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Methodology for Establishing Radiation Protection Goals for Nuclear-Powered Ships: Radiation Target Levels Study

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1. Introduction

As global efforts to reduce greenhouse gas emissions continue, the International Maritime Organization (IMO) has announced its goal of achieving carbon neutrality in the maritime sector by 2050 [1]. Greenhouse gas emissions from maritime activities account for approximately 3% of global emissions, equivalent to about 1 billion tons. Most of these emissions originate from maritime transportation (such as container ships), leading to increasing interest in nuclear-powered ships as an alternative [2]. Nuclear-powered ships emit no greenhouse gases and offer significant economic advantages by enabling continuous operation for 20-30 years with a single fuel load [3].

However, operating a reactor within the confined space of a ship raises concerns about radiation exposure among crew members. Additionally, when transporting nuclear materials across international waters and docking at ports, ensuring thorough radiation shielding becomes critically important. Radiation shielding is essential not only for protecting crew members and the environment but also for maintaining the economic viability of the vessel. If the shielding materials are too bulky or heavy, they can negatively impact the economic efficiency of container ships. Therefore, it is crucial to implement a safe yet cost-effective shielding strategy that follows the ALARA (As Low As Reasonably Achievable) principle [4].

To maximize space utilization while ensuring economic shielding, a zoning approach was adopted, categorizing the ship into a Shielding Zone (SZ) and a Non-Shielding Zone (NSZ) based on the intensity of radiation shielding. SZ includes the reactor space and the shielding materials necessary to reduce radiation intensity to an acceptable level. Shielding in the SZ must be sufficient to eliminate the need for additional shielding in the NSZ. The NSZ encompasses all areas outside the SZ, including crew living spaces, where radiation exposure is managed primarily by controlling time, one of the three key shielding factors (time, distance, and shielding).

At this point, it is necessary to determine how low the radiation emitted from the SZ should be. We define this as the Radiation Target Level (RTL). RTL represents the amount of radiation released from the SZ to the NSZ, and it must be at a level that allows crew members to reside in the NSZ.

In this study, the target ship is a 15,000 TEU-class container ship. To determine the dose rate in each zone of this container ship, MCNP6 was used to model the ship, and fission neutrons and photons were propagated to generate a radiation map, allowing for the measurement of radiation levels and stay areas. Based on these values, the recommended RTL was derived as 10 μSv/hr, ensuring sufficient residence time in the accommodation area. This value of 10 μSv/hr serves as the RTL (equal to target shielding level) for the SZ.

To derive an appropriate RTL, factors such as radiation exposure limits and working hours must be considered. This, in turn, can serve as the foundation for shielding design guidelines and ship operation planning.

2. Material and Methodology

2.1 Target Ship Modeling

To analyze the impact of the reactor on radiation levels across different zones of a vessel, a 15,000 TEU-class container ship was selected as the reference ship. The ship was modeled by MCNP6 with a simplified structure, as shown in Figure 1, with dimensions of approximately 400 meters in length, 50 meters in width, and 30 meters in depth. The reactor was placed at the center of the ship, while the accommodation area was positioned at the bow to maintain distance from the reactor. Additionally, key structural components such as the water ballast tank, watertight bulkhead, and cofferdam were modeled to reflect the ship's design [5].

The complex curved surfaces at the ends of the vessel were simplified into flat surfaces, as their impact on radiation shielding was deemed negligible. Furthermore, structures without shielding capability, such as the lashing bridge and support bulkhead, were excluded from the model. To ensure conservative calculations, no containers were included in the model, eliminating any shielding effect they might provide. The ship's hull material was assumed to be stainless steel 304, and no additional materials were used [6]. The neutron and photon energy emitted from the reactor space was assumed to follow a Watt energy spectrum for fissions [7].

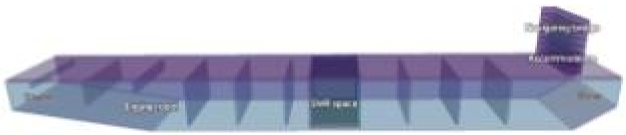

Fig. 1. Simplified nuclear-powered container ship 3D model from MCNP6

2.2 Shielding Zone(SZ) and Non-Shielding Zone(NSZ)

To achieve a shielding design that ensures both radiation safety and economic feasibility, the concepts of Shielding Zone (SZ) and Non-Shielding Zone (NSZ) were introduced. SZ includes the reactor and the area where shielding is implemented through shielding materials. NSZ refers to all areas of the ship excluding SZ, where the annual dose limit is met by adjusting the crew's residence time rather than relying on shielding materials. This approach is necessary because additional space occupied by shielding materials could interfere with the multi-layered modular container loading system, leading to economic drawbacks [8]. Moreover, it simplifies the ship's design.

In this study, the SZ is defined to include the reactor, the shielding structure surrounding the reactor, and the cofferdam, which serves as a protective structure for the propulsion system.

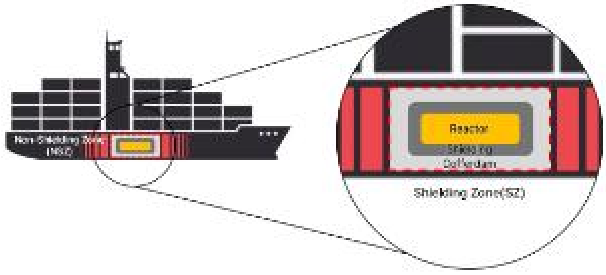

Fig. 2. Shielding Zone (SZ) and a Non-Shielding Zone (NSZ)

2.3 Meaning of RTL

Radiation Target Level (RTL) refers to the dose rate from the SZ to the NSZ and is determined by the shielding surrounding the reactor. A multilayered and robust shielding design can effectively reduce the RTL, ensuring that crew radiation exposure remains sufficiently low. However, excessive weight and volume of the shielding materials may compromise the economic feasibility of the ship.

Therefore, before designing the shielding, it is necessary to analyze the optimal level of shielding required to determine an RTL value that is neither too low nor too high. It is crucial to establish an RTL that allows crew members to work within the annual dose limit. In other words, RTL serves as a guideline for shielding design that both protects the crew and maintains the economic viability of the ship.

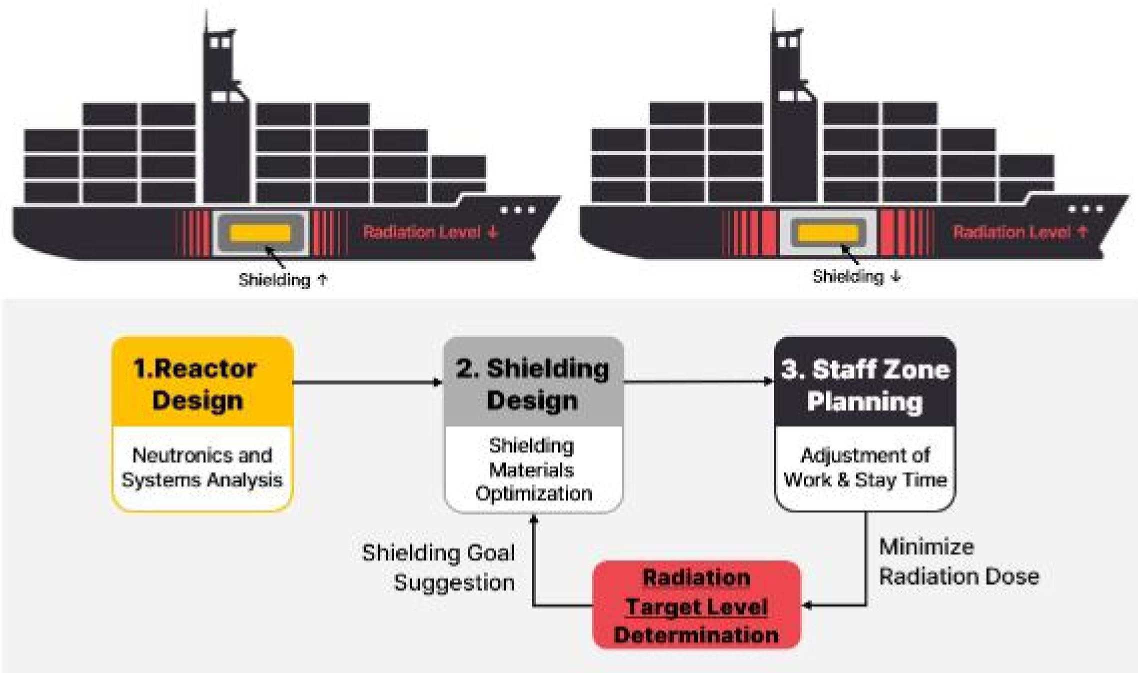

Fig. 3. Meaning and Role of RTL(Radiation Target Level)

2.4 RTL Study Process

The RTL Study is conducted before the reactor is installed on the ship to understand the relationship between radiation, the vessel, and the crew.

By simulating radiation on a modeled ship, it is possible to analyze crew radiation exposure. At this stage, the reactor is not present, and the SZ is assumed to be empty. The surface of the SZ is regarded as the radiation source—the point of RTL generation—allowing radiation to be distributed throughout the vessel. Measurement points are set in designated areas where the crew resides to assess dose rates in each zone.

This approach enables a sensitivity analysis of the radiation map by varying the scale of the RTL. In areas with high dose rates, the crew's residence time is adjusted accordingly, and the allowable residence time is calculated based on the RTL. The optimal RTL is then determined as the maximum RTL that still allows crew members to secure the minimum required residence time. This value serves as a target for shielding design.

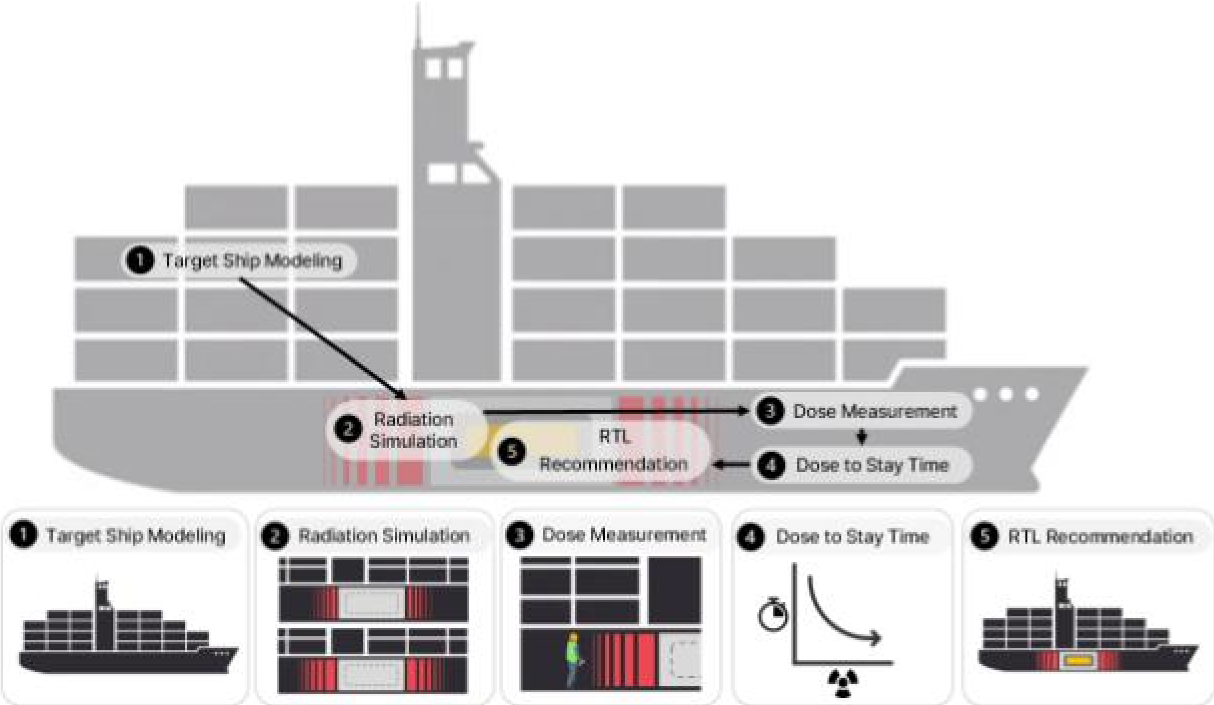

Fig. 4. RTL Study Process

3. Result

3.1 Determination of RTL Sensitivity Analysis Range

To analyze the radiation levels in different areas under varying RTL values, the RTL analysis range was first determined. The factors considered in selecting RTL included measurement locations and the annual radiation exposure limits specified by the International Commission on Radiological Protection (ICRP) [9]. The annual radiation exposure limit for the general public is 1 mSv, while the occupational exposure limit for radiation workers is a maximum of 50 mSv per year, with a five-year average limit of 20 mSv per year.

First, dose rates at the 2nd deck passenger way, the crew's nearest occupied area to the SZ, were evaluated. By assuming annual stay durations at this location, the required RTL values were determined to ensure compliance with general public and occupational exposure limits. Additionally, dose rates in the accommodation area, where crew members reside for extended periods, were analyzed under the assumption of continuous occupancy (24 hours per day, 365 days per year). This analysis was conducted for both general public and occupational exposure scenarios, resulting in four cases, as summarized in Table I.

Case 1 and 2 assume that crew members make a round trip through the 2nd deck passenger way—particularly a 30-meter section next to the SMR space—ten times per day, leading to an annual stay time of 50.7 hours. To meet the general public exposure limit (1 mSv/year), an allowable dose rate of 19.7 μSv/hr is required, corresponding to an RTL of 22.7 μSv/hr. For the occupational exposure limit (20 mSv/year), the permissible dose is 394 μSv/hr, with an RTL of 455 μSv/hr.

Case 3 and 4 Assume that crew members continuously reside in the accommodation area (24 hours per day, 365 days per year, totaling 8,760 hours annually). To meet the general public exposure limit, the required dose rate is 0.114 μSv/hr, with an RTL of 10.3 μSv/hr. For occupational exposure, the limit is 2.28 μSv/hr, with an RTL of 205 μSv/hr.

To simulate radiation emission from the SMR, a rectangular source corresponding to the cofferdam structure was modeled. The simulation was conducted using the Monte Carlo N-Particle Transport Code (MCNP6), employing a Watt energy spectrum for fission neutrons. MCNP6 is a probabilistic particle transport code that enables precise neutron, photon, and electron transport analysis [7].

Table I. Determining Range of RTL Sensitivity Analysis

Case	Measurement area	Stay time (hr/yr)	Exposure limit (mSv/yr)	Dose rate at measurement area (μSv/hr)	RTL (μSv/hr)
1	2nd deck passenger way	50.7	1	19.7	22.7
2			20	394	455
3	Accommodation	8760	1	0.114	10.3
4			20	2.28	205

3.2 Radiation Map Sensitivity Study

A radiation map was generated and sensitivity analysis was conducted for RTL values ranging from 1 to 500μSv/hr. Dose rates were measured at seven key locations, selected based on five measurement points specified in IMO A.491 for radiation limits across different areas of a ship, along with two additional locations considering crew occupancy [10].

Table II. Measurement Area in Container Ship

Area	Color	Contents
Navigating bridge		IMO A.491 requirements
Accommodation		
Upper deck		
Sides above waterline		
Bottom		
Engine room		Crew stay consideration
2nd deck passenger way		

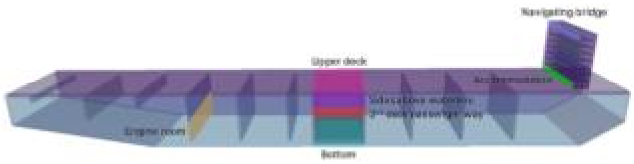

Fig. 5. Measurement Areas in Container Ship

The relationship between RTL, dose rate, and stay time was analyzed using eight RTL values: 1, 5, 10, 20, 50, 100, 250, and 500 μSv/hr. As RTL increases, dose rate rises, and allowable stay time decreases. The data was visualized in Fig. 6., where each line represents a different measurement area. The stay time calculations followed these equations:

Stay time (Public) = 1 mSv/year ÷ Dose rate (μSv/hr)

Stay time (Occupational) = 20 mSv/year ÷ Dose rate (μSv/hr)

Areas with similar distances from the SMR space, such as the bottom and sides above the waterline, exhibited comparable dose rates, resulting in overlapping data points on the graph. The same pattern was observed for the upper deck and the 2nd deck passenger way.

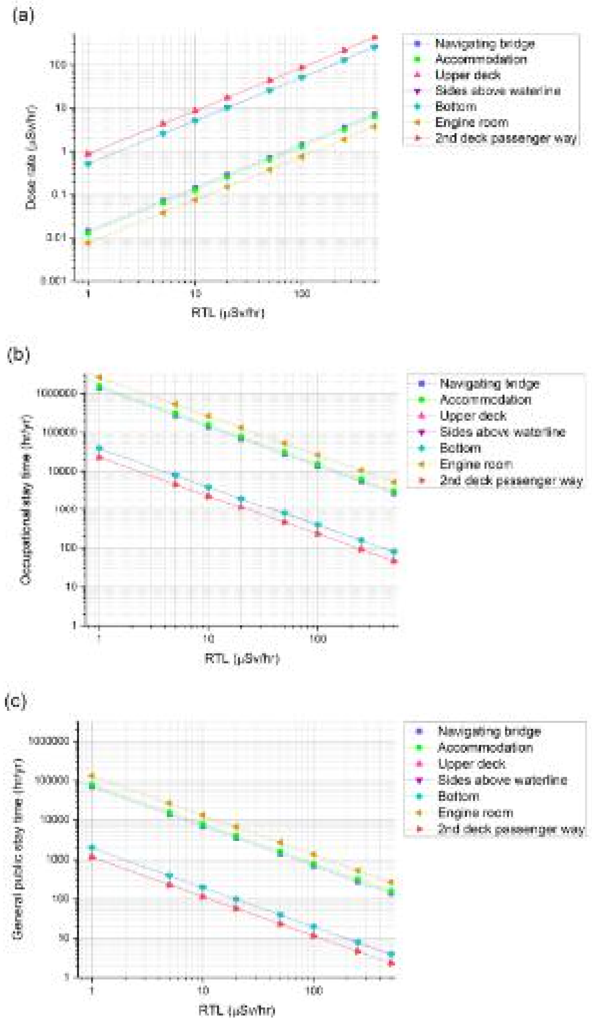

Fig. 6. (a) Dose Rate, (b) Occupational Stay Time, (c) General Public Stay Time by Area According to RTL

Based on the numerical results presented in these graphs, the next step is to determine the appropriate RTL by considering radiation exposure limits, working hours, and operational constraints.

3.3 RTL Recommendations

To determine the appropriate RTL based on the previously calculated dose rate and stay time, several additional factors must be considered. For instance, it is necessary to decide whether the crew operating a nuclear-powered vessel should be classified as radiation workers or general public workers. This decision is crucial in selecting the appropriate annual dose limit specified by the ICRP. Additionally, it must be determined whether to adhere to the dose rate limits for different zones as outlined in Appendix 4 of IMO A.491, which was referenced for selecting measurement locations. Although this document specifies radiation limits, it was published in 1981, making it outdated and not reflective of advancements in technology or safety philosophy.

The following assumptions are considered reasonable for deriving an appropriate RTL. While nuclear vessel crew members could be classified as either radiation workers or general public workers depending on their roles, managing different dose limits for workers sharing the same space would be challenging. Therefore, it is assumed that all crew members must comply with the general public dose limit. The radiation dose limits presented in IMO A.491 are highly conservative, and since the basis for these limits is unclear, this study suggests revising these values based on the calculated results.

Additionally, the RTL for the crew's living quarters should be set to ensure that they can reside in these spaces continuously for 8,760 hours per year. In order to operate the ship, crew members must be able to stay in designated work areas for 2,080 hours per year, based on the Seafarers' Act, which stipulates 8 hours per day and 40 hours per week [11]. These work areas include the navigating bridge and engine room. The minimum required stay duration for each measurement area can be regulated based on the derived RTL and the corresponding dose rate.

Table III. Classification of Areas by Purpose and Minimum Stay Time (RTL Setting Conditions)

Area		Stay time (hr/yr)	Contents
Living Area	Accommodation	8,760	Year-round residence
Work Area	Navigating bridge	2,080	8 hours per day and 40 hours per week
	Engine room		
Others	Upper deck	Stay time determined based on the RTL derived from the above time conditions	
	Sides above waterline		
	Bottom		
	2nd deck passenger way		

The RTL satisfying all these assumptions corresponds to 10 μSv/hr, and the dose rate and stay time for each area under this RTL are shown in the following figure. The allowable annual stay time in the accommodation area is 9,010 hours, which is sufficient. The annual stay duration in the navigating bridge is 6,410 hours, significantly exceeding the required 2,080 hours per year. The stay time in the 2nd deck passenger way is 115 hours, allowing for an average of 22.7 crossings per day, assuming an average round-trip time of 50 seconds for a 30-meter section. For other areas, appropriate working hours can be assigned based on the calculated stay duration to ensure low radiation exposure.

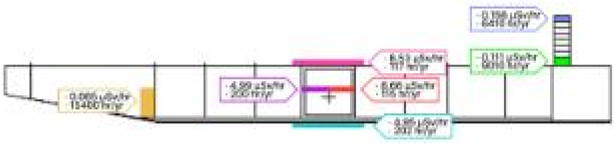

Fig. 7. Dose rate and Stay Time at 10 μSv/hr of RTL

4. Conclusions

As part of efforts to achieve carbon neutrality in the maritime sector, this study aims to establish an exposure management plan that minimizes radiation exposure for crew members while enhancing the economic feasibility of nuclear-powered ships. Using MCNP6. This study was conducted to determine how low the RTL must be to achieve this goal.

A range of RTL values from 1 to 500 μSv/hr was analyzed to encompass both the most optimistic and conservative scenarios. For each RTL value, the dose rates in different zones and the allowable stay times were calculated. Based on this data, an appropriate RTL was determined by considering the key assumptions and factors necessary for radiation management planning. All crew members onboard the vessel were classified as members of the general public, and an annual dose limit of 1 mSv was applied. The appropriate RTL was selected based on the assumption that crew members would stay in the accommodation area for 8,760 hours per year and in the navigating bridge and engine room for 2,080 hours per year. The RTL values that satisfied the stay-time requirements for each zone were calculated as 10 μSv/hr.

In this study, to ensure a conservative assessment of radiation exposure, certain ship structures that could function as shielding were omitted from the model. Additionally, measurements were taken at the surface closest to the crew in each zone. Furthermore, all crew members were assumed to be members of the general public, applying a lower dose limit. As a result, the dose rates and RTL measured in this study represent conservative values. Therefore, if economic feasibility is prioritized through discussions with shipowners, an alternative approach could involve classifying crew members on nuclear-powered vessels as radiation workers. In this case, the occupational exposure limit of 20 mSv per year could be applied. This adjustment would allow for an increased RTL, reducing the weight and volume of shielding structures.

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REFERENCES

[1] Ruikai Sun, “A comprehensive analysis of strategies for reducing GHG emissions in maritime ports,” Marine Policy 171, Marine Policy (2025).
[2] Rustam Abubakirov, Ming Yang, Giordano Emrys Scarponi, Valeria Casson Moreno, Genserik Reniers, Towards risk-informed design and operation of ammonia-powered ships: Critical aspects and prospective solutions, Ocean Engineering 314 (2024) 119753.
[3] S.E. Hirdaris, Y.F. Cheng, P. Shallcross, J. Bonafoux, D. Carlson, B. Prince, Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion, Ocean Engineering 79 (2014) 101-130.
[4] ICRP, “Scope of Radiological Protection Control Measures,” ICRP Publication 104. Ann. ICRP 37 (5), (2007).
[5] Yong Hwan Yoo, Han Koo Jeong, Wooseong Park, Soo Hyoung Kim, Yong Hoon Jeong, Study on the seawater cooled PRHRS of a nuclear propulsion ship with the upper heat exchanger for driving force and the seawater heat exchanger as an ultimate heat sink, International Journal of Naval Architecture and Ocean Engineering 16 (2024) 100588.
[6] McConn Jr, R.J., “Compendium of Material Composition Data for Radiation Transport Modeling,” National Technical Information Service: Springfield, (2011).
[7] Los Alamos National Laboratory. “MCNP Code Version 6.3.1 Theory & User Manual,” Los Alamos National Laboratory, (2024).
[8] Christine Natalia, Michael Holine, Agustinus Silalahi, A simultaneous container assignment and ship scheduling optimisation model in container shipping, The Asian Journal of Shipping and Logistics 37 (2021) 213-219.
[9] ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4).
[10] International Maritime Organization (IMO). “Code of Safety for Nuclear Merchant Ships,” Resolution A.491, (1981).
[11] Seafarers’ Act, Act No. 12844, Article 60 (Korea Ministry of Government Legislation, 2014).