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Radiation Dose Evaluation for Crew members in Nuclear-Powered Ship under Severe Shield Degradation Scenarios

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1. Introduction

The global shipping industry accounts for approximately 3% of total global CO_2 emissions, representing a significant contribution to greenhouse gas emissions. Among various vessel types, container ships contribute the dominant share of maritime emissions due to their high engine power demand and long-distance operational profiles. In response, International Maritime Organization (IMO) has established a strategy targeting net-zero greenhouse gas emissions by 2050. Although operational efforts such as hull-form optimization, resistance minimization, and low-speed operation have been widely adopted to reduce fuel consumption, these approaches remain insufficient to achieve the long-term decarbonization targets.

Therefore, a fundamental transition in the primary energy source from fossil fuels to nuclear power has been considered a viable solution for achieving this goal. Among various reactor types, the Molten Salt Reactor (MSR) has gained increasing attention for marine propulsion applications. MSR-powered ships offer several advantages, including high-speed, long-endurance operation enabled by high power density and inherent safety characteristics. Unlike a Pressurized Water Reactor (PWR), the molten salt used as the primary coolant in an MSR can be maintained as liquid from 500℃ to 1400℃ without pressurization. Similarly, the nuclear primary coolant, the fuel is also presented as molten salt without pressurization. Consequently, conventional core-meltdown accidents that may occur in PWRs are inherently improbable in MSR. Additionally, as a carbon-free energy source, MSRs contribute to reducing greenhouse gas emissions. Moreover, by utilizing a fast-neutron spectrum, long-distance operation is feasible, enabling up to 25 years of continuous operation without refueling.

However, unlike land-based nuclear power plants, nuclear-powered ships operate in a more dynamic and uncontrolled maritime environment, as they are not confined to fixed geographical coordinates. The maritime environment presents a broader spectrum of external hazards, including severe weather conditions, grounding, and vessel-to-vessel collisions. In addition, external emergency support may not be readily available at sea. During the initial hours to days following an incident, the crew must rely solely on onboard system and available equipment until external rescue or support teams arrive. Among various maritime accident scenarios, ship-to-ship collisions represent one of the most probable initiating events. [1]

2. Scenario and Results

2.1 Ship Structure Overview

The objective of this study is to evaluate whether radiation exposure to crew members remains within acceptable limits even under an extreme collision scenario involving a small modular reactor (SMR)-powered vessel. This study specifically considers a ship-to-ship collision scenario. The fundamental structural configuration of a nuclear reactor installed on a container ship is illustrated in Figure 1. All structural components include internal void spaces designed to enhance energy dissipation and improve impact mitigation performance. However, this study assumes that the collision-absorbing function of the cofferdam fails during the ship-to-ship collision. Consequently, all shielding structures except for the outermost Advanced Reduced-Activation Alloy (ARAA) are assumed to be failed. Under this assumption, the cofferdam is excluded from the MCNP shielding analysis.

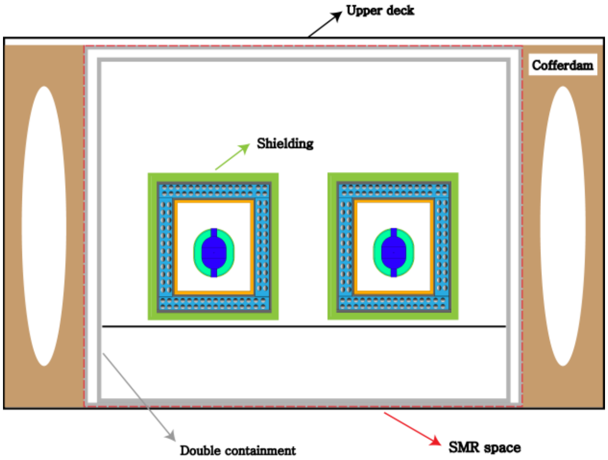


Fig. 1. Schematic cross-sectional configuration of the MSR compartment within the ship

For dose assessment, crew members are assumed to be located within the accommodation space shown in Figure 2. It is located at the aft upper deck of the vessel. The reactor module is in the lower central region of the ship. The effective dose rates are therefore evaluated at the accommodation space, representing a conservative yet realistic crew occupancy scenario.

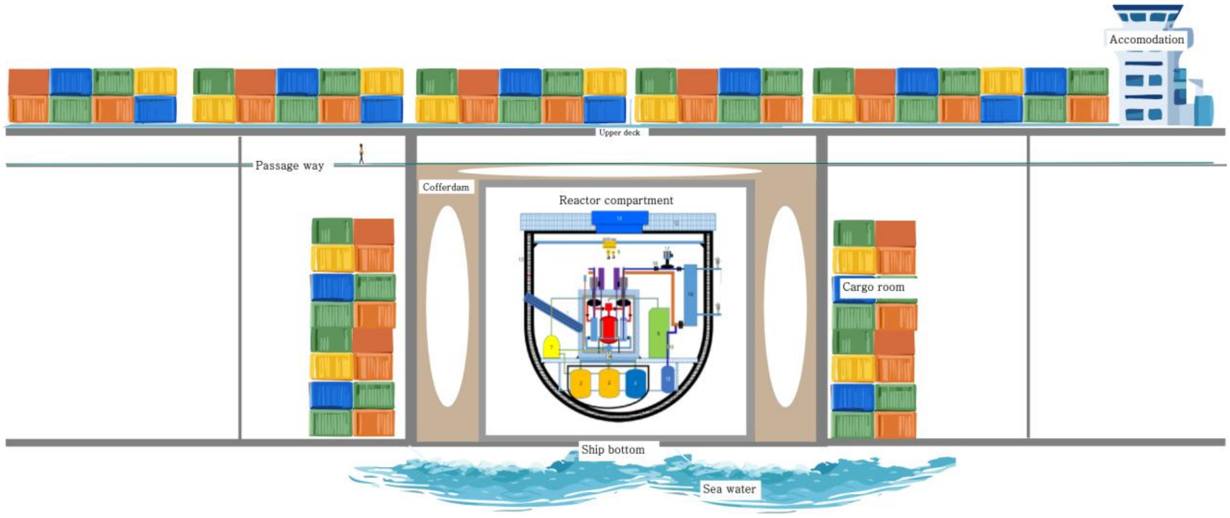


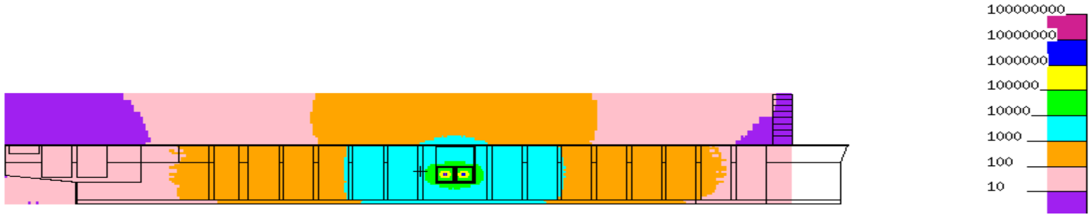
Fig. 2. Schematic side view of the nuclear-powered container ship

2.2 Scenarios

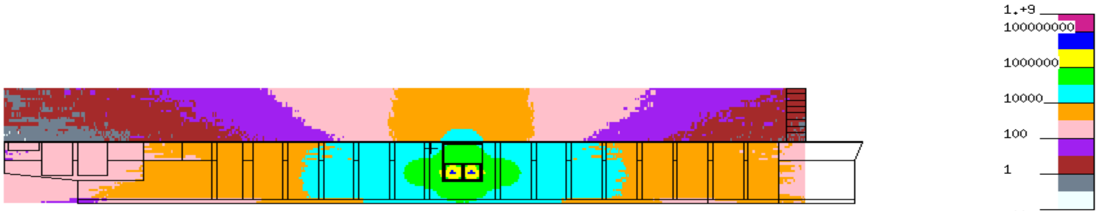
The accident scenario considered in this study involves a 15,000 TEU container vessel equipped with a 200 MWt K-MSR propulsion system, originally operating at a cruising speed of 25 knots (46.3 km/h) along a trans-Pacific route from Busan to San Francisco [2]. The total voyage distance is approximately 9,862 km. A ship-to-ship collision is postulated to occur near the midpoint of the voyage, leaving about 4,900 km remaining to the nearest accessible port, San Francisco. All shielding structures except for the outermost Advanced Reduced-Activation Alloy (ARAA) are assumed to fail under the collision scenario.

In Case 1, failure of the emergency power system is assumed. Consequently, the reactor continues operating at 20% of its nominal thermal power to provide minimum propulsion capability. Under this reduced-power condition, the vessel proceeds at 5 knots (9.26 km/h) toward San Francisco without external assistance. At a constant speed of 5 knots, and assuming no additional delays due to weather or navigational interference, the time required to traverse the remaining 4,900 km is approximately 529.16 hours. Because the reactor remains in low-power operation, two primary radiation sources are considered: neutron radiation and neutron-capture gamma radiation. The total effective dose to crew members is then obtained by multiplying the combined effective dose rate by the travel time of 529.16 hours.

In case 2, the emergency power system is assumed to function properly. According to the *Nuclear Ship Safety Handbook* published by MIT in October 2025 [3], emergency power systems on nuclear-powered vessels are not intended to provide propulsion capability. Instead, they are designed to ensure safe reactor shutdown, maintain essential safety functions, protect crew members, and minimize uncontrolled drifting of the vessel. The handbook specifies that the emergency power system should be capable of sustaining essential functions for 30 days while awaiting governmental

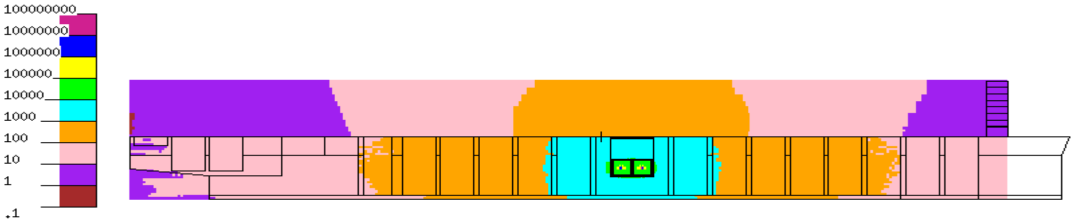


(a) Neutron dose rate distribution calculated using MCNP ($\mu Sv/hr$)

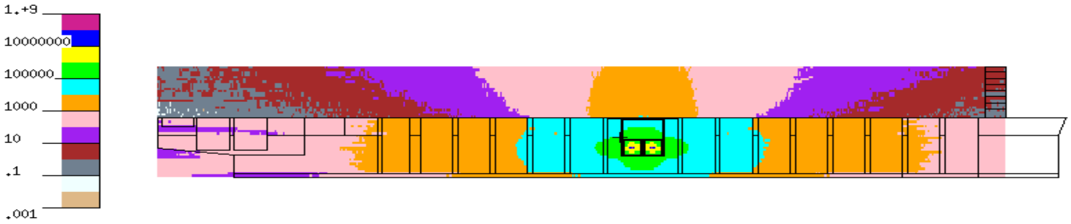


(b) Neutron-capture gamma rate distribution calculated using MCNP ($\mu Sv/hr$)

Fig. 3. Radiation dose rate during reduced-power operation (Case 1)



(a) Total neutron effective dose



(b) Total neutron-capture gamma effective dose

Fig. 4. Total effective dose by ship compartment for Case 1 (mSv)

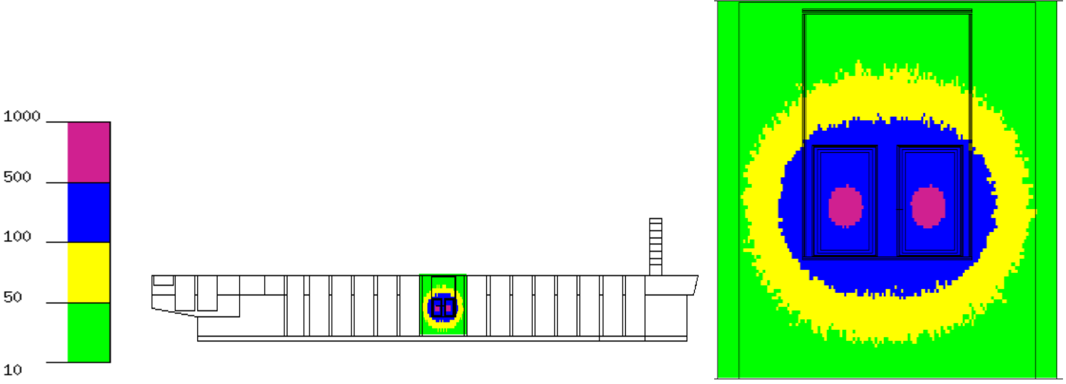


Fig. 5. Radiation dose rate during reduced-power operation for Case 2 ($\mu Sv/hr$)

response and external assistance. Under shutdown conditions, the dominant radiation source is decay gamma radiation. The effective dose rate associated with the decay gamma source term is calculated using MCNP. The total effective dose to crew members is then obtained by multiplying the effective dose rate by the 30-day exposure period.

2.3 Results

For case 1, 20% of reactor power is produced, affecting accommodation space with neutron radiation and neutron capture gamma radiation. The neutron dose rate is calculated as 6.831 $\mu Sv/hr$ while the neutron-capture gamma dose rate is calculated as 8.68 $\mu Sv/hr$. Figure 3 shows the illustration of both neutron and neutron-capture gamma dose rate in $\mu Sv/hr$ for Case 1. The combined dose rate is 15.511 $\mu Sv/hr$. Multiplying the period of 529.16 hours, the total effective dose rate for crew members is 8.207mSv as shown in Figure 4. For case 2, as emergency power is operated, the reactor is shut down and Shut Down Dose Rate (SDDR) is calculated from accommodation space. The decay gamma source term used for the SDDR calculation was evaluated by KAERI based on the assumption of 30 years of operation at 90% full power, followed by a 12-hour cooling period [4]. After 12 hours of reactor shutdown, fission reactions cease entirely. In Figure 5, the gamma dose rate at the outermost boundary of the reactor module, corresponding to the ARAA shielding layer, is 580 $\mu Sv/hr$. As the radiation propagates through the ship-side structural barriers, the attenuated gamma dose rate decreases to 10.43 $\mu Sv/hr$. No measurable gamma dose rate is detected at the accommodation space, indicating that the remaining structural distance provides sufficient additional attenuation.

3. Conclusion

The calculated cumulative effective dose at accommodation space is 8.21 mSv in Case 1, and no measurable gamma dose rate is detected in case 2. Both values are significantly below the ICRP recommended annual occupational dose limit of 50 mSv. Therefore, even under the conservatively assumed extreme collision and shielding failure conditions, the projected radiation exposure to crew members remains within acceptable regulatory limits.

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