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Integrating IAEA Safety Standards into Indonesia's Nuclear Regulation for Radiological Pollution Prevention in Molten Salt Reactors

Jacky Chin*, Pahotan D.P. Silaen

Mercu Buana University

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ABSTRACT

Nuclear power is a low-carbon energy source central to decarbonizing electricity generation, but its sustainable deployment also depends on effective radiological pollution prevention, particularly for Generation IV reactors such as the Molten Salt Reactor (MSR). Because MSR technology employs liquid fuel and continuously generates radioactive by-products, including fission gases, off-gas, and tritium, its pollution-control requirements are not yet fully addressed in Indonesia's national nuclear regulation. This study identifies regulatory gaps affecting MSR-specific radiological pollution control by benchmarking IAEA Safety Reports Series (SRS) No. 123 against the Management System elements of BAPETEN Regulation No. 6 of 2023 and prioritizes the associated risks using two rounds of Failure Mode and Effects Analysis (FMEA) involving a four-member expert panel. Ten pollution-control gaps were identified; eight were classified as critical and two as high in the first round, with tritium control yielding the highest Risk Priority Number (RPN) of 431.38. Following the implementation of proposed mitigation measures, the second-round assessment showed risk reductions of 75.56–91.48% across all gaps, with none remaining in the critical or high-risk categories. These findings are synthesized into an integration framework that embeds MSR-specific radiological pollution-control requirements within BAPETEN's Management System, providing a practical regulatory approach for pollution prevention and environmentally responsible deployment of Generation IV reactors while offering a transferable framework for adapting international safety standards into national regulatory systems

Keywords: Molten Salt Reactor; Radiological Pollution Prevention; Nuclear Safety Management System; Failure Mode and Effects Analysis; Regulatory Gap Analysis

*Correspondence author.
E-mail: jacky.chin@mercubuana.ac.id (Jacky Chin)

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INTRODUCTION

Nuclear power is increasingly recognized as a key low-carbon technology for decarbonizing the electricity sector while reducing industrial air pollution and greenhouse gas emissions compared with fossil fuel-based power generation. Consequently, global nuclear generating capacity is projected to continue expanding through 2050 as part of long-term climate mitigation and clean-energy strategies. Radioactive fission gases, activation products, tritium, and other radionuclides therefore require dedicated control measures, including containment, continuous monitoring, radioactive waste management, and controlled handling of radioactive effluents.

Unlike general reactor safety, which encompasses the broader prevention of accidents and protection of reactor systems, radiological pollution prevention focuses on limiting radioactive releases and ensuring the effective management of radioactive materials under both normal and abnormal operating conditions (Elsheikh, 2013; Fakhrudin et al., 2023; International Energy Agency, 2024; Shukla et al., 2022). Previous studies have identified several limitations, including the absence of reactor-specific safety performance indicators, insufficient provisions for advanced reactor security, fragmented emergency preparedness arrangements, incomplete licensing guidance, and operational challenges associated with radiation protection (Cusmanri & Lim, 2024; Fitra Nugraha, 2025; Government of Republic Indonesia, 2023; IRRS, 2019; Purba et al., 2016; Pratama et al., 2023; Soeparna Intan Innayatun et al., 2016).

The relevance of this assessment is further supported by Indonesia's previous consideration of the ThorCon TMSR-500 concept, which highlights the importance of preparing an appropriate regulatory framework for potential future deployment. While IAEA Safety Reports Series No.123 identifies operational novelties associated with advanced reactor technologies, BAPETEN Regulation No. 6 of 2023 establishes general Management System requirements that do not explicitly specify the operational controls necessary to address the particular radiological pollution challenges of liquid-fuel MSRs (Beils et al., 2019; IAEA, 2022; Lumbanraja et al., 2018; Waluyo & Khakim, 2021).

Specifically, the study derives an integrated assessment structure that (1) translates operational requirements from IAEA Safety Reports Series No. 123 into corresponding elements of BAPETEN Regulation No. 6 of 2023; (2) identifies and categorizes gaps according to their implications for radiological pollution prevention in MSR operation; (3) establishes a risk-prioritization profile by applying established FMEA parameters, severity, occurrence, and detection, to the identified gaps; and (4) evaluates the effectiveness of proposed corrective measures through a second round of expert assessment.

METHODS

Research Design

This study employed an integrated research design combining qualitative document analysis with a semi-quantitative expert-based risk assessment. Qualitative analysis was used to identify MSR-specific regulatory gaps by systematically comparing *IAEA Safety Reports Series* (SRS) No. 123 with BAPETEN Regulation No. 6 of 2023, while Failure Mode and Effects Analysis (FMEA) was applied to prioritize the associated radiological pollution risks based on expert judgment (John W. Creswell, 2014).

Data Sources

Secondary data consisted primarily of two regulatory and technical documents. The first was the International Atomic Energy Agency's (IAEA) Applicability of IAEA Safety Standards to Non-Water Cooled Reactors and Small Modular Reactors, published in November 2023 as IAEA Safety Reports Series No. 123 (STI/PUB/2027), which served as the principal technical benchmark for identifying operational considerations relevant to Molten Salt Reactors (MSRs). The second was BAPETEN Regulation No. 6 of 2023 concerning the Management System for Nuclear Energy Facilities and Utilization Activities, issued by the Nuclear Energy Regulatory Agency of Indonesia (BAPETEN) on 29 December 2023, which provided the national regulatory framework for the comparative assessment (Hallowell & Gambatese, 2010).

Regulatory Gap Identification

MSR-related operational considerations were extracted from the areas of novelty in IAEA Safety Reports Series No. 123, particularly Sections 3.2.3.3, 3.2.4.3, and 3.4.1, and the applicability assessments in Chapter 4. The extraction covered fuel salt and fission gas management, molten salt chemistry and corrosion control, residual heat removal, passive safety testing, gaseous effluents, and tritium management. Each consideration was coded and translated into a proposed operational control requirement, then cross-referenced with relevant provisions of BAPETEN Regulation No. 6 of 2023. The cross-referencing process involved four steps: (1) recording relevant IAEA passages and source references; (2) coding operational subjects and

formulating MSR-specific control requirements without assuming universal applicability across MSR configurations; (3) identifying corresponding BAPETEN provisions based on their explicit wording and underlying management objectives; and (4) classifying the matches as explicit, general or indirect, or no identifiable coverage. Gaps were retained only when existing provisions lacked sufficient operational specificity. Where direct textual correspondence was absent, findings were treated as analytical inferences rather than confirmed regulatory omissions.

Each identified regulatory gap was translated into a failure mode representing the absence or inadequacy of Management System controls for an MSR-specific operational requirement. For each failure mode, the associated effects, causes, and existing controls were identified before risk assessment.

Four experts independently assessed each identified failure mode using the conventional FMEA parameters of Severity (S), Occurrence (O), and Detection (D), each measured on a ten-point ordinal scale. The panel was purposively selected to obtain complementary perspectives on nuclear regulation, reactor engineering, MSR process engineering, and nuclear safety. To preserve confidentiality, individual experts were assigned anonymized identifiers (E1–E4). Although the assessment adopted the conventional S, O, and D structure described by Stamatis (2003) and the AIAG–VDA FMEA Handbook (2019), the operational anchors were adapted to the regulatory and operational context of MSRs.

$$\boldsymbol{RPN_{avg} = S_{avg} \times O_{avg} \times D_{avg}}$$

Risk levels were classified into four categories: Critical (200-1000), High (100-199), Medium (50-99), and Low (1-49). These thresholds were adopted as study-specific operational criteria for prioritizing the identified MSR-related implementation gaps, rather than as universally established FMEA thresholds. Since conventional FMEA literature does not prescribe universally applicable RPN cutoffs, the selected categories were used to facilitate comparative interpretation of the assessment results.

Accordingly, the second-round results represent expert-based projections of potential mitigation effectiveness, not post-implementation validation or empirical evidence of reduced radioactive releases. The mitigation effectiveness was estimated by comparing the initial and reassessed average Risk Priority Numbers (RPNavg). To examine the sensitivity of the risk classification, the resulting RPNavg values were also considered against alternative classification thresholds.

$$\boldsymbol{\Delta RPN = RPN_{Round1} - RPN_{Round2}}$$

where larger ΔRPN values indicate greater estimated reductions in radiological pollution risk.

Data Validity

The credibility and methodological transparency of the findings were supported through four complementary strategies (Creswell, 2014; Miles et al., 2014). First, source triangulation was conducted by comparing operational considerations identified in IAEA Safety Reports Series No. 123 with supporting literature on MSR technology. Second, methodological triangulation combined document analysis, expert judgment, and FMEA to examine the identified implementation gaps from complementary perspectives. Third, expert reassessment was conducted through a second assessment round involving the same four experts.

RESULT AND DISCUSSION

Identification and Mapping of MSR-Specific Regulatory Gaps

The comparison of MSR-specific operational requirements in IAEA Safety Reports Series (SRS) No. 123 with BAPETEN Regulation No. 6 of 2023 identified ten areas requiring further assessment for radiological pollution prevention (Table 1). These areas do not necessarily indicate complete regulatory gaps or deficiencies. Rather, they highlight potential implementation gaps where technology-neutral Management System requirements may require more specific operational controls, verification criteria, monitoring parameters, or competency arrangements for liquid-fuel reactors. Existing provisions on radiation protection, radioactive waste management, environmental release control, inspection, and organizational management are already covered by Indonesia's broader regulatory framework.

Table 1. Summary of the MSR Operational Safety Gap Register

Gap ID	Gap Statement (Summary)	Affected BAPETEN MS Element	Potential Pollution Impact
GAP-001	No procedure for managing fission gases (Xe, Kr)	Operations and Process Control	Worker and environmental radiation exposure
GAP-002	Drain tank verification/testing not specified	Verification and Validation	Undetected failure of passive safe-state function
GAP-003	Freeze valve/emergency fuel-draining oversight inadequate	Operational Surveillance	Failure of emergency liquid-fuel discharge
GAP-004	Molten salt physicochemical parameters not specifically monitored	Monitoring and Measurement	Undetected abnormal salt conditions
GAP-005	Overcooling risk not identified in emergency scenarios	Risk Management	Undetected fissile-material accumulation
GAP-006	Molten salt chemistry control not governed	Process Control	Corrosion and uncontrolled fissile concentration change
GAP-007	MSR/remote-operation operator competency not specified	HR and Competency Management	Operational error under MSR-specific conditions
GAP-008	No management of off-gas radioactive waste	Waste Management	Uncontrolled radioactive gas waste
GAP-009	No control for tritium from coolant salt	Radiological Protection	Uncontrolled tritium exposure
GAP-010	MSR operational knowledge transfer unstructured	Knowledge Management	Loss of safety knowledge during personnel turnover

The identified gaps contribute to radiological pollution through different causal pathways and can be classified as direct or indirect contributors. Direct contributors include fission gas management (GAP-001), radioactive off-gas management (GAP-008), and tritium control (GAP-009), where inadequate containment, treatment, or monitoring may result in radioactive releases or occupational exposure. Indirect technical contributors include drain tank verification (GAP-002), freeze valve and emergency fuel-draining oversight (GAP-003), molten salt parameter monitoring (GAP-004), overcooling risk management (GAP-005), and molten salt chemistry control (GAP-006). These gaps may impair abnormal-condition detection, compromise passive safety functions, or degrade system integrity, potentially increasing the likelihood of radioactive material release during abnormal operations (IAEA, 2022). This distinction is consistent with previous studies highlighting the need for reactor-specific operational guidance and licensing approaches for advanced reactors, given that existing regulatory frameworks were largely developed around water-cooled reactor technologies (Beils et al., 2019; Waluyo & Khakim, 2021).

Pollution Risk Prioritization: FMEA Round 1

The first-round FMEA identified substantial risks associated with most MSR-specific regulatory implementation gaps (Table 2). Eight of the ten gaps were classified as Critical (RPNavg ≥ 200), while the remaining two were categorized as High. No gap fell within the Medium or Low risk categories. The highest RPNavg values were associated with tritium management (GAP-009), radioactive off-gas management (GAP-008), fission gas control (GAP-001), and molten salt chemistry control (GAP-006). Conversely, operator competency (GAP-007) and knowledge management (GAP-010) received the lowest aggregate risk scores. However, these aggregate rankings should not be interpreted independently of the underlying Severity, Occurrence, and Detection assessments.

Table 2. FMEA Round 1 Risk Priorities

Gap ID	Failure Mode	S_{avg}	O_{avg}	D_{avg}	RPN_{avg} (Category)
GAP-009	No control for tritium from coolant salt	8.50	7.00	7.25	431.38 (Critical)
GAP-008	No management of off-gas radioactive waste	8.50	6.75	6.75	387.28 (Critical)
GAP-001	Fission gas (Xe, Kr) unmanaged	8.25	7.25	6.00	358.88 (Critical)
GAP-006	Molten salt chemistry control ungoverned	7.50	5.75	8.00	345.00 (Critical)
GAP-002	Drain tank readiness unverified	7.75	6.50	6.75	340.03 (Critical)
GAP-003	Freeze valve/emergency draining unmonitored	7.00	5.75	8.25	332.06 (Critical)
GAP-004	Abnormal salt condition undetected	6.75	6.25	7.25	305.86 (Critical)
GAP-005	Overcooling risk unidentified	7.00	4.75	7.00	232.75 (Critical)

GAP-007	MSR operator competency unassured	6.00	5.00	6.50	195.00 (High)
GAP-010	Knowledge transfer unstructured	5.25	4.50	5.50	129.94 (High)

By comparison, operator competency (GAP-007) and knowledge management (GAP-010) received lower average Risk Priority Number (RPNavg) values than the technical and process-related gaps. However, these rankings should not be interpreted as evidence that organizational factors have a lesser safety significance. Personnel competency and operational knowledge function as cross-cutting safeguards that influence the effectiveness of multiple technical controls, including radioactive gas management, molten salt chemistry monitoring, passive safety verification, and emergency fuel-draining procedures. Inadequate training, insufficient understanding of MSR-specific processes, or the loss of operational knowledge may contribute to human errors, delayed abnormal-condition recognition, and inconsistent implementation of safety procedures across several operational areas.

Mitigation Proposals and FMEA Round 2 Reassessment

Based on the Round 1 assessment, the expert panel proposed mitigation measures to strengthen radiological pollution prevention within the existing Management System. Although individual recommendations reflected different areas of expertise, they converged into five categories: (1) MSR-specific operating procedures and standard operating procedures (SOPs); (2) enhanced monitoring and early-warning systems for radioactive materials; (3) periodic inspection and verification of passive safety systems; (4) systematic molten salt chemistry control; and (5) strengthened operator competency and knowledge management.

The overall reduction in average Risk Priority Numbers (RPNavg) following the second-round assessment indicates that the expert panel anticipated a substantial reduction in the identified risks if the proposed Management System controls were implemented. In particular, the panel assessed that risks associated with radioactive by-product management and passive safety verification could be mitigated through formal operating procedures, defined monitoring requirements, inspection and verification programmes, and strengthened organizational controls.

Overall, the Round 2 assessment indicates that integrating MSR-specific operational requirements into Indonesia's existing Management System provides a practical strategy for substantially reducing estimated radiological pollution risks without requiring an entirely new regulatory framework.

Table 3. Comparison of Round 1 and Round 2 RPN and Percentage Risk Reduction

Gap ID	RPN R1	Cat. R1	RPN R2	Cat. R2	Reduction	% Reduction
GAP-001	358.88	Critical	43.59	Low	315.29	87.85%
GAP-002	340.03	Critical	34.88	Low	305.15	89.74%
GAP-003	332.06	Critical	43.59	Low	288.47	86.87%
GAP-004	305.86	Critical	51.05	Medium	254.81	83.31%
GAP-005	232.75	Critical	56.88	Medium	175.87	75.56%
GAP-006	345.00	Critical	65.25	Medium	279.75	81.09%
GAP-007	195.00	High	34.17	Low	160.83	82.48%
GAP-008	387.28	Critical	33.00	Low	354.28	91.48%
GAP-009	431.38	Critical	55.00	Medium	376.38	87.25%
GAP-010	129.94	High	29.53	Low	100.41	77.27%

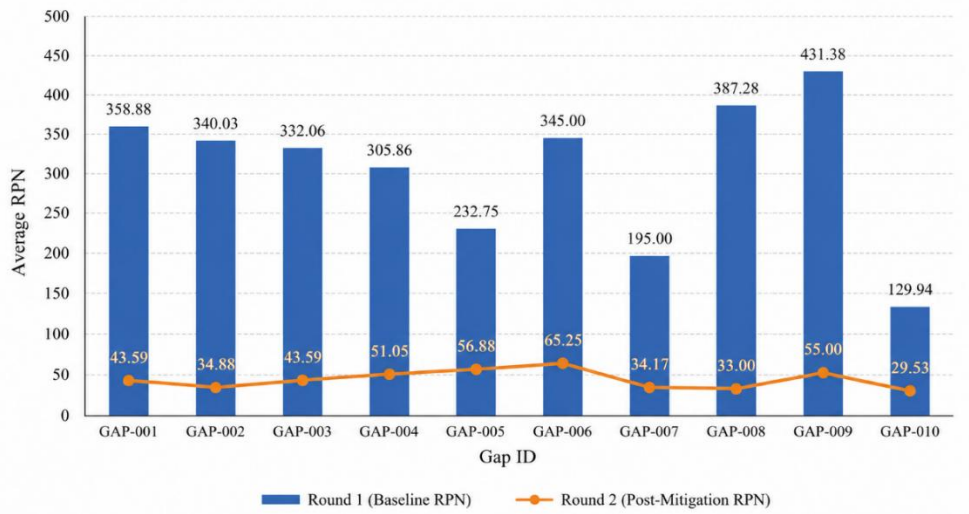


Figure 1. Comparison of RPN Values between Round 1 and Round 2 across the Ten MSR Operational Safety

Integration Framework for Radiological Pollution Prevention

The regulatory gap analysis and two-round FMEA assessment were synthesized into an integration framework for incorporating MSR-specific operational requirements into the existing Management System established under BAPETEN Regulation No. 6 of 2023 (Table 5). The framework does not propose a separate regulatory structure; instead, it translates MSR-related operational and radiological protection considerations into specific implementation measures within the existing Management System. Each proposed measure is linked to the relevant provisions of BAPETEN Regulation No. 6 of 2023 and, where applicable, to complementary regulatory requirements governing radiation protection, radioactive waste management, and environmental releases, particularly Government Regulation No. 45 of 2023.

Table 4. Proposed Integration Framework for Incorporating MSR-Specific Operational Requirements into BAPETEN Regulation

Requirement	Gap ID	Management System Element	Form of Integration
Fission gas management	GAP-001	Operations and Process Control	SOP for radioactive gas management, Xe/Kr monitoring, response procedure
Drain tank verification	GAP-002	Verification and Validation	Periodic inspection program, surveillance testing, function verification
Freeze valve monitoring	GAP-003	Operational Surveillance	Inspection program, function testing, emergency draining testing
Molten salt parameter monitoring	GAP-004	Monitoring and Measurement	Additional physicochemical parameters: temperature, viscosity, redox potential
Overcooling risk control	GAP-005	Risk Management	Overcooling integrated as a Postulated Initiating Event with mitigation procedure
Molten salt chemistry control	GAP-006	Process Control	Chemistry control program, salt composition monitoring, corrosion control
MSR operator competency	GAP-007	HR and Competency Management	MSR operator training, remote-operation training, certification
Off-gas waste management	GAP-008	Waste Management	Integration of off-gas into the radioactive waste management system
Tritium control	GAP-009	Radiological Protection	Monitoring, detection, and control of tritium in the coolant salt system
Knowledge transfer	GAP-010	Knowledge Management	Operational documentation, knowledge transfer, operating-experience feedback

The proposed framework is intended primarily as subordinate technical guidance to support the implementation of BAPETEN Regulation No. 6 of 2023, rather than as a direct proposal for regulatory amendment or the establishment of new licensing conditions. It translates each identified MSR-specific implementation gap into actionable Management System requirements by specifying the relevant regulatory instrument, accountable institution, evidence of compliance, and verification mechanism.

At the regulatory level, BAPETEN may use the framework to develop technical guidance and inspection criteria, while the licensee or operating organization remains responsible for establishing and implementing the corresponding operational controls. From a regulatory perspective, the findings suggest that the identified MSR-specific operational requirements may be accommodated by strengthening the existing Management System framework rather than developing an entirely separate regulatory structure. This approach can preserve regulatory consistency while providing additional technical guidance tailored to the characteristics of liquid-fuel reactor technology.

DISCUSSION

1. Why Generic Nuclear Management Systems Are Insufficient for Molten Salt Reactors

The findings demonstrate that the principal regulatory challenges associated with Molten Salt Reactors arise from the continuous generation, transport, and transformation of radioactive materials during normal operation rather than from conventional reactor operating practices. Most identified regulatory gaps were associated with radioactive by-products, molten salt chemistry, and passive safety verification, indicating that radiological pollution prevention in liquid-fuel reactors is fundamentally process-oriented rather than equipment-oriented.

This finding is consistent with *IAEA Safety Reports Series* No. 123, which identifies fuel circulation, tritium generation, radioactive off-gas management, and fuel-salt chemistry as key operational novelties requiring additional regulatory consideration. Similar conclusions have been reported by Beils et al., 2019, who argued that defence-in-depth strategies for molten salt reactors should be specifically adapted to liquid-fuel technology, while Walker et al., 2023 emphasized that maintaining stable fuel-salt chemistry is essential for controlling corrosion, radionuclide transport, and long-term reactor performance.

2. Implications of Risk Prioritization for Radiological Pollution Prevention

The FMEA results indicate that the highest regulatory priorities are associated with radioactive materials requiring continuous monitoring, particularly tritium, radioactive off-gas, fission gases, and molten salt chemistry. These findings reinforce the importance of integrating continuous monitoring and operational surveillance into Management System requirements, as failures in these areas may remain undetected until radioactive materials are released to the environment.

Measures such as improved operating procedures, monitoring programmes, inspection and verification activities, and operator competency development were considered by the expert panel to have the potential to reduce the likelihood of failure or improve its detectability. However, these results do not establish that the identified risks originate exclusively from insufficient operational controls rather than inherent technological limitations. Similar observations have been reported for advanced reactor systems, where effective operational safety depends on the integration of engineered safety features with reactor-specific operational management (Beils et al., 2019; Walker et al., 2023).

3. Implications for Environmental Technology and Nuclear Regulation

The findings indicate that strengthening radiological pollution prevention in Molten Salt Reactors does not require an entirely new regulatory framework. Integrating reactor-specific operational requirements into existing Management Systems offers a practical approach to enhancing environmental protection while maintaining regulatory consistency. Beyond Molten Salt Reactors, the proposed methodology provides a transferable framework for assessing regulatory readiness for other Generation IV technologies by combining international safety guidance, regulatory gap analysis, and risk prioritization to support national regulatory adaptation and environmentally responsible deployment.

CONCLUSION

This study identified ten MSR-specific regulatory implementation gaps through a systematic comparison of the operational requirements presented in IAEA Safety Reports Series No. 123 and the Management System provisions of BAPETEN Regulation No. 6 of 2023. The identified gaps primarily concern operational arrangements for radioactive by-product management, passive safety verification, molten salt monitoring and chemistry control, tritium management, and organizational support for safe MSR operation. The expert-based Failure Mode and Effects Analysis (FMEA) ranked these gaps according to their assessed Severity, Occurrence, and Detection characteristics, with the initial assessment identifying varying levels of operational risk. In the second assessment round, the expert panel evaluated the anticipated effectiveness of the

proposed Management System enhancements and assigned lower average Risk Priority Number (RPNavg) values across all identified gaps. Future research should validate the proposed framework using operational evidence from demonstration or commercial Molten Salt Reactor facilities as such data become available. Further studies should also investigate the integration of advanced monitoring technologies and digital decision-support systems to strengthen radiological pollution prevention for next-generation nuclear reactors.

Research Transparency and Ethics Statements

Author Contributions (CRediT): Author 1: Conceptualization, Methodology, Writing – Original Draft, Supervision, Project Administration, Funding Acquisition;
Author 2: Investigation, Data Curation, Visualization;
Author 3: Investigation, Formal Analysis, Validation.

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The study was conducted in accordance with applicable institutional requirements.

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