Impact of Radiation Protection Philosophy on Shielding Design Optimization for a Marine SMR

Nuclear Power & Propulsion Lab

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Background

IMO's GHG (GreenHouse Gas) Strategy

❑ **Emission Reduction Goals**

- The IMO (International Maritime Organization) aims to achieve zero carbon emissions from ships by 2050.
- This will require significant **reductions in GHG emissions** across the maritime industry.

❑ **Conventional Diesel Engines**

- To comply with these regulations, **conventional diesel engines must be phased out**.
- This pushes the industry toward **cleaner alternatives**.

❑ **Need for Alternative Solutions**

- Alternative solutions are essential for sustainable and efficient operations.
- As a viable alternative, **Nuclear propulsion systems** are emerging.

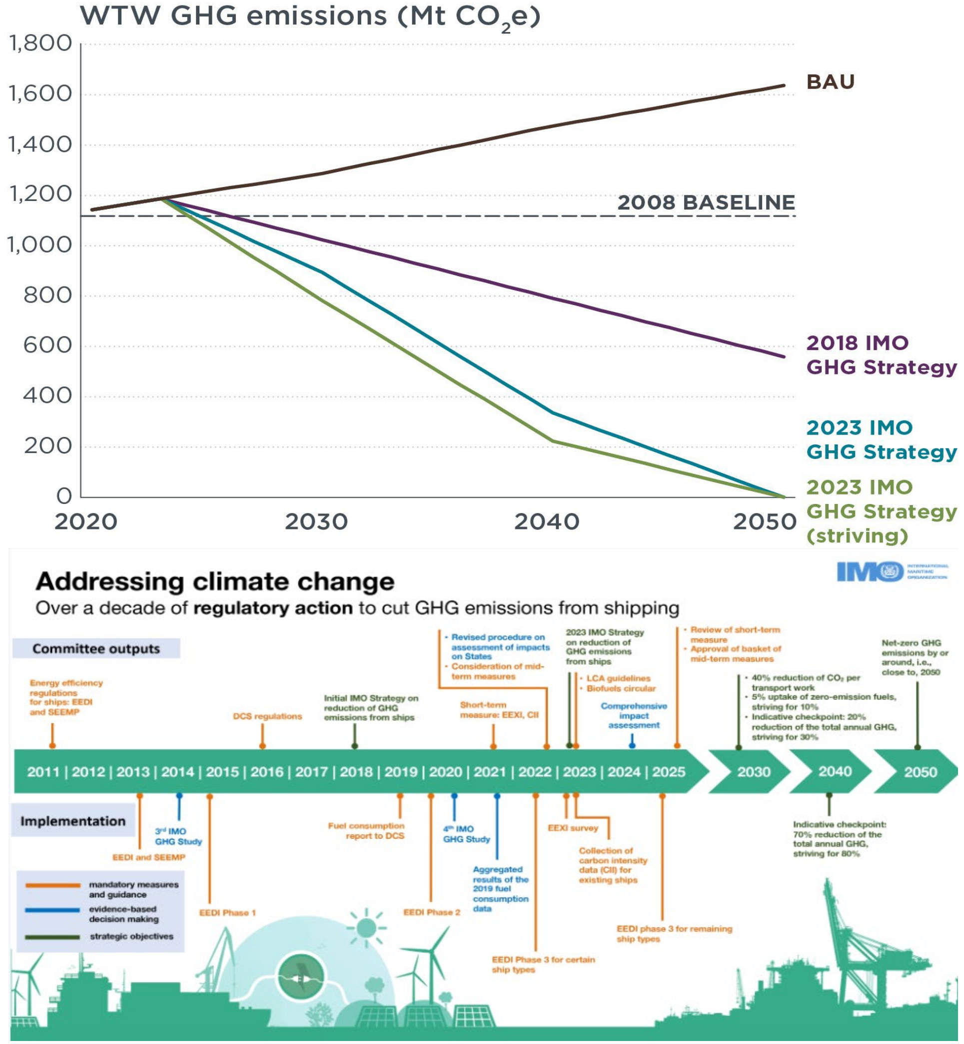

Fig. 1. IMO GHG Strategy

Background

Why nuclear-powered ships are needed

❑ Growth in cargo carried by large vessels

- Global seaborne trade in 2023: 12,292 Mt, +2.4% year-on-year. Ocean shipping carries over 80% of world trade by volume.
- Ton-miles in 2023: 62,037 billion, +4.2% year-on-year, rising even faster than volume.
- Upsizing trend in container ships: from 1996–2015, average container ship size (DWT) +90%, bulk carriers +55%, tankers +21%

→ the average ship size keeps increasing.

→ A propulsion energy source with high efficiency and long high-utilization time is required.

❑ Fundamental constraints of alternative fuels (LNG, methanol, ammonia)

- Energy-density limits (especially volumetric): large fuel-tank volume reduces cargo capacity.
- Fueling, safety, and handling issues: cryogenic temperature, toxicity, and flammability. → We need very high energy density and independence from frequent resupply for long intervals.

Characteristic	HFO	LFO	LNG	LPG	Methanol	Bio-Fuels	Ammonia (NH_3)	Hydrogen (H_2)
Boiling Point (°C @1 bar)	177	170	−162	−26	65	315	−33	−253
Lower Heating Value (MJ/kg)	39	40	48	46	20	40	18	120
Flammable Range (% vol. in air)	0.5–7	0.6–7.5	5–15	9–19	6–26	0.6–7.5	15–28	4–74
Energy Density (MJ/L)	35	39	22	25	16	34	12	9
Tank Size (ratio to LNG)	0.6	0.6	1.0	0.9	1.4	0.6	1.8	2.4
Reduction rate of Carbon (vs HFO)	–	2%	26%	16%	11%	5–10%	95%	99%
Others / Notes	Low cost high CO_2	High cost	Cryogenic storage	Easier Storage vs LNG	Toxic material	Toxic material	Toxic material	Cryogenic storage

Comparison between LNG and Carbon-neutral fuels

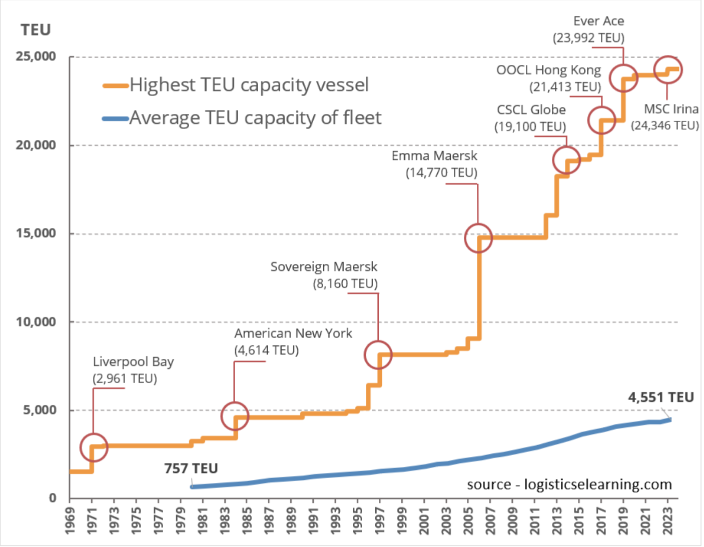

Fig. Evolution of the capacity of container ships

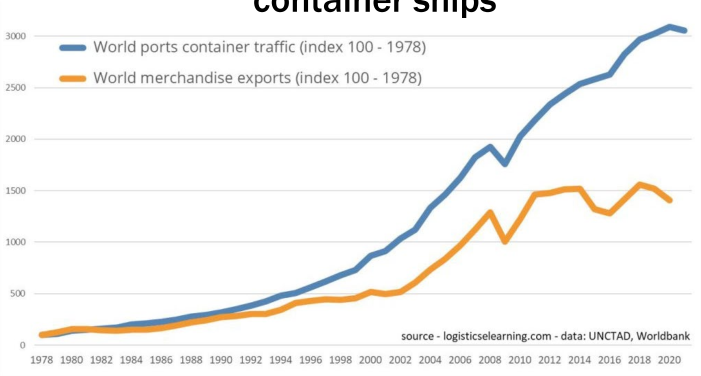

Fig. Container throughput compared to world exports

Background

Why nuclear-powered ships were constrained in the past — and the current direction

Why nuclear ships were limited in the past

Constraints: economics, port acceptance, regulatory framework

1 Insufficient economic viability

- NS Savannah recorded annual losses of about USD 0.64–0.75 million (1960s dollars) in early commercial service, relying on government subsidy and special treatment.
- Steam cycle equipment plus radiation shielding imposed large space and weight penalties, reducing net cargo capacity and profitability.

2 Limited port acceptance and immature regulatory/insurance frameworks

- Gaps in standardized liability and insurance regimes led to port-entry restrictions and extra costs.
- Even after the IMO Nuclear Merchant Ship Code (1981), commercial application remained uncertain.

3 Complexity of shielding technology and the sequential design process

- NS Mutsu (1974) experienced neutron streaming at low power (~1.4%), causing long port bans and subsequent shielding upgrades.
- The typical sequential process (fix the core → fix the source term → then design shielding) made it hard to optimize penetrations, layout, and spectra together.

Current direction for nuclear-powered ships

Technology maturity + integrated design + LEU/HALEU + Regulations

1 Operating track record and technology maturity

Over 60 naval and civilian nuclear vessels worldwide, with 200+ reactors operated to date.

2 Tools and data for shielding optimization

Monte Carlo transport codes with ICRP Publication 116 dose coefficients enable simultaneous optimization of the core, shielding, penetrations, and layout.

OpenMC MCNP

3 Expanding enrichment supply for civilian use

Finding a Better Way to Transport HALEU

The United States is going to need a lot of high-assay low-enriched uranium (HALEU) in the coming years to support the development and deployment of advanced reactors. We don't currently have licensed containers designed specifically to transport HALEU.

Office of Nuclear Energy

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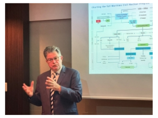
4 Ongoing modernization of IMO regulations



Major milestone for nuclear-powered ships as IMO agrees outdated regulations revision

(Posted on 27/06/25)

The IMO has formally agreed to start the revision of outdated regulations for nuclear-powered ships.

The 110th session of the IMO's Maritime Safety Committee heard proposals from several Member States and NGOs calling for a revision of the Code of Safety for Nuclear Merchant Ships (Resolution A.491) and relevant parts of the SOLAS Convention.

A working group at MSC 110 prepared instructions for relevant sub-committees to initiate the revision. This Thursday (June 26), MSC 110 assigned this task to the Sub-Committee on Ship Design and Construction (SDC), requesting SDC to start this work at the next session if

possible. The next session of SDC is scheduled for January 2026.

A key part of the instructions for SDC when updating the Code of Safety for Nuclear Merchant Ships (Resolution A.491(XII)) is to ensure it is not limited to designs of Pressurized Water Reactors (PWRs) with direct steam cycle propulsion systems but adequately address recent advances in new nuclear technologies and the All-Electric-Ship concept.

During a presentation by the World Nuclear Transport Institute (WNTI) to MSC 110, just after IMO Member States had agreed that revision of the Nuclear Code should go ahead, Mikal Bøe, CEO of CORE POWER, thanked the IMO delegates for their support and welcomed closer links between the global maritime regulator and the International Atomic Energy Agency (IAEA).

CORE POWER is the leading developer in the OECD of both advanced nuclear technologies and shipyard construction designs for maritime applications.

"This means that we can move forward to create the international framework that governs the safety and security of civilian nuclear shipping," said Bøe.

Growing interest in nuclear propulsion suggests it can become a central energy option for future shipping.

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02

Motivation

Motivation

Key constraints in marine environments: space and weight

❑ Land-based NPPs vs. Nuclear-powered ships

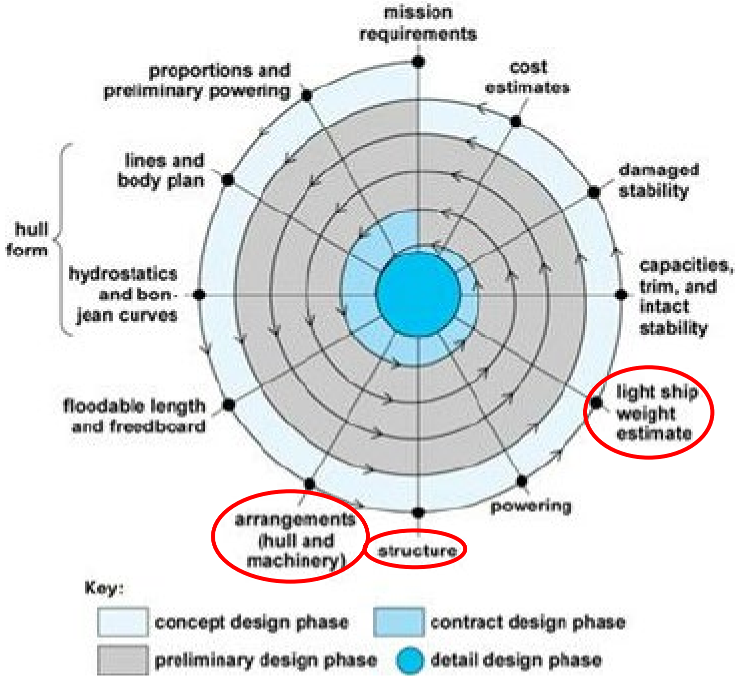
Item	Land-based nuclear power plants (NPPs)	Nuclear-propelled ships
Platform / Space	Fixed site; ample plant layout space	Tight engine room and reactor compartment; constraints from hull form and deck height
Weight & Stability	Buildings are fixed little need to consider stability	**KG** (vertical center-of-gravity height) and **GM** (metacentric height), trim and list are primary constraints sensitive to weight and center-of-gravity shifts
Regulatory	National nuclear regulation + grid/power regulations	Classification society + flag state / port state + **IMO** frameworks (**SOLAS**, **MARPOL**) combined with radiation / nuclear regulations

❑ Space constraints

- Installation space: Unlike land plants with ample sites, ships are physically limited by hull form and deck height.
- Arrangement task: Within tight space, ensure efficient radiation zoning and secure maintenance/inspection routes.
- Radiation protection: Unlike land plants where far-field shielding dominates, ships must prioritize near-field protection for crew living areas.

❑ Weight & safety constraints

- Stability sensitivity: Unlike fixed land structures, changes in light-ship weight and KG (vertical center of gravity) directly affect ship stability (GM).
- Economic impact: Higher light-ship weight → lower deadweight tonnage (DWT) → reduced cargo capacity and profitability.
- Structural task: Weights placed high raise KG and hinder stability; concentrated loads require local structural reinforcement.



< Ship design spiral concept >

Weight and space are more important on ships than on land-based power plants.

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Motivation

Designing a Nuclear System for Space Efficiency

Reactor / Systems

- Integral PWR (in-vessel steam generators, pumps)
- steam generator
- Low-profile CRDM (control-rod drive mechanism)

Mechanism

- Fewer loops and pipes → smaller installation footprint
- Fewer pumps/rooms → lower weight

Key Performance Indicator

- Installation volume (m^3) ↓
- Shield mass (kg) ↓
- Maintenance headroom ↑

Core / Fuel

- LEU/HALEU fuel optimization
- BA/IFBA (integral fuel burnable absorber) for peaking/control optimization

Mechanism

- Lower core power peaking → reduced shielding demand
- Ensure shutdown margin (SDM)

Key Performance Indicator

- Shield thickness (cm) ↓
- Shield mass (t) ↓
- Engine-room space envelope (m^3) ↓

Shielding / Radiation

- Graded shield (low-Z → high-Z)
- Optimized placement on top / bottom / sides

Mechanism

- Select shielding criteria
- stabilize deck and accommodation dose
- Use local reinforcement to optimize total thickness

Key Performance Indicator

- Meet accommodation/work-area dose targets Minimize kg per m^2
- Minimize total shield mass (t)

Fuel handling & radioactive waste

- Minimize shared trunks and penetrations
- Temporary water shielding for maintenance openings

Mechanism

- Secure fixed hoisting paths → better maintenance access
- Reduce required structural reinforcement

Key Performance Indicator

- Installation volume (m^3) ↓
- Upper-level reinforcement mass (kg) ↓
- Plant availability ↑

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Motivation

The Importance of Shield Weight Ratio

Vessel (Country)	Total Weight (t)	Total Reactor System Weight (t)	Reactor Weight (t)	Shielding Weight (t)	Shielding-to-Reactor Weight Ratio	Shielding-to-Total Weight Ratio	Reactor System-to-Total Weight Ratio
NS Savannah (U.S.)	22,000	2,800	600	2,200	3.64 : 1	10%	12%
NS Otto Hahn (Germany)	16,870	3,000	480	2,520	5.25 : 1	14.9%	17.7%
NS Mutsu (Japan)	8,240	2,800	525	2,275	4.33 : 1	27.6%	33%
Arktika (Russia)	23,000	3,000	320	2,680	8.38 : 1	11.7%	13%

- Findings from past nuclear powered ship designs
  - The reactor system accounts for ~10–30% of total ship weight (the share is higher on smaller ships).
  - Shielding dominates reactor-system mass: typically, 3–8× the reactor weight, about 80–90% of the reactor-system total.
- Key Factors Determining Shielding Weight

Regulation

- The final mass and thickness of shielding are directly set by the regulatory target (the allowable dose limit).
- Stricter dose limits demand heavier shielding; adopting reasonable criteria (ALARA) is a key premise for light-weighting.

Material

- Even for the same protection performance, the choice of material can change shield mass and volume dramatically.
- Beyond traditional materials such as water, lead, and concrete, applying advanced, high performance-per-mass materials can be decisive for lightweight shielding.

Shielding carries significant weight and is highly regulated

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Motivation

Radiation Dose Regulations (International / ICRP)

❑ Three Basic Principles of Radiation Protection (ICRP Publication 103 paragraph 203)

Justification	Optimization of Protection (ALARA)	Dose Limitation
"Any decision that alters the radiation exposure situation should do more good than harm"	"Doses should all be kept as low as reasonably achievable, taking into account economic and societal factors"	"The total dose to any individual … should not exceed the appropriate limits"

❑ ICRP Publication 103 (2007)

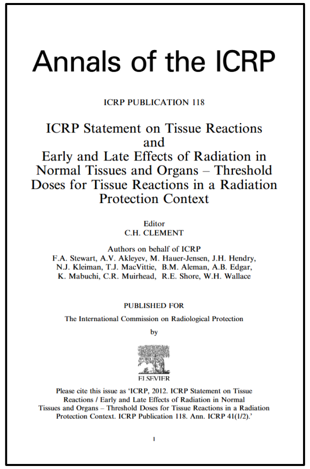
- ➢ Effective Dose : Limited to an **average of 20 mSv per year**, not exceeding **100 mSv over 5 years**, with a maximum of **50 mSv in any single year** * To manage the risk of stochastic effects such as cancer
- ➢ Equivalent Dose : **500 mSv/year for the skin**, **500 mSv/year for the hands and feet**
  * To prevent deterministic effects like skin burns and cataracts

❑ ICRP Publication 116 (2010)

- ➢ ICRP 116 provides updated conversion coefficients to translate measured external radiation (fluence) into doses absorbed by organs and effective dose.
- ➢ The coefficients account for different radiation types, energies, and exposure geometries.
- ➢ This publication replaces previous ones like ICRP 74 and reflects the latest science and methods for radiation protection dose assessment.

❑ ICRP Publication 118 (2012)

- ➢ Scientific evidence has shown that radiation-induced cataracts occur at a much lower threshold dose of about **0.5 Gy.**
- ➢ ICRP 118 recommended lowering the occupational equivalent dose limit for the lens to an average **of 20 mSv per year (100 mSv over 5 years, not exceeding 50 mSv in a single year)** * To prevent cataracts


Annals of the ICRP

ICRP PUBLICATION 118

ICRP Statement on Tissue Reactions and Early and Late Effects of Radiation in Normal Tissues and Organs – Threshold Doses for Tissue Reactions in a Radiation Protection Context

Editor
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▲ ICRP Publication 118

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Motivation

Radiation Dose Regulations (By Country)

Jurisdiction	Effective Dose (Annual Average / 5-year Total)	Effective Dose (Maximum in a Single Year)	Equivalent Dose-Lens of the Eye (Annual)	Equivalent Dose-Skin (Annual)	Equivalent Dose-Hands / Feet (Annual)	Fetal Dose (During Pregnancy)
ICRP Recommendations	20 mSv / 100 mSv	50 mSv	20 mSv (5-year Average)	500 mSv	500 mSv	Approx. 1 mSv
USA (NRC) * 10 CFR Part 20	50 mSv * Inconsistency with ICRP Recommendations (20mSv)	50 mSv	150 mSv	500 mSv	500 mSv	5 mSv
Republic of Korea (NSSC) * Act on Nuclear Safety	20 mSv / 100 mSv	50 mSv	150 mSv (Revision in progress)	500 mSv	500 mSv	2 mSv (Surface of the lower abdomen)
Japan (NRA)	20 mSv / 100 mSv	50 mSv	20 mSv (5-year Average)	500 mSv	500 mSv	1 mSv (Internal exposure)
France (ASN) * Council Directive 2013/59/EURATOM	20 mSv	20 mSv	20 mSv	500 mSv	500 mSv	1 mSv
Russia (Rostekhnadzor) * SanPiN	Based on ICRP (Annual Average 20 mSv)	50 mSv	Based on ICRP	500 mSv	500 mSv	Based on ICRP
China (NNSA) * GB 18871-2002	20 mSv / 100 mSv	50 mSv	150 mSv	500 mSv	500 mSv	Based on ICRP

* U.S Navy nuclear-powered vessels apply self-regulation, setting the annual dose limit at 2 rem (20 mSv/year)

Motivation

Radiation Dose Regulations (International / IMO)

❑ IMO CODE OF SAFETY FOR NUCLEAR MERCHANT SHIPS (A.491(XII)) (1981)

- An international safety code supplementing SOLAS Chapter 8, covering technical requirements for the design, construction, and operation of nuclear merchant ships, as well as emergency response and radiation protection standards

Category	Definition and Dose Limits
Controlled Area	An area subject to special radiation protection rules and access control. Workers in this area may receive more than 3/10 of the ICRP occupational dose limit (Exceeding **15 mSv** per year)
Supervised Area	An area requiring appropriate supervision for radiation protection purposes. Workers here may receive more than 1/10 of the ICRP occupational dose limit (Exceeding **5 mSv** per year)
Uncontrolled Area (General Area)	All areas of the ship not designated as a controlled or supervised area. Individuals in this area are not expected to exceed the ICRP recommended public dose limit (≤ **1 mSv** per year)

Uncontrolled Area (General Area)	Dose-equivalent rate
1. In the navigating bridge	0.75 μSv/h
2. In accommodation spaces	0.15 μSv/h
3. On upper deck and in cargo spaces	0.50 μSv/h
4. On ship's sides above the waterline	0.50 μSv/h
5. On ship's bottom, where "in water" maintenance or survey is contemplated	7.5 μSv/h

* Based on ICRP 26 (Using dose-equivalent rate as the standard)

❑ SOLAS CHAPTER VIII - NUCLEAR SHIPS (1992)

- Scope: Applies to all nuclear-powered ships (excluding warships)
- Key Provisions
  - ✓ Radiation Safety: Each government must ensure that crew, passengers, the public, waterways, food, and water supplies are not subject to **unreasonable radiation risk.**
  - ✓ Safety Assessment: The safety of nuclear installations and ships must be **evaluated**, with documentation **provided** in advance to the government of the port state.
  - ✓ Operating Manual: A **detailed manual** containing all information necessary for the safe operation of the nuclear installation must be carried onboard.
  - ✓ Surveys and Certificates: Nuclear ships must **undergo regular inspections** and be issued a Nuclear Ship **Safety Certificate**, including special requirements.
  - ✓ Special Control: Prior to and after entering port, ships must be subject to **special control** to verify valid certificates and absence of radiation hazards.

Motivation

Optimization of Radiation Protection Design Criteria

❑ Design Criteria: ICRP Recommendations and Research Approach

Category	Contents
ICRP Recommendation	Limited to an **average of 20 mSv per year**, not exceeding **100 mSv over 5 years**, with a maximum of **50 mSv in any single year**
Baseline Design	**20 mSv/yr: A conservative standard strictly applying current regulations**
Optimized Design	**50 mSv/yr: A rational standard applying the maximum value permitted by regulations**

❑ Feasibility of Applying the 50 mSv/yr Standard

- Occupancy Factor
  - ✓ The crew does not reside in high-dose areas 24 hours a day, and actual occupancy time is limited.
  - ✓ Even if the dose rate (mSv/h) in a specific area is somewhat high, the total annual exposure dose reflecting actual occupancy time can be sufficiently managed within the standard limits.
- Operational Flexibility of the Shipowner
  - ✓ The shipowner can actively manage exposure doses through operational procedures, moving beyond passive protection that relies only on fixed shielding.
  - ✓ Management Measures
    - (1) Work Management: Limiting work time in high-dose areas, utilizing remote equipment.
    - (2) Crew Management: Tracking individual exposure history, distributing cumulative dose through crew rotation.
    - (3) Area Control: Subdividing radiation zones within the ship and strengthening access control.

Proposal of a rational optimization method possible within current regulations

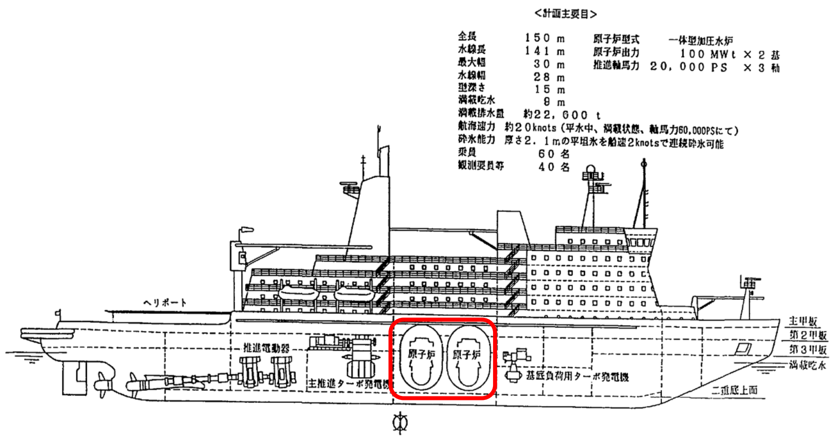
03

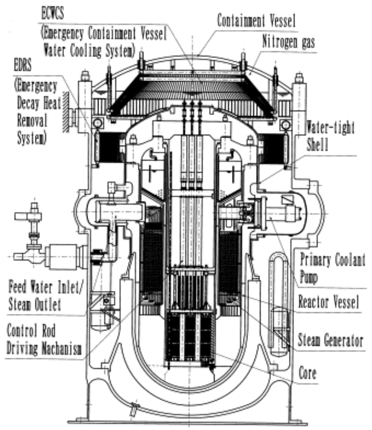
Methodology

Methodology

Select and Model Reference Reactor: MRX

- **MRX Conception**
  - Developer & timeline: JAEA pursued a next-generation marine reactor from 1983; issued the MRX concept design report in 1991, and conducted a four-year engineering design program in 1993–1996.
  - Marine application: Envisioned primarily for ship propulsion (e.g., icebreaker, container ship).
- **Rationale for Selection**
  - Chosen as a representative 100 MWth marine integral reactor (Integral PWR) design by JAEA, serving as a suitable reference model for this study's shielding analysis.
  - Its integral design, which places key components like steam generators inside the reactor vessel, presents unique radiological shielding challenges, making it a highly relevant case study for this analysis.





Parameter	Parameter	Specification
Reactor Type	Thermal Power	100 MWth X 2
	Reactor type	Integral type
Reactor Coolant	Core Inlet / Outlet T	297.5 / 282.5 °C
	Flow rate	4,500 t/h
	Refueling Cycle/Life of Fuel	4 Calendar Years (at 50% CF)/ 8 Calendar Years (at 50% CF)
	Operation Pressure	12 Mpa
Core/ Fuel	Fuel	UO_2 (Gd_2O_3)
	Av. linear heat flux/ Maximum linear heat rate	7.9 kWm^{-1} / 30.4 kWm^{-1}
	Fuel type/Moderator	UO_2/H_2O
	Fuel Av. burn-up	22.6 GWd t^{-1}
	Enrichment	4.3/2.5 (with Gd) wt%
	Core Equivalent Diameter	1.492 m
	Core Effective Height	1.4 m
	Number of Fuel Assembly	19 (Hexagonal)
	Number of fuel rods (Gd rod)	468(25) / 456(37)
	Fuel rod out. Dia	9.5 mm
	Pitch of assemblies/fuel rods	326 mm / 13.9mm (triangle)
	Clad Thickness	0.57 mm (zircalloy 4)
	Number of control rods	54 (per assembly / B_4C 90 %)
	Number of CRDMS	13 (In-Vessel type)
	Burnable poison material	Fuel rod with Gd_2O_3 and burnable poison rod of borosilicate glass

Methodology

Detailed shielding-zone criteria

Category	Location / Area	Distance from core center	Criterion	Conditions / Notes
During normal operation	Reactor compartment (outside containment vessel)	≈ 3.5 m	Not detectable (≤ 0.01 mSv/h) (20mSv/year ,2,000h)	Controlled area 48 h/week work basis (25mSv/year)
	Double bottom (below containment vessel)	≈ 3.2 m	Not detectable (≤ 0.05 mSv/h)	Controlled area 10 h/week work basis (26mSv/year)
	Engine room	≥ 4 m from outside of containment	Not detectable (≤ 0.006 mSv/h) (12mSv/year ,2,000h)	Supervised area 50 h/week work basis (15.6 mSv/year)
	Accommodation spaces	≥ 10 m	Not detectable (≤ 0.05 mSv/yr)	Unrestricted area; standard for unlimited annual occupancy
Major equipment integrity	Outer bottom shell (lowest part of hull)	≈ 5.4 m	Activation < 3.7×10^{-2} Bq/g	Limit activation due to core neutrons
	Reactor pressure vessel (inner wall)	≈ 1.85 m	Fast-neutron exposure ≤ 10^{19} n·vt	20-year life basis, E ≥ 1 MeV
	Inside containment vessel	≈ 2.0–3.4 m	Long-duration work permissible	After shutdown and reasonable cooldown
	Lower ship compartments	≈ 5.4 m	Unrestricted stay and repair work possible	After reactor shutdown
Shutdown & accident conditions	Control room / wheelhouse (accident)	–	100 mSv	–
	Around reactor (accident)	–	10 mSv	Well below typical mass public emergency guidance (~250 mSv)

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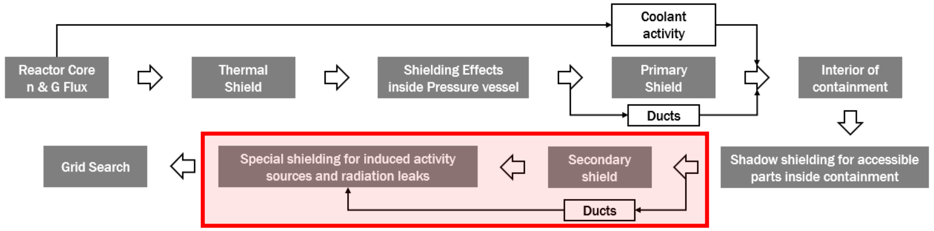
Methodology

Shielding Configuration (Water/Steel Shielding)

- **Design Objective**
  - Objective is to remove the existing bulky Secondary Shield for the compactness and weight reduction of the naval reactor.
  - Configure the shielding system using only water and steel instead of traditional lead and concrete.



- **Core Configuration**
  - Water-filled Containment Vessel
    - ✓ Fill the space inside the containment vessel with water, utilizing this water simultaneously as a shield (radiation attenuation, streaming prevention) and a passive safety system (core cooling during an accident).
  - Internal Steel Shield
    - ✓ Iron Shield: Installed between the core and the Steam Generator to shield high-energy neutrons.
    - ✓ Cast Steel Sahield: Installed in the water within the containment vessel to effectively shield secondary gamma rays, etc.

- **Main Effects: Successfully removed the secondary shield, drastically reducing the plant weight by approx. 50% and the containment vessel volume by approx. 70% compared to conventional shielding (while reactor power is 2.8 times larger).**

Shielding Target	Role of Water	Role of Steel
Neutron	• **Fast Neutron Slowing Down:** Effectively slows down (moderates) fast neutrons through elastic scattering with Hydrogen (H) atoms. • **Thermal Neutron Absorption:** Hydrogen (H) captures and absorbs the slowed-down thermal neutrons.	• **High-Energy (>10 MeV) Neutron Shielding:** Excellent for shielding high-energy neutrons that cause secondary system activation. • **Secondary System Activation Prevention:** The Iron (Fe) shield between the core and SG suppresses $^{16}O(n,p)^{16}N$ and $^{17}O(n,p)^{17}N$ reactions.
Gamma-ray	• **γ-ray Attenuation:** Attenuates gamma-ray energy through Compton Scattering. • **Accident Shielding:** Shields γ-rays from Fission Products released during an accident. • **Streaming Prevention:** Water fills vulnerable areas like the Air gap around the pressure vessel, preventing radiation leakage.	• **Primary γ-ray Shielding:** High-density steel effectively attenuates high-energy primary γ-rays emitted directly from the core. • **Secondary γ-ray Shielding:** Cast Steel within the containment vessel effectively shields secondary γ-rays generated from neutron capture. • **Post-Shutdown Dose Reduction:** Blocks post-shutdown γ-rays, reducing worker exposure during maintenance inside the containment.

Methodology

Weight and Thickness Minimization

- Source Term Definition: Set core-emitted neutrons and gamma rays as the source term, based on the MRX (Marine Reactor X) design.
- Optimization Variables: Set two key shielding layers, which have a dominant impact on shielding performance and total system weight, as variables.
  - Containment Flooding Water (Water, Layer 9), Cast Steel (Steel, Layer 10)
- Parametric Study: Calculate the dose rate outside the containment vessel for each case while varying the thickness of the two variables (Water, Steel).
- Optimum Point Derivation: Among the design combinations that satisfy the target dose rate of 20/50 mSv/year, derive the optimal design with the Lightest Weight and Thinnest Profile.

Order	Material		Density (g/cm3)	Main Features and Roles
1	**Core**	-	4.26	Radiation source (generates neutrons and primary γ-rays)
2	**Assembly basket**	Steel	7.85	Core internal structure
3	**Reflector and thermal shield**	Steel	7.28	Neutron reflector and thermal shield
4	**Support skirt**	Steel	7.85	Core support structure
5	**Primary water**	Water	0.756	Primary coolant, neutron slowing down (H) and shielding
6	**Pressure vessel**	Steel	7.85	Reactor pressure boundary, primary shield
7	**Air and insulator**	Air	0.0012	Thermal insulation gap between pressure vessel and external shield
8	**Steel**	Steel	7.85	5cm steel shield immediately after pressure vessel. Purpose is to reduce worker exposure inside containment post-shutdown
9	**Water**	Water	0.98	(Core of water-steel shield ①) • Neutron slowing down and absorption • γ-ray attenuation • Prevents radiation streaming (Streaming) through Air gap
10	**Cast steel**	Steel	7.85	(Core of water-steel shield ②) • Effectively shields secondary γ-rays generated from neutron capture in water • Placed in optimal position for shield weight minimization
11	**Water**	Water	0.98	Additional shielding for residual radiation after passing through Cast steel
12	**Containment vessel**	Steel	7.85	Final protection barrier (also serves as secondary shield)

Set Variables

Methodology

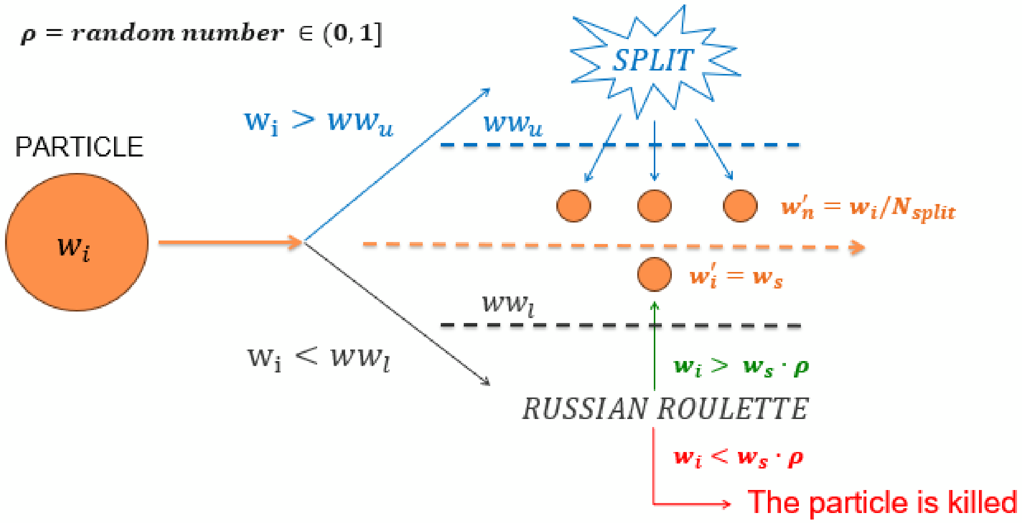
Deep Penetration Problem and Variance

- Mathematical Principle of Weight Window (WW) Technique: A technique that statistically controls the particle population (population control), saving important (detector-bound) particles and eliminating unimportant ones.
  - **WW Generation:** The Weight Window ($[ww_l, ww_u]$) for each space-time cell (*i*) is set to be proportional to the scalar flux ($\emptyset_i$) of that cell (Proposed by Cooper & Larsen).

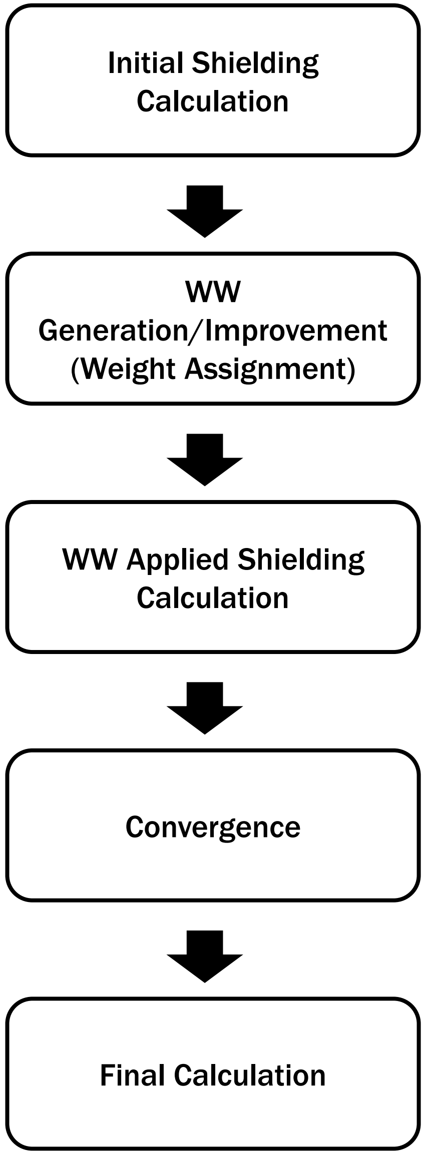
$$\overline{w}_j \propto \emptyset_j(r)\; ww_l = \frac{\overline{w_j}}{\rho} \; and \; ww_u = \overline{w_j} \cdot \rho$$

($\overline{w_j}$: WW center weight of cell, $[ww_l, ww_u]$: lower bound/upper bound , ρ: user-defined constant determining the window width)

  - WW Operating Principle (Particle Control): When a particle enters a cell, its weight (w_i) is compared with the WW.



Weight window scheme



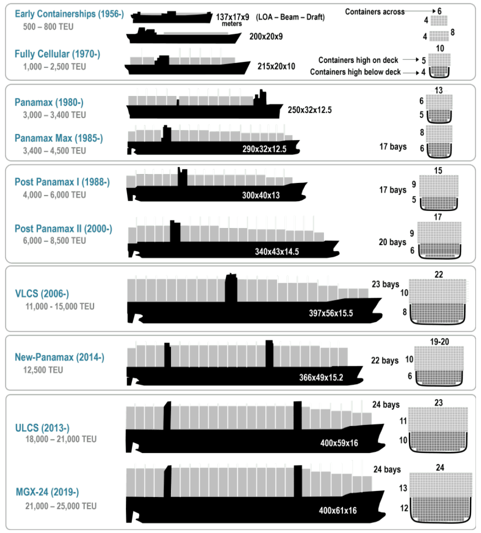
04

Results

Results

Derive Applicable Nuclear Powered Ship

Class	TEU Capacity boundary	Approximate dwt	Overall length [m]	Breadth [m]	Draught [m]	Design speed [kts]
Feeder/Feedermax	1,000-3,000	13,000-40,000	160-215	23-32.2	11.5	21.0
Panamax	3,000-5,100	40,000-65,000	215-295	32.2	12-13	23.0
Post/New-Panamax	5,100-18,000	65,000-165,000	272-365	42.8-50.8	12-15.5	23.0
ULCV	18,000+	165,000<	400	59-61.5	16-16.5	22.0



Target Shaft Power

$$P_{shaft} = \frac{89.2x^{0.91}}{10050^{0.91}+x^{0.91}}\ [\mathrm{MW}]$$

$$x = Vessel\ Capacity\ [TEU]$$

Electric motor to power conversion unit efficiency

$$P_{elec,prop} = \frac{P_{shaft}}{\eta_{drive}}\ [\mathrm{MW_e}]$$

$$\eta_{drive} = \eta_{gen} * \eta_{motor} = 0.95$$

Required Generator Output

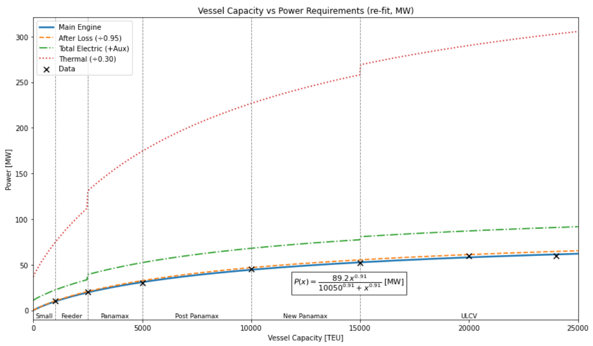
$$P_{total\_elec} = \frac{P_{elec,prop}+P_{aux}}{0.1(Margin)}\ [\mathrm{MW_e}]$$

Required Reactor Heat Output

$$P_{thermal} = \frac{P_{total_{elec}}}{\eta_{thermal}}\ [\mathrm{MW_{th}}]$$

$$\eta_{thermal} = 0.30$$

Class	Main Engine Power [MW_e]	Auxiliary Power [MW_e]	Total Power [MW_e]	Thermal Power [MW_{th}]
Feeder/Feedermax	2 - 19	5	7- 26	24 – 84
Panamax	16 – 32	5	21 – 37	73 – 130
Post/New-Panamax	32 – 59	7	39 – 66	136 – 231
ULCV	59 – 62	7	66 - 69	231 – 242



Class	ULCV
TEU Capacity	15,000 TEU
DWT	220,000 tons
L x B x D [m]	400 x 60 x 21
Design Speed	22 knots
Main Engine Power	$52MW_e$
Aux Power	$7MW_e$
Total Power	$200MW_{th}$

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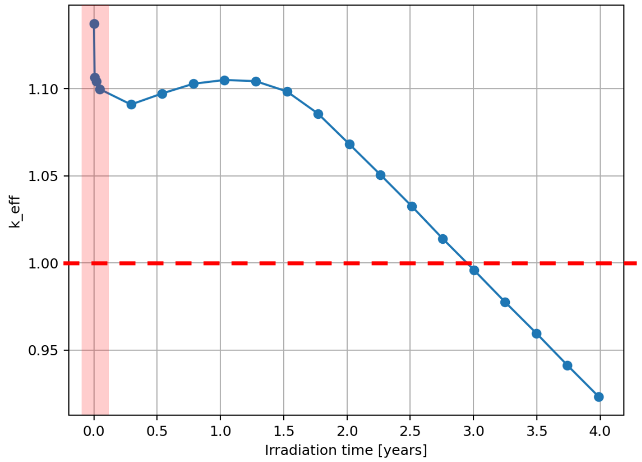
Results

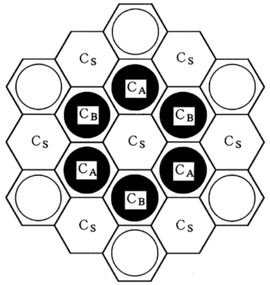
Deriving Refueling Cycles with EFPY

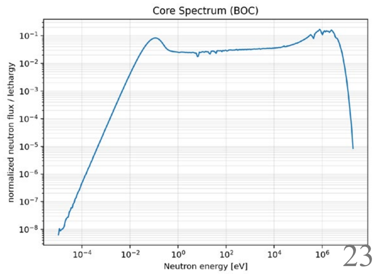
TEU Class	Rep. TEU	Avg. moves per call	Terminal productivity (moves/h)	Time alongside per call (h)	Representative route	Round-trip distance (NM)	Port calls per round trip	Annual sailing hours ($h \cdot yr^{-1}$)	Annual port hours ($h \cdot yr^{-1}$)	Annual maintenance ($h \cdot yr^{-1}$)	**Capacity Factor**
Feeder/ Feedermax	2,500	750	80	13.4	Intra-Asia	2,700	6	5,168	3,232	360	**0.59**
Panamax	4,500	3,000	100	34.0	Trans-Pacific	11,800	8	5,491	2,909	360	**0.63**
Post/New-Panamax	15,000	4,000	100	44.0	Trans-Pacific	11,800	8	4,982	3,418	360	**0.57**
ULCV	22,000	6,500	120	58.2	Asia–Europe	21,100	10	5,228	3,172	360	**0.60**

❑ Analysis of Synchronization between Refueling Cycle and 5-year Dry-docking Cycle

- Core design results
  - As a result of new core design based on MRX, the maximum potential lifetime (EFPY) of the core was confirmed to be 3 years (3 EFPY)
  - k_{eff} = 1.0 is reached at the 3-year point during continuous operation at full power (HFP, ARO)
- Disel Merchant Ship Capacity Factor
  - The cycle for Dry-docking and Special Survey for commercial ships is typically 5 years.
  - The actual average capacity factor (CF) of existing diesel-powered container ships (ULCV, Panamax, etc.) is approximately 0.60.
  - Therefore, this analysis applies a conservative operational scenario (CF 0.60) identical to that of diesel ships.
- Operating Cycle Calculation and Conclusion
  - Result: 3 EFPY (design core lifetime) / 0.60 (conservative CF) = 5.0 years
  - Satisfactorily achievable with margin, as merchant ships do not always operate at full power during transit.







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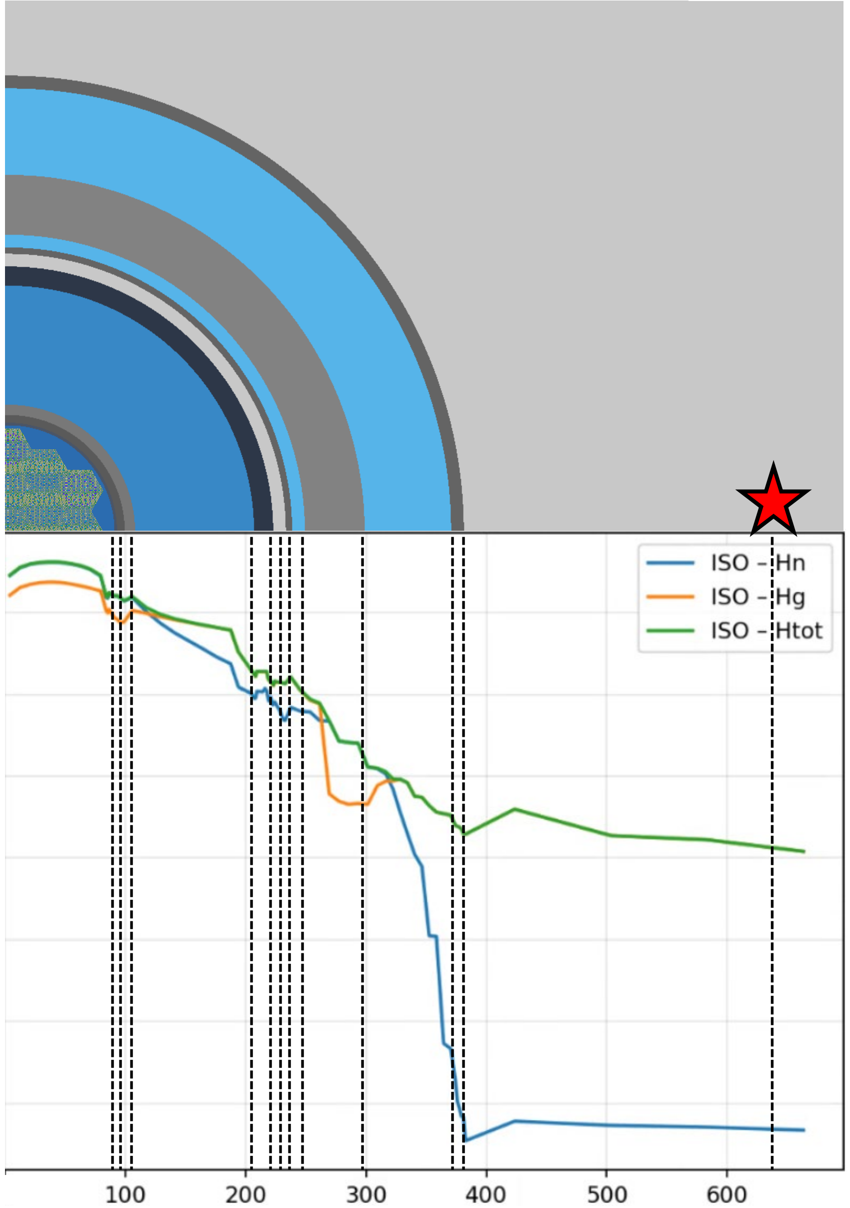
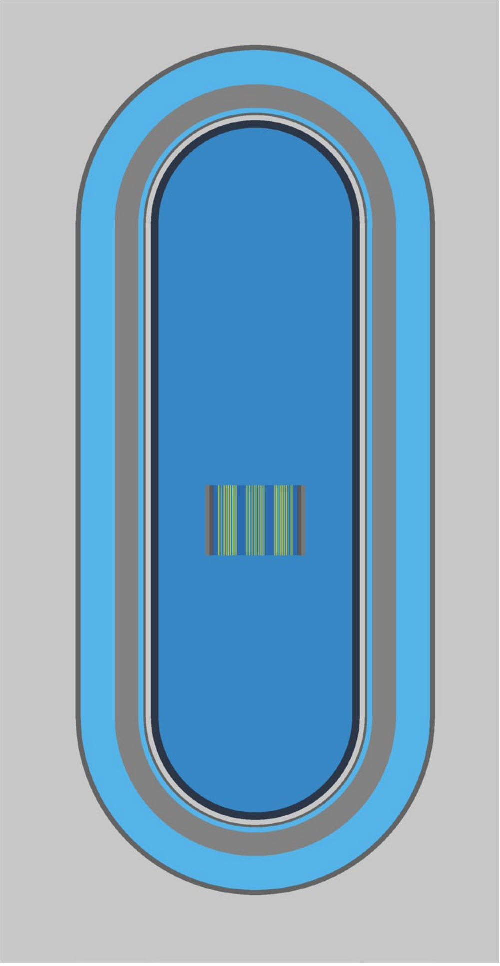
Results

Core & Shield Design Results

Order	Material		Thickness [cm]
1	Core	-	81
2	Assembly basket	Steel	2
3	Reflector and thermal shield	Steel	6.1
4	Support skirt	Steel	8.1
5	Primary water	Water	93.5
6	Pressure vessel	Steel	15.1
7	Air and insulator	Air	9.9
8	Steel	Steel	5
9	Water	Water	10
10	Cast steel	Steel	Variable
11	Water	Water	Variable
12	Containment vessel	Steel	10





Results

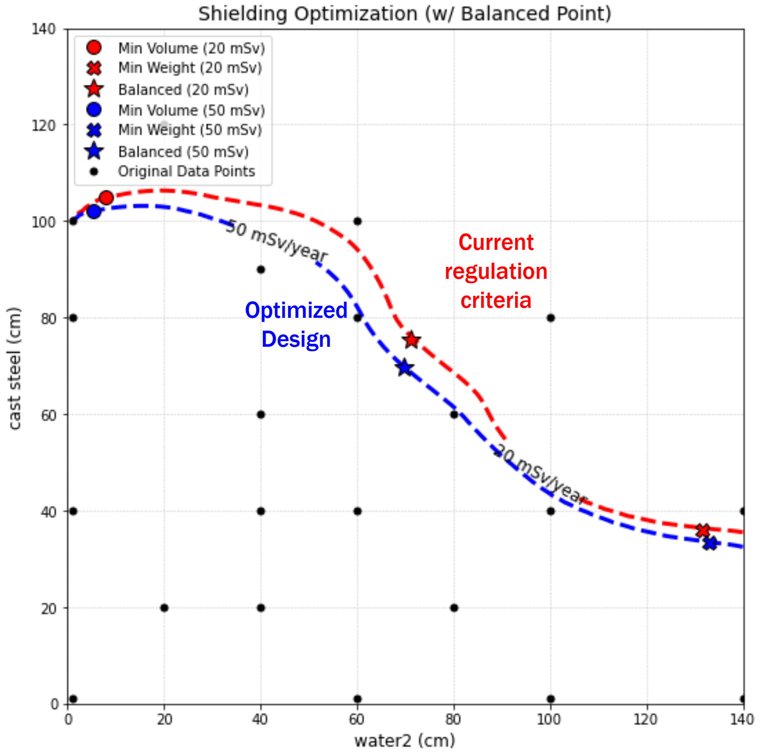
Shielding Results

❑ Results of Shield Thickness and Mass Variation (Engine Crew Basis)

* Radiation weighting factors from ICRP116 applied (DE/DF card input)
* Calculations based on Engine Crew, exposure for General Crew assessed by distance to verify compliance

Current Regulation	20 mSv/year (latest ICRP 103 standards)
Optimized Design	50 mSv/year

* Calculation based on Engine Crew criteria (3.5m)



Category	Total Dose (2,000hr)	Water 2 (cm)	Cast Steel (cm)	Total Thickness (cm)	Shielding Weight (t)	Reactor Weight (t)	Nuclear System Weight (t)	Shield-to-System Weight Ratio (%)
Min Thickness	20	12.3	102.7	274.7	1606.0	600	2206.0	72.8
Min Mass	20	134.1	35,8	329.6	1373.1		1973.1	69.6
Min Thickness	50	10.2	99.9	269.8	1534.1		2134.1	71.9
Min Mass	50	140.0	31.8	331.5	1320.6		1920.6	68.8
Optimization	20	59.7	80.3	299.7	1679.2		2279.2	73.7
Optimization	50	55.4	75.6	290.7	1525.0		2145.0	72.0

With Optimized applied: Shielding weight in the nuclear system reduced from 73.7% -> 72.0%

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Results

System and Ship-Level Impacts with Economics Assessment

❑ Physical Impact Following Design Criteria Change

- Total Shield Mass: 1,679.2 t → 1545.0 t
  - ✓ △DWT (Mass Reduction): 134.2 t
- Total Shield Thickness: 299.7 cm → 290.7 cm
  - ✓ Thickness Reduction: 9.0 cm
- Optimization Mechanism: Optimal point search via Grid search of water and steel

❑ Economic Conversion Process

- Mass to Cargo

$$N_{TEU,eff} = \lambda \times \frac{\Delta DWT}{\Delta W_{TEU}} = 3.83\$$$

$(\Delta DWT\text{:}\ \ 134.2,\ \lambda(Mass - Cargo\ Conversion\ Factor)\text{:}\ 0.3,\ W_{TEU}(Avg.Payload\ per\ TEU)$: **10.5t**)

- Cargo to Revenue

$$\triangle\ Revenue_{year} = N_{TEU,eff} \times r_{TEU} \times N_{boyages} = 3.83 \times (800 - 1500\ USD \times 10 times = 30{,}640 \sim 57{,}450\ USD$$

$(N_{TEU,eff}(Extra\ TEU)\text{:}\ 3.83\$,\ r_{TEU}$(**Avg. Revenue per TEU**): $800 \sim 1{,}500\ USD,\ N_{boyages}$(**Voyages per year**): **10**$times$

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05

Summary and Further Works

Summary and Further Works

Further Works

❑ Response to enrichment change (LEU → HALEU)

- Core becomes more compact and the spectrum hardens (fast fraction ↑) → moderation demand increases.
- Increase H-rich layer thickness by ~10–20% (maintain moderation margin).
- Keep the B-bearing layer (stabilizes capture of residual thermal neutrons).
- For the same thermal power (MWth), the required number of half-value layers (HVLs) for the high-Z γ layer is roughly unchanged.

❑ Shielding materials

* Units: H-atom density in 10^{22} cm^{-3}; ΣR/ρ in cm^2/g; ΣR, μ in cm^{-1}.

Aspect	**PE / BPE**	**ZrH_2**	**TiH_2**	**Concrete (normal)**	**Pb**
Neutron shielding	O	O	O	△	X
Gamma shielding	△	△	△	△	O
Pros	Very high H density easy blocks **B-doped (BPE)** boosts absorption	Superb moderation per volume non-flammable	High moderation per mass Light metal mounting	Cheap, buildable, structural	Excellent γ shielding mature supply
Cons	Flammable thermal/radiation aging	Dehydrogenation/ brittleness at high costly	Oxidation/dehydrogenation control density control	Thick sections; cracking chloride corrosion	Toxic; very heavy weak for neutrons
Recommended Placement	Basket outer **H-rich** layer penetration Liners	**Thin H-layer** near RPV where space is Tight	H-layer in **weight-sensitive** tops/Lines	Outer bulk/ structural fill	**Thin liner / part of high-Z stack**
Key data	ρ=0.94; H=8.07 ΣR/ρ=0.167 ΣR=0.157 μ/ρ=0.07262 μ=0.0683 HVL=10.15 cm	ρ=5.6; H=7.33 ΣR/ρ=0.0494 ΣR=0.277 μ/ρ=0.0664 μ=0.372 HVL=1.86 cm	ρ=3.76; H=9.25 ΣR/ρ=0.0683 ΣR=0.257 μ/ρ=0.0660 μ=0.248 HVL=2.79 cm	ρ=2.3; H=– ΣR/ρ=0.0455 ΣR=0.105 μ/ρ=0.06495 μ=0.149 HVL=4.64 cm	ρ=11.34; H=0 ΣR/ρ=0.0184 ΣR=0.208 μ/ρ=0.07102 μ=0.805 HVL=0.861 cm

Thank you