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Framework Development and Initiating Event Analysis of the Probabilistic Safety Assessment of Floating Molten Salt Reactors

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1. Introduction

With the growing global demand for decarbonization and climate change mitigation, the importance of nuclear power has significantly increased, as it can provide a stable supply of electricity without carbon emissions. In response, the government has launched a national project in 2023 to develop the core technology of a chlorine-based molten salt reactor (MSR) for marine applications. The project aims to achieve demonstration by 2030 to strengthen energy security and respond to the global market for advanced reactors[1].

MSR utilizes nuclear fuel dissolved in high-temperature molten salt in a liquid state, and in the event of an accident, a freeze valve located at the bottom of the core opens to automatically drain the fuel salt into a drain tank, thereby removing heat without manual intervention through its inherent passive safety feature.

In particular, marine molten salt reactors are installed on offshore platforms and thus are exposed to conditions that differ entirely from those on land, such as waves, shocks, and salinity. Therefore, it is essential to conduct safety analyses that take into account the unique risk factors associated with the marine environment.

Previous research has already addressed related topics in the context of probabilistic safety assessment. For example, research has been conducted on the identification of initiating events for floating power platforms [2], as well as on the implementation of safety assessment methodologies for molten salt reactors [3]. These works provide an important foundation for extending PSA methodologies to floating MSRs, while highlighting the need for a tailored framework that considers both the unique characteristics of molten salt fuel and the external conditions associated with marine environments.

Due to the specific design and safety features of MSRs compared to pressurized water reactors (PWRs), as well as the unique risks associated with the marine environment, it is necessary to develop a probabilistic safety assessment (PSA) model specifically for marine molten salt reactors. Therefore, this study aims to develop a PSA model specialized for floating MSRs. As a first step, the initiating events specific to floating MSRs were identified.

2. Safety Assessment of Molten Salt reactor

The regulatory framework established primary for pressurized water reactor (PWR) does not sufficiently reflect the characteristics and risk factors of advanced reactors. Therefore, a risk-informed and performance-based approach that considers the specific feature of new reactor technologies is required. In this context, the U.S. Nuclear Regulatory Commission (NRC) issued a new regulatory guideline (NRC RG 1.233) to support the licensing of non-light water advanced reactor in response to the commercialization of advanced reactor technologies[4]. This guideline adopts the methodology proposed by the Nuclear Energy Institute (NEI) in NEI 18-10[5], which is structured into three key activities:

1. Selection of Licensing Basis Events (LBEs)
2. Classification and special treatments of structures, systems, and components (SSCs)
3. Assessment of defense in depth (DID)

Based on this framework, the definition and scope of LBEs were established, and a classification scheme was developed

2.1 Definition of defense in depth (DID) for MSR

A conceptualization of DID is required in order to establish LBEs. The top event of accident progression initiated by an LBE is defined as the failure of a physical barrier in the DID framework. For example, in conventional PWR PSA models, fuel cladding failure is defined as core damage and serves as the top event in Level 1 PSA. However, due to the liquid-fuel characteristics of MSR, DID for MSR can be defined as shown in Table I.

Table I: Comparison of DID levels between PWR and MSR[6].

Levels of DID	PWR	MSR
Level 1	Fuel pellet matrix	Reactor pressure boundary
Level 2	Fuel cladding	
Level 3	Reactor pressure boundary	

Level 4	Containment building	Containment building
Level 5	Off-site release	Off-site release

Accordingly, an LBE can be defined as an event that causes the release of fuel salt beyond the reactor pressure boundary.

2.2 Classification of Structures, systems and components (SSCs)

The classification of SSCs is required in order to determine the scope of LBEs. SSC can be categorized into three groups below[4]:

- SR (safety-Related): SSCs selected by the reactor from the SSCs that are available to perform the required safety functions to mitigate the consequences of LBEs.
- NSRST (Non-Safety-Related with Special Treatment): Non-safety-related SSCs that perform functions having a significant impact on safety. And, the SSCs relied on to perform functions requiring special treatment for the adequacy of DID.
- NST(Non-Safety-Related with No Special Treatment): All other SSCs

Since SR and NSRST are directly related to reactor safety, it is necessary to identify the LBEs that may occur within these systems. An analysis of SSC classification for currently designed MSR concepts shows that the freeze valve, drain tank are classified as SR, while the off-gas system, intermediate heat exchanger, and fuel reprocessing system are classified as NSRST[7]. Accordingly, in this study, all systems carrying fuel salt, which may affect the integrity of DID, were additionally included, and the scope of LBEs was defined as the events occurring within these systems, as summarized in Table II.

Table II: Classification of SSCs for MSRs, with the proposed additional category relevant to DID integrity.

Category	SSCs
SR	Freeze valve, Drain tank
NSRST	Off-gas system, Intermediate heat exchanger, Fuel reprocessing system
Special Treatment needed SSCs	Core, Fuel salt pump, Pipe

2.3 Licensing Basis Events (LBEs) for MSR

The LBEs of a floating MSR can be divided into those inherent to the MSR itself and those arising from the floating characteristics, which are appropriately classified as internal and external events, respectively. This distinction is reasonable because the MSR within a floating platform is enclosed in a containment building; therefore, some internal events would occur regardless of the floating nature, while others are induced by transients unique to the floating platform and can thus be regarded as external events. In this chapter, internal events are discussed, while external events are treated in the following chapter.

In the context of PSA, LBEs are hereafter referred to as initiating events (IEs).

The identification of internal events adopted an integrated approach combining top-down and bottom-up methods. In the top-down approach, a deductive method was applied through the development of a Master Logic Diagram (MLD). By structurally expanding events from higher to lower levels, focusing on barrier failures at the system level, IEs were systematically and consistently derived around key functions and barriers. In the bottom-up approach, an inductive method was employed, in which possible event types were defined and subdivided based on combinations of parameters that could classify IEs. This approach minimized the omission of IEs that might otherwise be overlooked at the system or component level. [8]

2.3.1 Development of Master Logic Diagram (MLD) for MSR

The starting point of the MLD is identical to that of the MLD for PWRs, with the release of radioactive material to the off-site defined as the top event. This is represented by an AND gate combining the release of fuel salt or fission products with containment failure, since radioactive material cannot escape to the outside as long as the integrity of the containment is maintained. The release of fuel salt or fission products is then decomposed into the detailed contributing events that could lead to the top event. Based on this structure, groups of internal IEs capable of directly causing leakage or inducing transients were identified and categorized by SSCs. For each SSC, events were further classified into direct releases caused by leakage and indirect releases caused by transients. In the case of transients, they were subdivided by the specific types of transients that could occur in the respective SSCs. The MLD was developed according to the following levels, as illustrated in Fig. 1 and Fig. 2.

Level 1: Release of radioactive material
Level 2: Physical barriers of the MSR
Level 3: Internal / external events
Level 4: Types of IEs (direct vs. indirect release)
Level 5: SSC in which the IEs occur
Level 6: Events causing SSC failures
Level 7+: Detailed events that lead to Level 6 events

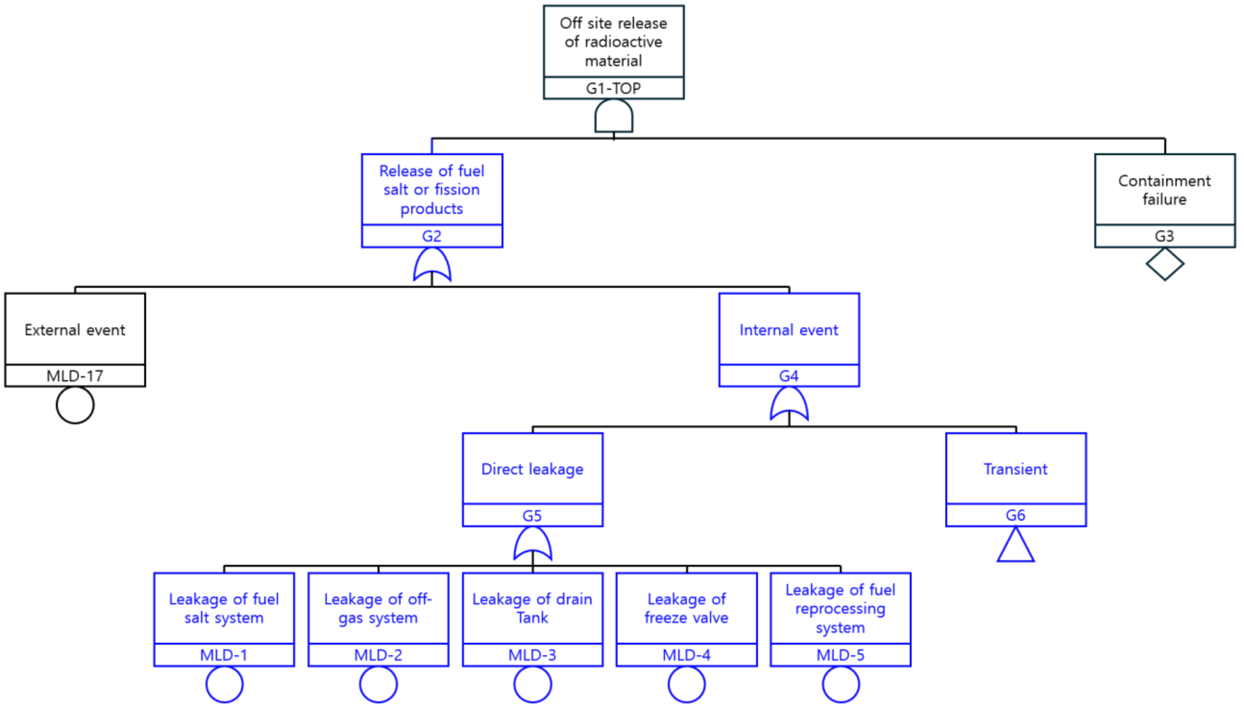

Fig. 1. MLD Levels 1–5 of a floating MSR for direct leakage

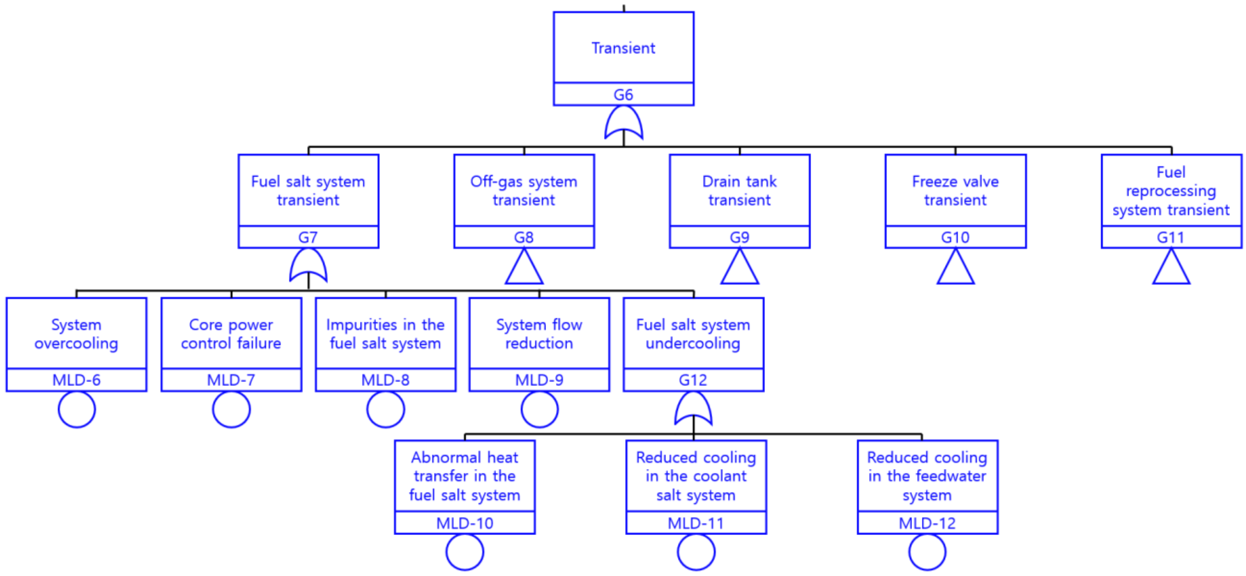

Fig. 2. MLD Levels 5-7+ of floating MSR for Fuel salt system transient

2.3.2 Inductive method for defining IEs

To systematically derive internal IEs, groups of IEs were constructed by combining specific parameters that characterize IEs. The resulting groups were refined to capture a comprehensive set of potential events, and each group was subsequently examined for the occurrence potential of IEs, thereby minimizing the likelihood of omission. Two parameters were combined to construct the groups. The first parameter is the system components of the MSR, as each system affected by or carrying the fuel salt must be analyzed according to its function. The elements of this parameter correspond to the items summarized in Table 2. The second parameter is the state of the fuel salt. This parameter was selected because an accident occurring in a specific system may induce abnormal states of the fuel salt, and such changes can have cascading effects on other systems. The state of the fuel salt was classified into six conditions, namely leakage, overheating, freezing, contamination, plugging, and transient.

In classifying these groups, two major data sources were referenced. First, an ORNL workshop summary on MSR IEs and licensing basis events [9] was utilized. This report was developed based on a workshop involving experts from U.S. and Canadian national laboratories, regulatory bodies, and academia, and it served as a fundamental source for comprehensively identifying IEs in MSRs. Second, an ORNL report on the development status of molten-salt breeder reactors [10] was consulted. This report provides detailed design information of a commercial MSR, developed from the operational data of the Molten Salt Reactor Experiment (MSRE). Using this design information, additional IEs were identified to supplement items that had been overlooked in existing sources. While IEs were derived and grouped for the systems, representative examples for the core are presented in Table III.

Table III: Examples of core IEs derived from different fuel salt conditions based on [9,10].

State of fuel salt	IE(Core)
Leakage	Nozzle cracking, plus 2 other IEs
Overheating	Inadvertent decreasing of void fraction, plus 5 other IEs
Freezing	Graphite scape, plus 8 other IEs
Contamination	Fuel salt contamination due to graphite fracture
Plugging	Graphite swelling due to radiation effect and thermal expansion, plus 3 other IEs
Transient	Premature criticality due to control rod misalignment, plus 3 other IEs

2.3.3 Integration of Top-down and Bottom-up Results

The final set of IEs can be mapped to the groups in the MLD. Through this correspondence, accident scenario insights can be obtained from the results of the inductive approach, while detailed contributing factors of accidents can be derived from the deductive approach, with selected examples summarizing in Table IV.

3. Safety Assessment of Floating Plant

The external event PSA, conducted for external initiating events, is fundamentally an evaluation of the risks imposed on nuclear power plants by external hazards, in addition to mechanical failures or human errors within the plant. At present, the standard scope of external event PSA is limited to three hazards: earthquake, fire, and flooding. However, external event PSA should take into account a variety of factors, including the plant's location, operational experience, and design characteristics, in order to select appropriate external hazards. A floating MSR is exposed to external conditions that differ from those of conventional land-based nuclear power plants, such as ship collisions and wave-induced motions. Therefore, it is necessary to redefine the list of external events suitable for floating MSRs and to expand the scope of PSA accordingly.

In this study, various marine accident reports were analyzed to identify potential events that may occur in the marine environment.

3.1 Identification of marine accident types

In classifying external marine events, three reference reports were utilized. First, *Incidents Associated with Oil and Gas Operations* [11] provided a broad overview of accidents in offshore oil and gas activities. Second, *Accident Statistics for Floating Offshore Units on the UK Continental Shelf 1980–2005* [12] presented statistical data on accidents involving floating offshore units. Third, *Failure Rate and Event Data for Use within Risk Assessments* [13] compiled generic failure rate and event frequency data commonly applied in probabilistic risk assessments. The events described in these reports were grouped according to similarity, and overlapping items were removed, resulting in the development of a preliminary draft of external IEs, as shown in Table V.

Table IV: Representative IEs corresponding to MLD groups derived from the integrated top-down and bottom-up approach.

group in MLD	Initiating evet
Leakage of fuel salt system (MLD-1)	Large break of the fuel salt boundary
	Nozzle cracking
	Fuel salt pump seal failure
Leakage of Drain tank (MLD-3)	Break of the drain tank
	Inadvertent opening of vent valve
	Inadvertent opening of drain tank valve
	Drain tank vent valve stuck open
Core power control failure (MLD-7)	Graphite scape
	Uncontrolled rod withdrawal/ insertion
	Accidental absorption impurities insertion
	Control rod thimble break
	Failure of core flow distributors
Reduced cooling in the coolant salt system (MLD-12)	Blockage in the coolant salt system
	Inadvertent reduction of coolant salt flow
	Sudden change in coolant salt properties
	Coolant salt leakage
	Coolant salt pump under-speed/trip
	Inadvertent withdrawal of coolant salt

Table V: Preliminary draft of external IEs for floating MSRs derived from marine accident reports.

External event	Description
Anchor failure	Anchor, mooring equipment, or winch failure

Blowout	Uncontrolled release due to pressure loss in oil/gas wells
Capsize	Capsizing due to overturning, loss of stability, or equipment malfunction
Collision	Collision with ship or offshore facilities
Contact	Accidents caused by contact when a ship approach
Crane accident	Crane-related accident
Explosion	Explosion caused by chemical reactions or pressure boundary failure
Falling object	Drop of equipment or cargo
Fire	Fire occurring inside or outside the plant
Foundering	Sinking or severe flooding of a vessel
Aircraft strike	Collision with aircraft, missiles. Etc.
Listing	Severe tilting or listing of a vessel
Well problem	Pressure-related problems in wells
Towing/ Towline failure	Failure of towing or towline equipment
Earthquake	Severe Seismic activity that may simultaneously induce tsunami and oscillation
Flooding	Flooding inside or outside the plant
Weather	Extreme weather conditions
Lightning	System malfunction or fire triggered by lightning strikes
Fatality	Fatal accident
Injury	Injury accident
Helicopter accident	Collision with helicopter

3.2 Classification of External Events for floating MSR

Since the draft list of external events was not originally developed from the perspective of nuclear power plants, it included not only mechanical and systemic damage but also human casualties such as fatalities and injuries. However, in the operating state of a nuclear power plant, operators are stationed in the main control room, and thus accidents resulting from plant failures that directly cause harm to operators are excluded. To classify external events suitable for floating MSRs, the derived event list was therefore organized into categories, and the classification scheme was optimized at higher-level categories. Accidents specific to the marine environment were distinguished from those that are not, and among the external events considered in conventional land-based nuclear plants, only those relevant to the marine environment were selected. Marine-specific accidents were further divided into those induced by external stimuli and those arising from machinery failures within the floating MSR. Among the draft external events, those that are not limited to marine conditions but are not considered in conventional nuclear plants, as well as system failures not applicable to marine nuclear platforms, were excluded. The filtered results of external events considered applicable to floating MSRs are presented in Table VI, and the overall classification framework is illustrated in Fig. 3.

Table VI: Classification results of external events applicable to floating MSRs.

External event	Description
Anchor failure	Anchor failure may induce unexpected transients
Capsize	The change in direction of gravity caused by capsize can lead to the loss of core safety functions in the MSR.
Earthquake	external events already considered in conventional nuclear plants.
Collision	Collisions with ships can have significant impacts on floating MSRs, which are more lightweight compared to conventional nuclear plants due to weight limitations.
Flooding	an external event already considered in conventional nuclear plants.
Aircraft strike	Floating nuclear power plants may be vulnerable to aircraft or missile strikes due to weight limitations.
Listing	Since the fuel salt is in a liquid state, listing can induce severe transient conditions within the system.
Fire	an external event already considered in conventional nuclear plants.

4. Conclusion

This study developed a preliminary framework for the PSA of floating MSRs based on the regulatory guidance of NRC RG 1.233, with a focus on the identification and classification of IEs. Internal IEs were systematically derived through an integrated top-down and bottom-up approach, employing the MLD for deductive analysis and parameter-based grouping for inductive analysis. This process enabled both accident scenario insights and detailed contributing factors to be captured in a consistent manner.

For external IEs, existing marine accident reports were reviewed to identify a comprehensive set of potential events. These events were subsequently screened and categorized to exclude those irrelevant to nuclear plant operation. The outcomes presented in this work provide

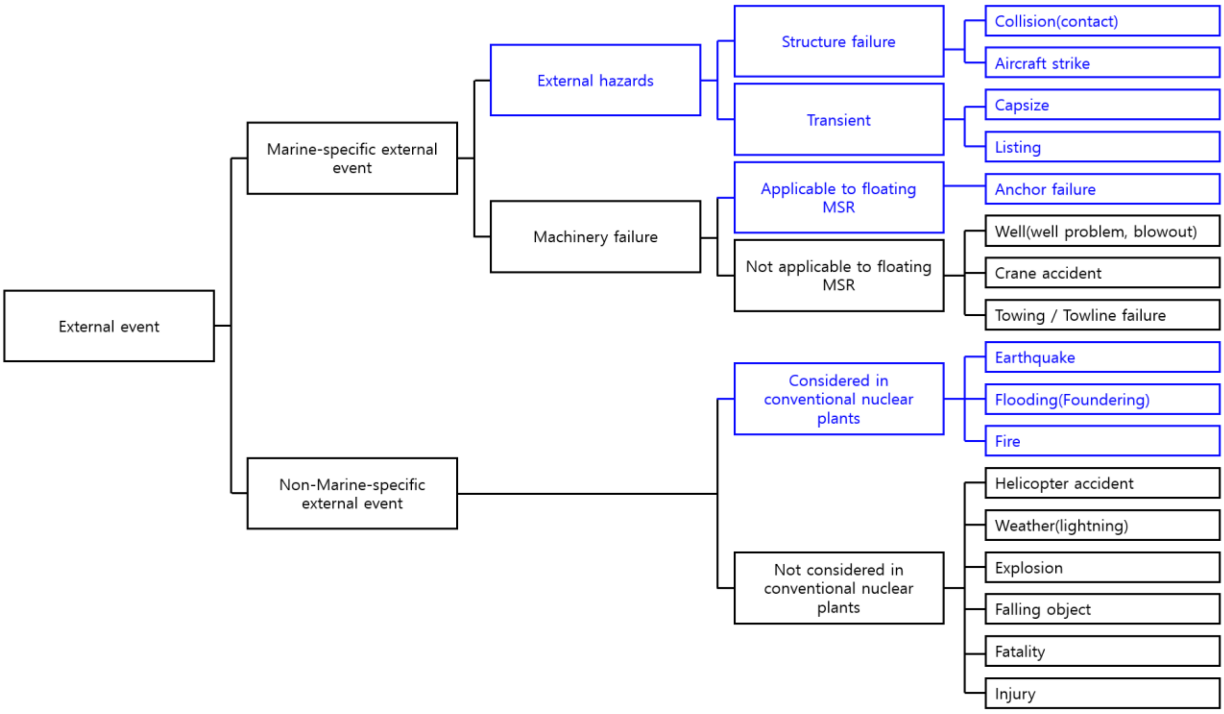

Fig. 3. Framework for classifying external events applicable to floating MSRs

the foundation for developing a PSA model tailored to floating MSRs.

Future work will involve the development of event trees and fault trees for each IE group, followed by quantification to derive failure rates for floating MSR-specific IEs.

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