

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

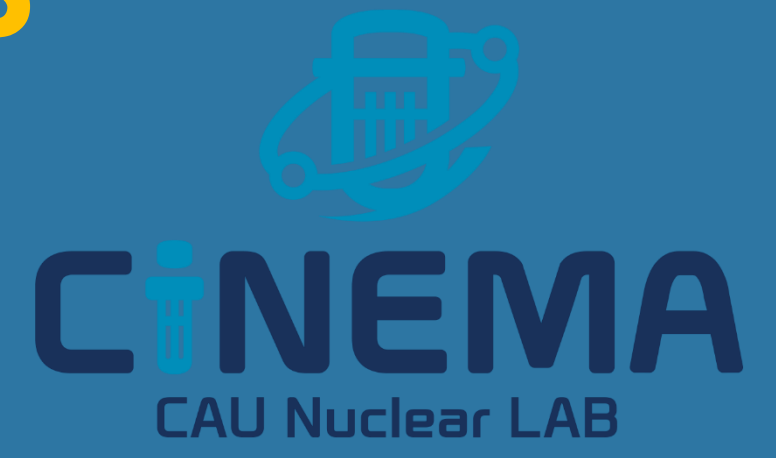


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INTRODUCTION

In response to the IMO's 2050 net-zero targets, the maritime industry is transitioning to alternative propulsion systems, including nuclear-powered vessels. Among them, molten salt reactors (MSRs) are promising due to their high-power density and inherent safety. However, unlike land-based plants, **nuclear ships operate in dynamic maritime environments** with potential external hazards and delayed emergency support. Therefore, this study evaluates **whether crew radiation exposure remains within acceptable limits under an extreme collision scenario involving an SMR-powered vessel.**

ANALYSIS & METHODS

Experimental Ship Model & Accident Scenario

A 352 m × 51 × 32.6 m container ship (15,000 TEU) with **two 100 MWt reactors (total 200 MWt)** is considered.

A ship-to-ship collision occurs near the middle of the Busan–San Francisco route, **damaging both primary and secondary shielding of the reactor.**

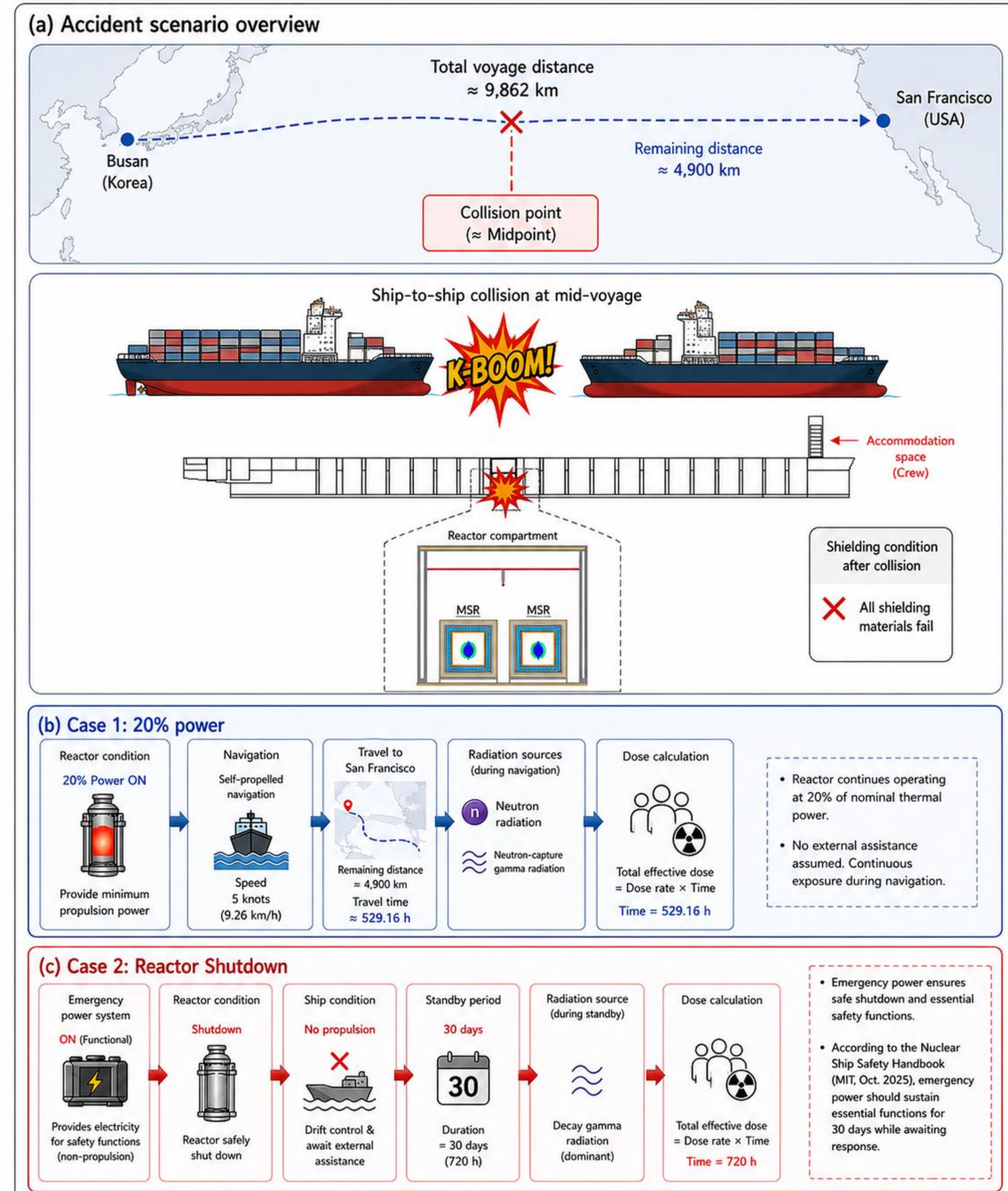
Case 1: 20% Power

Emergency power fails, and the reactor operates at 20% power while the ship moves toward the nearest land.

Case 2: Emergency Power

Emergency power is available, the reactor is shut down, and the ship drifts for up to 30 days awaiting rescue.

<Fig.1. Schematic overview of severe shield degradation scenarios>

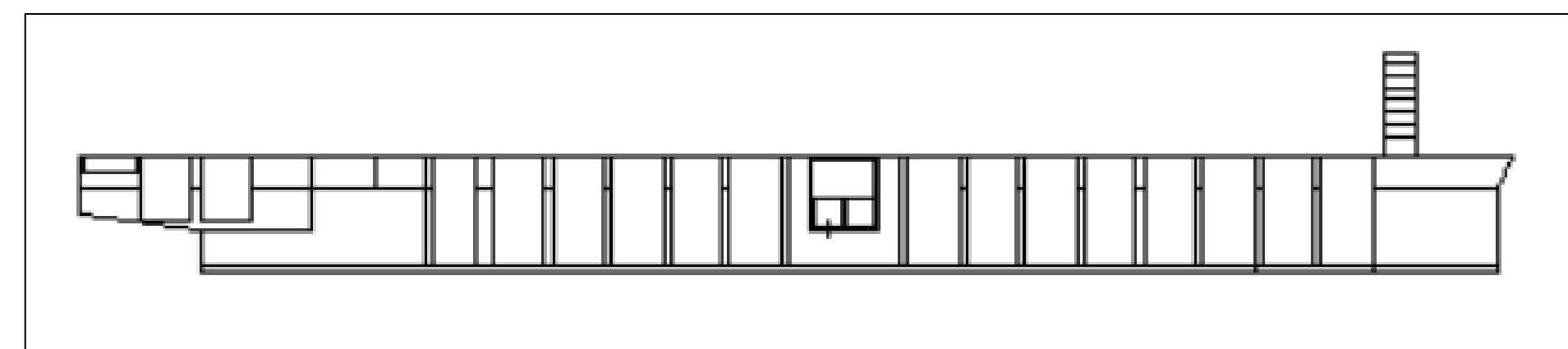


Code Description

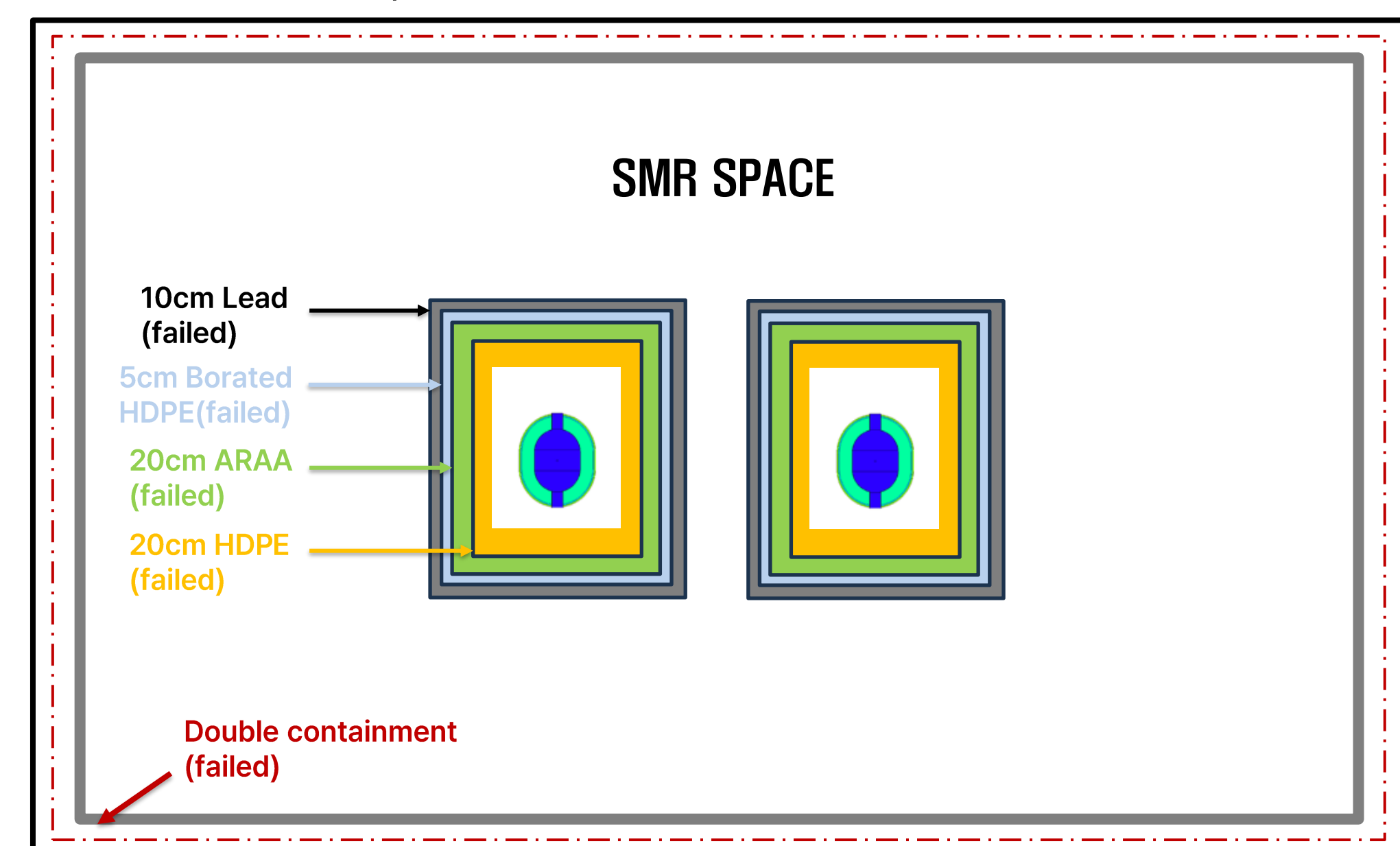
- The radiation transport analysis was performed using the MCNP code with continuous-energy cross-section data from the lib81 library, based on ENDF/B-VIII.0.
- Effective dose rates were evaluated using appropriate tally functions, and case-dependent FM multipliers were applied to convert particle flux into effective dose rate.

- The geometry was simplified by neglecting minor structural details while preserving the key features affecting radiation transport.
- Effective dose was evaluated using energy-dependent fluence-to-dose coefficients from ICRP 116 (AP geometry).
- The insulator layer and thermal shield (water+steel mixture) between the reflector and borated-HDPE are assumed to remain intact.
- The reactor configuration and the shutdown dose rate (SDDR) for Case 2 were evaluated based on the methodology presented in the KAERI study.
- The statistical uncertainty of all results was maintained below 5%.

<Fig.2. Simplified geometry model of the containership used for simulation>

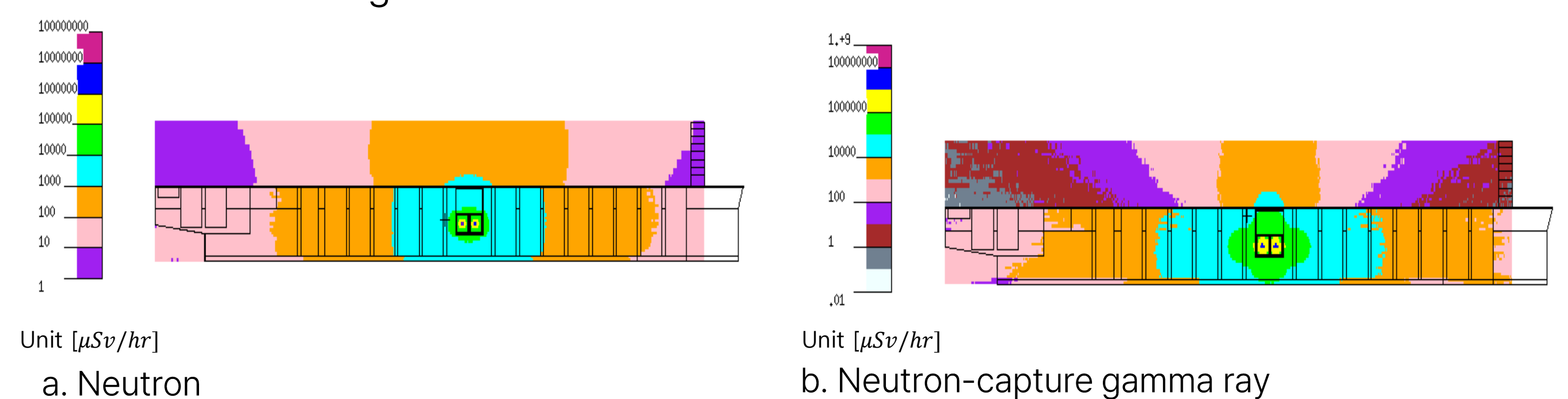


<Fig.3. Schematic of SMR space under the accident scenario considered in this study>



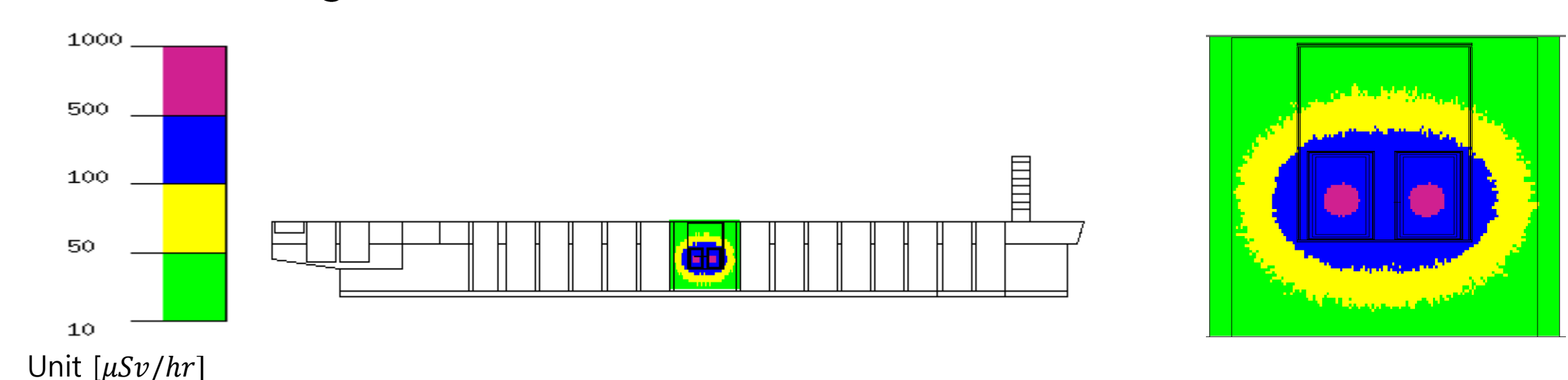
RESULTS

<Fig.4. Effective dose rate distribution for Case 1>



For Case 1, the neutron dose rate is 6.831 $\mu\text{Sv/hr}$ and the neutron-capture gamma dose rate is 8.68 $\mu\text{Sv/hr}$, resulting in a total dose rate of 15.511 $\mu\text{Sv/hr}$. Over a period of 529.16 hours, the total effective dose to crew members is estimated to be 8.207 mSv.

<Fig.5. Effective dose rate distribution for Case 2>



For Case 2, the reactor is shut down under emergency power conditions, and the SDDR is evaluated using a decay gamma source term based on 30 years of operation followed by a 12-hour cooling period. The gamma dose rate decreases from 580 $\mu\text{Sv/hr}$ at the reactor boundary (Advanced Reduced Activation Alloy (ARAA)) to 10.43 $\mu\text{Sv/hr}$ after attenuation through the ship structure. No measurable dose is observed at the accommodation space.

DISCUSSION & CONCLUSION

- Under the conservatively assumed extreme collision and shielding failure conditions, the projected radiation exposure to crew members **remains within acceptable regulatory limits.**
- Key features such as the SMR space and accommodation spaces were modeled in detail, while other structures were simplified or omitted, which may result in minor uncertainties outside the accommodation space.
- A highly conservative accident scenario was assumed, involving the failure of both primary and secondary shielding, which is unlikely under realistic maritime conditions.