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Applicability of TI-RIPB Methodology to Maritime MSR

Seung-Cheol Jang* and Sung-Il Kim
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057
**Corresponding author: scjang@kaeri.re.kr*

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1. Introduction

In response to global carbon neutrality policies and tightening environmental regulations of International Maritime Organization (IMO), the marine transport sector urgently needs to develop new carbon-free propulsion technologies. Molten Salt Reactors (MSRs) are gaining attention as a viable alternative due to their high-temperature operation, superior thermal safety, and inherent safety characteristics. Currently, conceptual design for MSRs as propulsion power sources for container ships (exceeding 15,000 TEU) is underway, with the ultimate goal of obtaining design licensing.

MSRs utilize a design where nuclear fuel and coolant are mixed in a liquid state, differing from traditional Light Water Reactors (LWRs). They can operate at high temperatures with low pressure, offering enhanced design simplicity and safety compared to conventional Pressurized Water Reactors (PWRs). MSRs also enable continuous operation without fuel replacement and can simultaneously meet the high power output and thermal efficiency required for ship propulsion. However, the unique characteristics of the maritime environment create distinct risk profiles for MSRs compared to land-based reactors. The confined space and harsh marine environment necessitate a systematic risk assessment that accounts for these novel risk elements.

This study aims to evaluate the suitability of currently applicable methodologies for the risk assessment of maritime MSR propulsion ships[1]. Based on this review, it seeks to provide foundational data for deriving technical requirements or establishing guidelines for risk assessment in MSR propulsion ship design licensing. It particularly focuses on whether the Technology-Inclusive, Risk-Informed and Performance-Based (TI-RIPB) methodology, which forms the basis of the Non-LWR Advanced Nuclear Reactor (NLANR) licensing regulatory framework, is adequately suited for the risk assessment requirements of IMO's International Convention for the Safety of Life at Sea (SOLAS).

2. Overview of TI-RIPB Methodology

The TI-RIPB methodology is a novel approach for licensing NLANRs, being legislated by the U.S. Nuclear Regulatory Commission (NRC) under 10 CFR Part 53. This framework is anticipated to be fully implemented by the end of 2027. The primary objective of nuclear facility safety is to protect human health (both the public and workers) and the environment from the harmful effects of ionizing radiation. While traditional deterministic safety assessment based on Design Basis Accidents (DBA) and Defense-in-Depth (DiD) has been the cornerstone of nuclear safety, the TI-RIPB approach expands the role of Probabilistic Safety Assessment (PSA) to enhance the effectiveness and efficiency of regulatory decision-making.

A core component (risk acceptance criteria) of the TI-RIPB regulatory framework is the Frequency-Consequence (F-C) target, as shown in Fig.1 ([2],[3]). Unlike traditional methods that use risk surrogates like Core Damage Frequency (CDF) or Large Early Release Frequency (LERF) for LWRs, the F-C target provides a technology-inclusive risk assessment criterion for NLANRs. Risk in the F-C Target is defined as the product of the Licensing Basis Event (LBE) occurrence frequency and the exposure dose (30-day Total Effective Dose Equivalent, TEDE) at the Exclusive Area Boundary (EAB). The application requires demonstrating that all LBE risk assessment results fall below the iso-risk baseline. Dose acceptance criteria are conservatively set based on existing nuclear facility standards, such as 25 rem over 30 days at EAB (from 10 CFR 50.34) and 1 rem at the Emergency Planning Zone (EPZ) boundary, which is often aligned with the EAB for Small Modular Reactor (SMR). Quantitative Health Objectives (QHOs) for early fatalities are also incorporated.

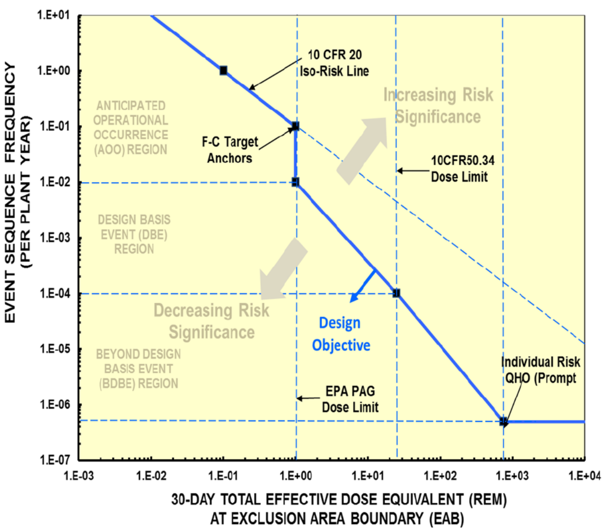

Fig. 1. F-C target in TI-RIPB Methodology.

The TI-RIPB methodology expands the role of PSA into three key design areas([2],[3]):

- ✓ *LBE Selection*: Events are categorized based on their frequency of occurrence. LBEs include Anticipated Operational Occurrences (AOO; 1.0e-2/year or more frequent), Design Basis Events (DBE; 1.0e-2 ~ 1.0e-4/year), and Beyond Design Basis Events (BDBE; 1.0e-4 ~ 5.0e-7/year). The process for selecting LBEs involves iterative PSA modeling and evaluation of Structures, Systems, and Components (SSCs) and DiD in design stage.
- ✓ *Structure, System, and Component (SSC) Classification*: SSCs are classified into three safety classes: Safety-Related (SR), Non-Safety-Related SSCs with Special Treatment (NSRST), and Non-Safety-Related SSCs with No Special Treatment (NST). This classification is based on the SSCs' functions in mitigating DBEs or preventing BDBEs from exceeding F-C Target acceptance criteria. It distinguishes between "safety-significant" and "risk-significant" SSCs, where risk-significant SSCs are those whose single failure could lead to an LBE exceeding 1% of the F-C Target value.
- ✓ *Defense-in-Depth (DiD) Adequacy Evaluation*: DiD in TI-RIPB involves creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures. The evaluation process integrates PSA, deterministic analysis, and risk insights through iterative feedback.

3. Regulatory Requirements for Risk Assessment of Nuclear Propulsion Ships

IMO's regulatory requirements for risk assessment of nuclear propulsion ships are primarily governed by the SOLAS[4], specifically Chapter VIII, Regulations 6 and 7. Regulation 7 broadly mandates the preparation of a Safety Assessment, similar to a Safety Analysis Report (SAR) for nuclear facilities, based on deterministic safety assessment. This is further elaborated in IMO Resolution A.491(XII), known as the Code for Safety of Nuclear Merchant Ships[5]. Key aspects of Resolution A.491(XII) include:

- ✓ *Principles of Risk Acceptance*: All foreseeable situations in a nuclear propulsion ship are qualitatively ranked based on their frequency and magnitude of consequences. This framework defines four Plant Process Conditions (PPC) categories as shown in Table 1.

Table 1. PPC Categorization

PPC	General description	Likelihood of occurrence	Consequence class
1	Normal operation	Continuous of frequent	1
2	Minor occurrences	Infrequent	2
3	Major occurrences	Remote	3
4	Severe accident	Extremely remote	4

Note: PPC 4 may be further subdivided into two categories. Category 4A should be used for those PPCs if some engineered energy sources are available. Category 4B should be used if no engineered energy sources are available.

- ✓ *Basic Safety Criteria*: These include Criterion A (maintaining radiation exposure as low as reasonably acceptable), Criterion B (means for residual heat removal from the core), and Criterion C (means for safe reactor shutdown and long-term maintenance of safe state).
- ✓ *Safety Functions*: Specific safety functions are defined for each criterion, such as maintaining integrity of fuel cladding, primary pressure boundary, containment structure, and safety enclosure (Criterion A); transferring residual heat and maintaining coolant inventory (Criterion B); and adequately controlling reactivity (Criterion C). It's noted that some of these functions, defined for LWRs, may not be directly applicable to MSR propulsion ships.
- ✓ *Safety Class Definition*: SSCs are categorized into four safety classes (SC-1 to SC-4), similar to land-based nuclear facilities.
- ✓ *Limiting Dose Equivalent Rates*: The code defines allowable dose equivalent rates for various locations on the ship as shown in table 2.

Table 2. Limiting Dose Equivalent Rates for Nuclear Propulsion Ship

	Area or space	Dose-equivalent rate*
1.	In the navigating bridge	0.75 μSv/ h (0.075 m rem/h)
2.	In accommodation spaces	0.15 μSv/ h (0.015 m rem/h)
3.	On upper deck and in cargo spaces	0.50 μS v/ h (0.05 m rem/h)
4.	On ship's sides above the waterline	0.50 μS v/ h (0.05 m rem/h)
5.	On ship's bottom , where "in water" maintenance or survey is contemplated: with the reactor at 10 per cent power.	7.5 μS v/ h (0.75 m rem/h)

4. Review on the Applicability of TI-RIPB to Maritime MSR

The primary question regarding the licensing of MSRs for container ships (exceeding 15,000 TEU) is whether the application of the TI-RIPB methodology alone is sufficient. The technical review indicates that TI-RIPB, designed primarily for land-based power reactors, is not sufficient for maritime MSRs for several critical reasons:

- ✓ *Scope of Risk Assessment Target*: The TI-RIPB methodology's assessment criteria are limited to the public for land-based power reactors. In contrast, nuclear propulsion ships, as per SOLAS, require risk assessment to cover not only the public but also the crew and passengers. For the MSR propulsion ship currently under development (targeting container ships), passengers are excluded from the scope, but the crew remains a key risk assessment target.
- ✓ *Operational Environment and Location*: The F-C Target in TI-RIPB is specifically tailored for the public in ports. However, maritime MSRs operate at sea as well as in ports, and separate risk assessment acceptance criteria are needed for workers (crew) in both environments.

- ✓ *Specific Ship Characteristics*: Maritime operations introduce unique considerations. Radiation safety verification is required for onboard food supplies and potable water, in addition to the distinct environments of at-sea, in-port, and navigation channels. This necessitates a significantly broader scope of risk assessment compared to land-based power reactors.

Therefore, to ensure comprehensive safety, the scope of risk assessment for maritime MSRs must be expanded to evaluate the impact of ionizing radiation on human health (both public and workers) and the environment, both at sea and in ports. This requires the development and verification of two distinct types of risk assessment methods:

- ✓ Risk assessment methods for the public in ports (e.g., TI-RIPB methodology).
- ✓ Near-field risk assessment methods for workers (crew) at sea and in ports.

For the latter, potential existing methodologies that could be adapted include:

- ✓ *Integrated Safety Analysis (ISA)*([6],[7]): Adopted by the U.S. NRC as a standard review plan for Non-Power and Utilization Facilities (NPUFs), including nuclear fuel cycle facilities. ISA requires qualitative risk assessment for both the public and workers (facility and co-located). It employs a risk matrix (e.g., 3x3) to categorize consequences and likelihood, defining "Items Relied On For Safety" (IROFS) based on risk indices.
- ✓ *Documented Safety Analysis (DoSA)*([8],[9]): Proposed by the U.S. Department of Energy (DOE) as a method for workplace risk assessment in compliance with 10 CFR 851 (Worker Safety and Health Program). DoSA utilizes a qualitative risk ranking group in a 4x3 risk matrix, classifying consequences based on radiation exposure limits for various analysis targets (maximally exposed offsite individual, co-located and facility worker).

While Formal Safety Analysis (FSA) based on Hazard Identification (HAZID) and Failure Mode & Effect Analysis (FMEA) is also an option, its limited application experience to nuclear propulsion ships and the need for developing specific radiological criteria for this domain make it a more time-consuming prospect. Therefore, for immediate application, integrating ISA or DoSA alongside TI-RIPB can be considered more practical for covering worker-specific risks.

The strategic decision regarding the graded approach to PSA application for maritime MSRs is also crucial. The extent of PSA usage can range from minimal (e.g., only for Maximum Credible Accident (MCA) selection) to extensive (e.g., use in design as per 10 CFR Part 53's TI-RIPB framework for LBE selection, SSC classification, and DiD adequacy evaluation).

5. Conclusions

The technical review confirms that while TI-RIPB methodology is robust for land-based NLANR licensing, it is insufficient for the comprehensive risk assessment of MSR propulsion ships. This insufficiency stems primarily from TI-RIPB's focus on public risk for land-based operations, whereas the IMO SOLAS convention, including the Code for Safety of Nuclear Merchant Ships (Resolution A.491), mandates risk assessment for both the public and the crew (and passengers, if applicable) across both in-port and at-sea conditions. Therefore, the risk assessment scope for MSR propulsion ships, particularly for container ships (excluding passengers), must be expanded to evaluate the impact of ionizing radiation on the health of both the public and workers (crew) in both maritime environments. From a technical standpoint, this necessitates the development and application of a hybrid risk assessment methodology:

- ✓ The TI-RIPB methodology can be utilized for risk assessment targeting the public in ports.
- ✓ Supplementary methodologies, such as ISA or DoSA, designed for NPUFs, should be additionally incorporated for near-field risk assessment targeting workers (crew) at sea and in ports.

These findings provide essential foundational data for establishing future risk assessment methodologies and guidelines for MSR propulsion ships.

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