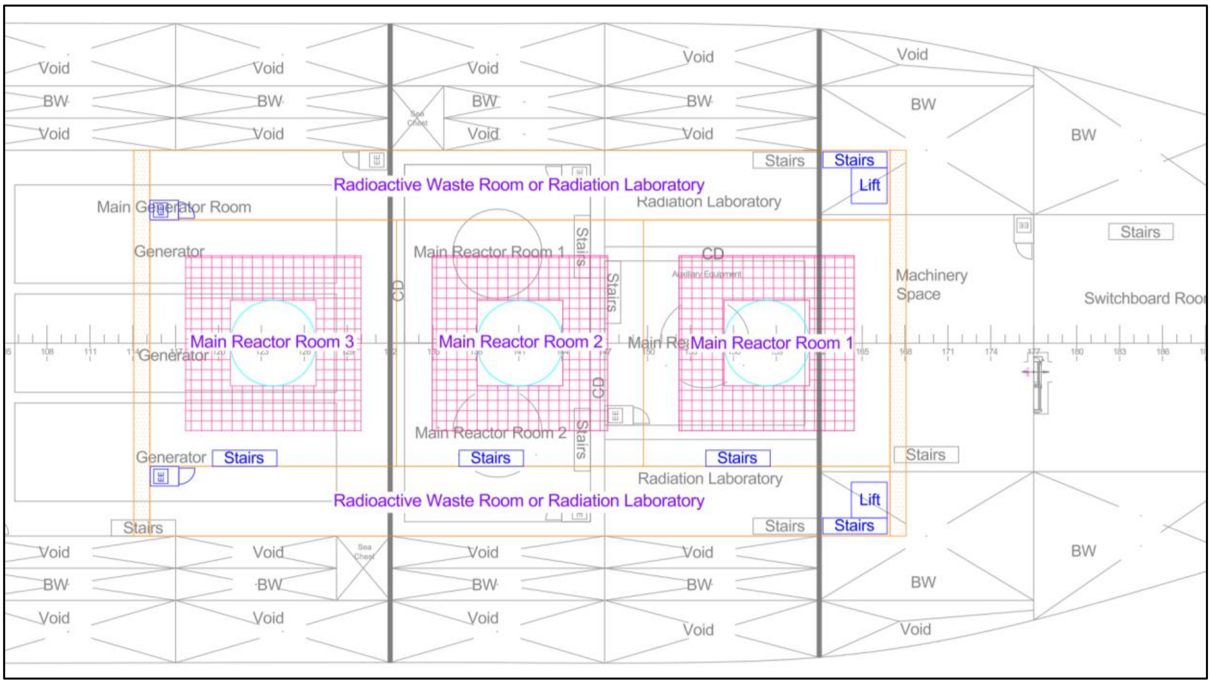

Figure 15. Proposed reactor compartment space reservations on 3 DECK.

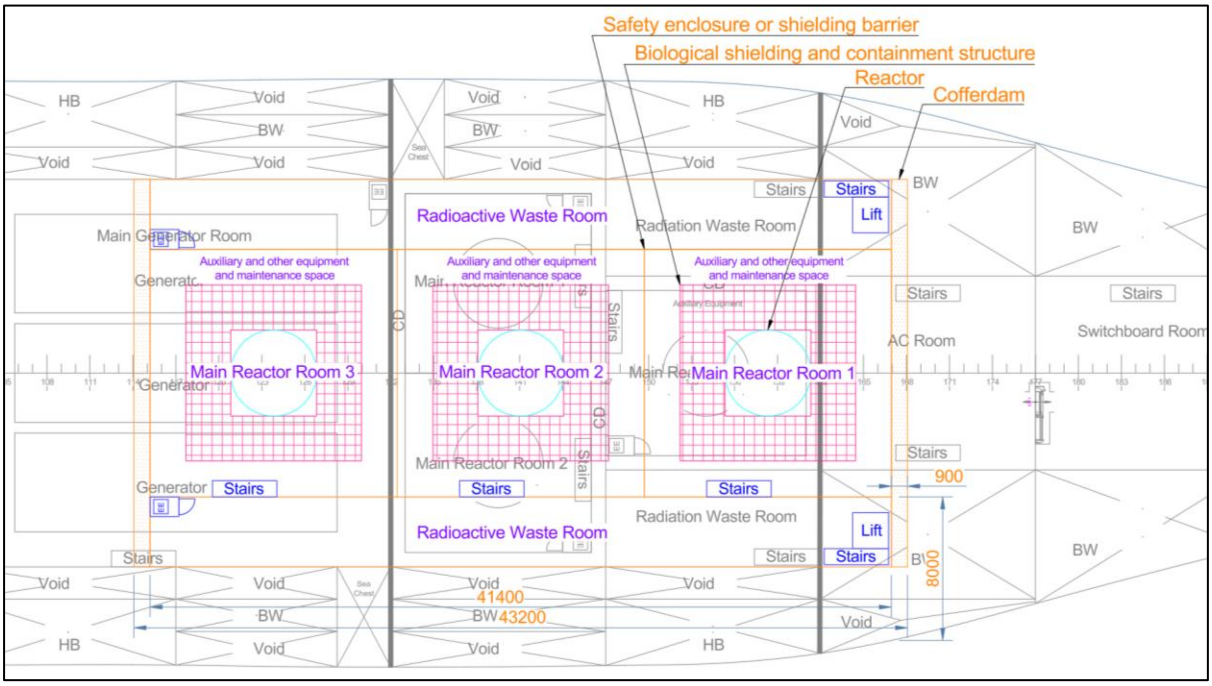

Figure 16. Proposed reactor compartment space reservations on TANKTOP.

5.4 Emergency preparedness and future investigations

According to the IMO, in the event of a fire or other emergency, a person must be able to exit any compartment immediately, regardless of any security measures [30]. Entry into a compartment to perform required safety functions under emergency conditions must also not be prevented by such measures [30]. From a radiation safety perspective, this may increase the risk of contamination in areas where contamination should not occur. On the other hand, requiring personnel to undergo decontamination procedures before exiting would slow evacuation and could pose a greater threat than contamination itself. If a safety function must be performed inside the reactor compartment and the radiation shield fails to reduce exposure to acceptable levels, personnel performing these tasks may be subjected to elevated radiation doses. A detailed emergency procedure plan should therefore be established, and radiation levels must be continuously monitored to help prevent such situations. If personnel from controlled areas must evacuate without decontamination, directing all radiation workers to a single designated location would help avoid unnecessary or excessive contamination during emergency operations. The emergency reactor control room is also designed to prevent such situations and to ensure the safety of radiation workers and all persons on board. In IBELO, it is located next to the bridge, approximately 29 meters from the reactors.

According to RINA, ”In case of major faults and or severe accident conditions, the containment may be vented into the atmosphere but through filters capable to ensure the required rate of air cleaning” [32]. ABS further states that an emergency shutdown must be possible at inclination angles of up to 90°, and the system must be capable of maintaining the shutdown state at all angles. ABS also requires protection and safety systems to activate automatically when an emergency occurs. The power supply system must be redundant so that power remains available to the reactor controls, cooling systems, emergency cooling systems, and other safety equipment in the event of a loss of power from the nuclear power plant. Power must remain available for as long as necessary to achieve a safe shutdown, cooldown, and a stable safe state [23].

As this is the first version of the radiation protection plan for the IBELO concept ship, there are numerous topics that should be examined further in the next studies. It is also essential that Blykalla advances their reactor concept design to provide additional information that will support the design of the reactor compartment and the radiation shields. Regarding the radiation shields, a more comprehensive comparison of potential materials is needed, both in terms of shielding performance and other characteristics such as structural integrity. Advanced materials such as borated concrete or borated polyethylene could be evaluated in more detail. A more thorough and accurate analysis of radiation fluxes should also be conducted to optimize the required extent of shielding. After these steps, a more detailed radiation shielding design can be developed. It is also important to note that the regulatory framework for nuclear ships is still being updated to reflect modern technologies. Until the IMO publishes its revised regulations, following the RINA Guide appears appropriate for reactor technologies other than PWRs. Additionally, an early investigation should be conducted into port acceptance for the nuclear ship, as well as matters related to liability and indemnification. Addressing these issues as early as possible in the first ship-design phases will help avoid major complications later.

6 Conclusions

Regulations regarding nuclear ships are mostly prescriptive and do not provide very specific requirements for radiation protection. All plans must be approved by authorized parties, typically the nuclear regulator of the country whose flag the ship flies. The regulations issued by the IMO, ABS and RINA were reviewed in this thesis, and in many cases the strictest requirements were followed when developing the radiation protection plan. Of these three, only the RINA Guide is currently fully applicable to this ship due to its reactor technology neutrality, and because nuclear power is used for propulsion, which is an area not covered within the scope of ABS.

A method for calculating the gamma and neutron radiation fluxes was developed to estimate the highest possible radiation levels under normal operating conditions at nominal power. Using the resulting fluxes together with the material’s attenuating properties and thicknesses, the attenuated radiation fluxes were calculated. Radiation doses were then determined from the attenuated fluxes to define the shielding thickness required to achieve acceptable radiation levels. The target was to achieve an annual dose of less than 1 mSv at a distance of 6 meters from the reactors. Such an annual dose is very small – lower than the dose typically received from natural background radiation.

It was found that the reactor coolant attenuates gamma radiation sufficiently, meaning that the biological shielding should focus primarily on neutron radiation. Approximately 2.5 meters of sequential shielding, composed mainly of water and concrete, was determined to be adequate for reducing the neutron radiation dose to the targeted levels. A preliminary shielding concept was developed based on these calculations. It consists of a square-shaped water tank surrounding the reactor on all sides, with a width of 1200 mm to effectively slow neutrons, followed by a thin layer of lead to capture any remaining gamma radiation. Next, an approximately one-meter-thick concrete wall, potentially doped with a strong neutron absorber such as boron, would surround the water tank structure to further moderate and absorb neutrons. Another thin layer of lead would then be added to attenuate any secondary gamma radiation. A steel wall would enclose the entire shielding assembly. A clearance of 2 meters on all sides of the shielding would be reserved for auxiliary systems related to the reactor and its shielding, and maintenance access. Access to the reactors would be provided through the shielding structure from above.

Since the width of one reactor is 4.8 m, the radiation shield occupies approximately 2.5 m on all sides, and 2 m of space is reserved around it, the width of the square-shaped reactor room becomes 13.8 m. The height of the room is 10.5 m, which is appropriate given that the reactor height is 5.5 m and roughly 2.5 m of shielding is required. The boundaries forming the 13.8 m wide reactor room must be watertight, gastight, and airtight, and can therefore be considered the safety enclosure. Housing each reactor in its own watertight space also ensures redundancy in the event of flooding.

The location of the nuclear compartment in the current plan is the safest feasible placement for nuclear reactors. The approximate location should be retained in future versions of the concept, but the arrangement of reactors, and therefore the size of the compartment, must be re-evaluated. With the currently estimated reactor room dimensions, all reactors must be placed in a row along the ship's centerline. This is because the damage extent region between the safety enclosure and the hull shell must be at least 8 meters on all sides. Due to this requirement, the reactor compartment must be at least 41.4 meters in length, and with cofferdams at both ends of the compartment, at least 43.2 meters. The compartment should extend through four decks: the three lowest decks housing the reactors, and the deck above reserved for reactor control rooms, decontamination facilities, access barriers and other spaces related to reactor operations and the personnel within the compartment. In addition to the reactor rooms, the three lower decks should also accommodate radioactive waste treatment and storage facilities and radiation laboratories. The waste treatment and storage plant is planned for the lowest deck, TANKTOP, and if additional capacity is required, the facilities could extend to 3 DECK. The overall configuration of the three lowest decks would place the reactor rooms in the center, with other facilities located on the port and starboard sides between the reactor rooms and the hull. Access to all these spaces would be provided through 1 DECK.

Regulations require a categorization of spaces into controlled and supervised areas. In the current plan, the controlled areas include the reactor rooms, as well as the radioactive waste rooms and radiation laboratories located on the sides of the reactors. The supervised areas include the spaces on 1 DECK that belong to the reactor compartment, along with the areas adjacent to the reactor rooms, which are the main generator room, machinery space and AC room in the current plan. In controlled areas, personal protective equipment must be worn, and the workplace is continuously and carefully monitored for radiation hazards. In supervised areas, radiation levels are monitored, but protective measures are not normally required.

It is possible that the required shielding thickness has been overestimated due to the rough calculations used to determine the worst-case radiation levels under normal operating conditions at nominal power. Additionally, the targeted dose limit may be stricter than necessary, which would also lead to a higher shielding estimate. However, because potential accident conditions were not considered in the calculations, it is assumed that the shielding results are still reasonably close to the requirements that will be specified later. The shielding design must also be re-evaluated from a regulatory perspective and approved by the appropriate authorities.

The next development steps of the radiation protection plan could include creating a new version of the GA in which the reactors are placed according to the space requirements estimated here, along with a more detailed reactor compartment layout that includes decontamination facilities, a reactor control room or rooms, planned access routes, a radiation laboratory, and radioactive waste rooms. A more thorough investigation of the shielding materials and their interactions with radiation and adjacent materials should also be carried out in the next phase to further refine the required extent of shielding. Once the SEALER-55 reactor concept is further developed and more information becomes available regarding its required radiation shielding and auxiliary systems, a more detailed model of the reactor room can be produced. The radioactive waste facilities and reactor control rooms will also require biological shielding, which must be designed in future phases, together with determining the required capacity of the waste management facilities. Improved plans must also incorporate the arrangements for ventilation, piping, and bilge systems within the reactor compartment.

Because nuclear ships are rare, and the technology is not widely familiar or favored, the concept may face some resistance. The initial phase of the concept design should therefore include a liability and indemnification assessment, including identifying ports that are willing to accept a nuclear-powered vessel. Ideally, once the radiation protection plan is carefully developed, considering all aspects related to ionizing radiation, and accepted by the relevant authorities, IBELO could operate in all polar waters without radiation related concerns among the crew, passengers, or the communities in the ports it visits.

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Appendices

Appendix 1 A summary of relevant requirements

Relevant requirements by the IMO, RINA and ABS.

- Distance from the outer shell to the safety enclosure is to be at least B/5 (8 m)
- Double bottom must be at least 2 m thick
- Safety enclosure must be watertight, gastight and firetight
- Cofferdam must extend through the reactor compartment
- Cofferdam width must be at least 900 mm
- Medium and low activity waste must be treated and stored in separate spaces
- Independent, separate and isolated ventilation system for controlled and supervised areas from uncontrolled areas
- Airflow in controlled areas must be from a space with less potential airborne contamination to spaces with more potential airborne contamination
- Ventilation must be redundant and standby fans must be provided
- A dedicated mast must be provided for discharge of air in controlled areas
- Controlled areas must have a bilge system independent from other areas
- Interconnections between piping systems should be minimized
- Interconnections between radioactive fluid systems and potable water systems are prohibited
- Controlled areas must remain in underpressure even when one entrance is open
- Storage capacity must account for all bilge liquids generated in controlled areas
- At least two storage containers must be provided
- Two separate pipelines are needed for transferring liquid waste out of the vessel
- Appropriate pressure vessels and pipelines are to be provided for gaseous waste compression and storage
- Shielding towards the bottom of the unit is to be provided
- Biological shielding should be provided for pumps and pipelines where necessary
- Radiation waste rooms and the radiation control room are to have biological shielding
- Access openings in watertight, gastight or fire tight boundaries of or within the reactor compartment must maintain the watertight, gastight or firetight integrity of the boundary
- Number of openings in watertight bulkheads should be kept to the minimum possible

- Stairways are to have at least 800 mm in clear width
- At least two means of escape must be provided from each watertight space
- Two means of escape with effective fire shelter to the weatherdeck must be provided from the reactor control room
- Access barriers are to be provided for entry points to the controlled areas
- Decontamination facilities must be provided for access points
- Decontamination facilities: contamination monitoring for skin and clothing and for objects or materials exiting the area, washing and showering facilities and storage for contaminated personal protective equipment.

Allowed by the IMO, RINA and ABS regulations,

- reactor foundation structure may be integrated with hull structure
- it is permitted to fill cofferdams and double bottom with only non-potable water
- airlocks may be used in entrances between lower and higher pressure area if needed
- a single means of escape may be accepted to spaces that are accessed only occasionally.

Appendix 2 Colour codes on Figures 6 and 13–16

	Water
	Lead
	Concrete
	Walls
	Cofferdam
	Reactor
	Shielding structure
	Access points
	Access barrier

Figure 17. Table of colour codes and their meanings on Figures 6 and 13–16.