

Development of a Probabilistic Safety Assessment Framework for Marine Molten Salt Reactors Considering Ocean Motion

Seungmin Lee^a, Dowon Lee^a, Juhyeong Lee^a, Joon-Eon Yang^{a*}, Sungjoong Kim^{a,b}

^aDepartment of Nuclear Engineering, Hanyang University
222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

^bInstitute of Nano Science & Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763
Republic of Korea

*Corresponding author: jeyang25@hanyang.ac.kr

***Keywords:** marine MSR, probabilistic safety assessment, RIPBTI, ocean motion, human reliability analysis

1. Introduction

Molten salt reactors (MSRs) are attracting renewed interest because they combine low-pressure operation, high-temperature heat supply, strong negative reactivity feedback, and flexible fuel-cycle options. In liquid-fueled concepts, fuel salt can also be drained by gravity to geometrically favorable drain tanks for shutdown and decay-heat management. These features make MSRs attractive power sources for marine ships that require compactness, long endurance, and low-carbon operation.

Recent Korean activities indicate that marine MSRs are moving from a conceptual option toward practical ship-integration studies. In 2026, the Korea Atomic Energy Research Institute (KAERI) announced that an MSR-based 15,000 TEU container-ship conceptual design had received Approval in Principle from the American Bureau of Shipping, a U.S.-based ship classification society [1].

Such activities show that licensing, safety assessment, and ship-specific probabilistic safety assessment (PSA) methods are becoming essential to the implementation of marine MSRs. A risk-informed, performance-based, and technology-inclusive (RIPBTI) licensing process provides a practical framework for licensing advanced reactors such as MSRs [2]. In a RIPBTI licensing process, PSA provides risk insights for defining licensing basis events, developing success criteria, classifying safety-significant structures, systems, and components (SSCs), and evaluating the adequacy of defense-in-depth.

However, a PSA methodology tailored to marine MSRs is still immature because the marine environment introduces unique challenges. Unlike land-based MSRs, marine MSRs are continuously exposed to ocean motion and marine environmental loads that can alter both the physical progression of an accident and the reliability of mitigation actions. Ship roll, pitch, heave, vibration, acceleration, and sloshing can affect pump performance, valve actuation, drain line behavior, heat exchanger performance, tank inventory distribution, operator workload, and access to local equipment. Therefore, a PSA for a marine MSR cannot be developed by simply transferring land-based MSR assumptions. A marine MSR PSA should explicitly assess the effects of ocean motion on the technical elements addressed in the

ASME/ANS advanced non-LWR PRA standard, including initiating events, accident sequences, success criteria, systems analysis, data analysis, quantification, and human reliability analysis (HRA) [3]. The objective of this paper is not to produce a best-estimate risk result for a specific shipboard MSR design, but to demonstrate how the effects of ocean motion can be incorporated into a marine MSR PSA framework using the Molten Salt Reactor Experiment (MSRE) component cooling pump (CCP) failure sequence as an illustrative example.

2. Methods and Results

Despite the importance of PSA for marine MSRs, existing PSA studies for MSR applications remain limited. MSRE PSA-related studies provide valuable insights, and the EPRI compilation report summarizes the technical, hazard, and risk analyses performed for the MSRE [4, 5]. In Korea, K. Kim performed a simplified PSA for the KAERI MSR [6]. Y. C. Kim investigated MSR component failure-rate data and discussed how component reliability information should be compiled for MSR PSA applications [7].

Furthermore, even though J. S. Kim performed initiating-event analysis, including floating MSR-specific event groups [8], no complete framework has yet been established for marine MSR PSA. Such a framework should provide a method for evaluating the following PRA technical elements: (1) Initiating-Event Analysis (IE), (2) Accident Sequence Analysis (AS), (3) Success Criteria (SC), (4) Systems Analysis (SY), (5) HRA, (6) Data Analysis (DA), (7) Quantification (QU), and (8) LERF Analysis (LE). In this study, four elements were selected as the initial focus: AS, SC, HRA, and DA. These elements were selected because ocean motion can directly modify the event tree structure, the time available for safety functions, operator performance, and component failure probabilities. The present study focuses on how marine conditions should be reflected in downstream PSA tasks after initiating events have been identified.

The MSRE CCP failure event described in Ref. [4] was selected as the example case. This sequence was selected because it involves several safety functions and

physical phenomena that are particularly sensitive to marine conditions: standby equipment start, freeze-valve thermal behavior, gravity drainage, drain-tank heat removal, containment isolation, ventilation, and operator response. In the original MSRE CCP failure sequence, the normally operating CCP-1 fails, and the operator must respond to a control room alarm and initiate the standby CCP-2. If CCP-2 starts successfully, cooling air is restored to the freeze valve FV-103 and normal operation continues. If CCP-2 fails to start, loss of cooling air allows the frozen salt plug in FV-103 to melt in less than 15 minutes. The fuel salt then drains by gravity to Drain Tank No. 1, where the afterheat removal system must remove decay heat. Without drain-tank heat removal, the fuel salt can approach a temperature that threatens drain-tank structural integrity within approximately 3 hours. Although these studies provide a useful basis for component reliability and initiating event definition, additional modeling is required before their assumptions can be applied to a moving ship environment.

In this study, two supporting analyses were performed for the illustrative ocean-motion case. The first is the FV-103 thawing-time analysis, whose purpose is to determine whether the available time for the operator to start the standby CCP-2 is significantly shortened by ocean-motion-induced changes in local heat transfer and cooling-air distribution. Freeze valve FV-103 is a section of a 1.5-inch pipe machined flat over a length of 50.8 mm with a 12.7 mm gap in which the salt plug is frozen by cooling air. When that air is lost, residual heat in the pipe wall thaws the plug and the fuel salt drains by gravity. The valve is mounted near horizontally with a 3-degree tilt. Fig. 1 shows the valve geometry.

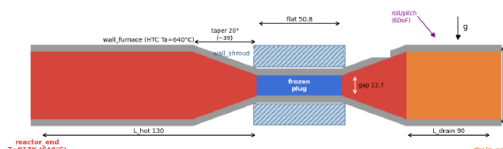


Fig. 1. Valve geometry

The analysis was performed using the icoReactingMultiPhaseInterFoam solver in OpenFOAM v2406 on a 149,760-cell mesh assuming laminar flow. During normal operation, the cooling air keeps the plug frozen, and this cooling corresponds to a heat transfer coefficient of 1,400 W/m²-K. Cooling is lost at $t = 0$, and the transient calculation starts from the frozen steady state. Seal loss is defined as the time at which the liquid fraction of the thinnest plug slab reaches 1 percent. Ship motion is imposed as a time-varying acceleration that reorients the effective gravity vector. All cases share the same mesh, initial and boundary conditions, and time controls. Only the imposed motion differs among cases, and the period is fixed at 10 s. Roll, pitch, surge, sway, and heave were examined. The yaw rotation axis is

parallel to gravity; therefore, yaw does not change the effective gravity vector in this simplified model.

Without motion, the model gives seal loss at 614.5 s and drain initiation at 684.0 s. The seal-loss time lies within the ORNL window of 9 to 11 minutes for the same initial condition[9]. Fig. 2 shows the shift in seal-loss time from the reference of 614.5 s for the examined motion components. Roll is the dominant contributor, and its effect tends to saturate above about 20 degrees. Roll advances seal loss by 1.4, 9.6, 14.4, and 17.3 percent at amplitudes of 10, 20, 30, and 40 degrees. Pitch at 40 degrees advances seal loss by 11.0 percent, comparable to roll at 20 degrees. The effect of the three translational motions is negligible, remaining within 2 percent.

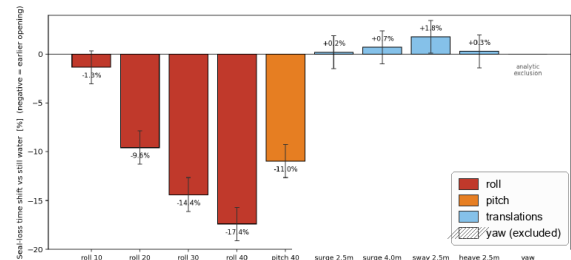


Fig. 2. Freeze valve opening sensitivity to ocean motion

The second is the drain-tank high-temperature and high-pressure response analysis, which evaluates whether ship inclination changes the time margin before drain tank structural challenge by modifying salt distribution, free-surface configuration, effective heat-transfer area, and cooling system performance. Fig. 3 shows the drain-tank afterheat removal system modeled in this analysis. When fuel salt enters the drain tank, water from the feedwater tank drains by gravity into the steam drum, flows down the bayonet downcomer and boils as it rises through the riser annulus, removing heat from the salt in the drain tank. The steam passes to the condenser, condenses and returns to the feedwater tank, so the loop operates by natural circulation.

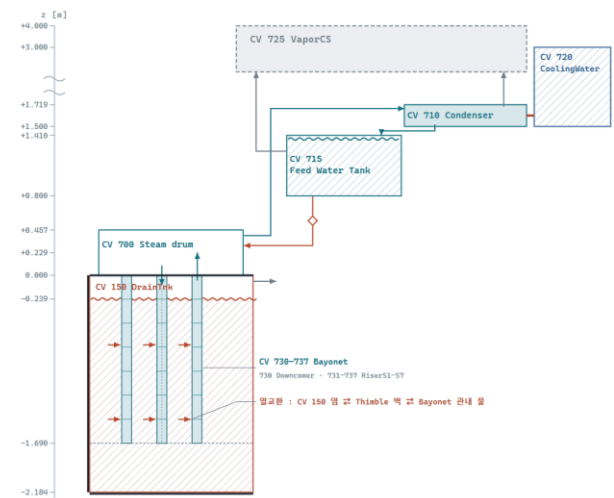


Fig. 3. Drain-tank afterheat removal system of the MSRE

Fig. 4 shows the corresponding thermal-hydraulic nodalization. The analysis was performed with MELCOR 2.2, which resolves the plant-level energy balance coupling the salt pool, the bayonet cooling thimbles and the feedwater loop over a 24-h transient. Loss of component cooling is assumed to start draining the entire fuel salt inventory at 922 K into a single drain tank at $t = 0$. The acceptance criteria follow the original design basis: 977.59 K (1300 °F) for the structures and 549.5 kPa for tank pressure. Pressure peaks near at 106 kPa because the tank vents continuously to the off-gas system and is not limiting.

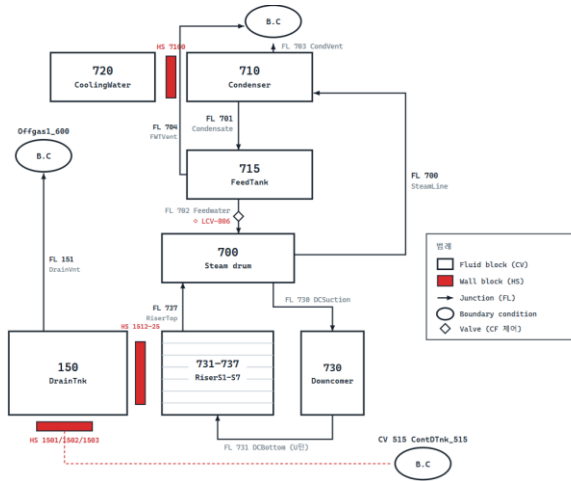


Fig. 4. MELCOR nodalization of the drain-tank afterheat removal system

In this preliminary analysis, ocean motion is represented by a sustained static heel, which is conservatively assumed to bound the effect of dynamic roll on feedwater retention. Only a sustained heel can keep the intakes uncovered long enough for the bayonet tube to dry out. MELCOR cannot rotate the gravity vector, so heel enters the model through three channels: the number of thimbles retaining feedwater, $N(\theta)$, which falls as the heel tilts the steam drum water surface and exposes the feedwater intakes on the uphill side; the natural circulation driving head; and the inclined boiling heat transfer coefficient. The latter two effects, the change in natural-circulation driving head and boiling heat-transfer coefficient, change the peak temperature by less than 0.01 K, so the only material path is the reduction of N .

At heel angles of 0, 30, and 45 degrees the credited thimble counts are 32, 18 and 14. Fig. 5 shows the drain-tank structure temperature response at the three heel angles. Heel raises the peak structure temperature from 924.7 K to 935.6 K and 948.4 K, but all three remain below the 977.59 K limit, with margins of 52.9 K, 42.0 K and 29.2 K. $N(\theta)$ is a step function that reaches 14 at 31.25 degrees and remains there to 60 degrees, so the 45-degree case also bounds heel angles up to 60 degrees. Without feedwater, the structure temperature criterion is exceeded irrespective of heel angle. N is zero at any

angle once the bayonets are dry and the remaining heel effects are too small to change the outcome.

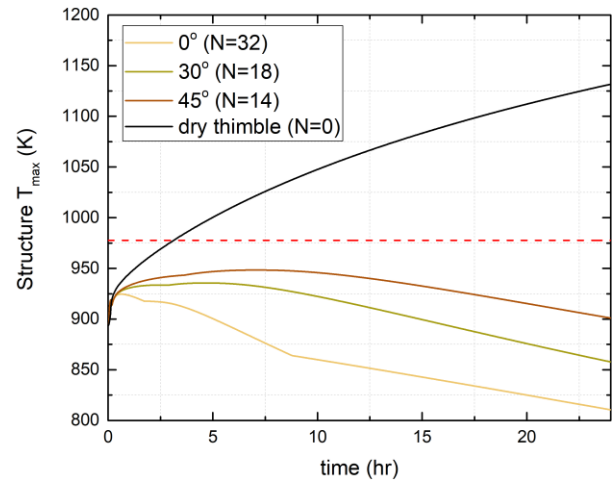


Fig. 5. Drain-tank structure temperature at heel angles of 0, 30 and 45 degrees. Dashed line: design limit 977.59 K.

The results indicate that, for the illustrative ocean-motion cases considered in this study, the original MSRE success criteria for FV thawing and drain-tank heat-up remain applicable within the uncertainty of the simplified supporting analyses. Therefore, the same accident sequences were used for storm conditions, as shown in Fig. 6. Fig. 6 shows the CCP-1 failure event tree revised for marine MSR PSA. The ocean condition branch in Fig. 6 is introduced as a simplified way to represent the conditional effect of marine operating conditions on the subsequent event tree headings. In a full-scope marine MSR PSA, the single ocean condition branch used here could be decomposed into multiple marine states defined by sea state, roll and pitch amplitudes, vibration level, ship speed, and operating mode.

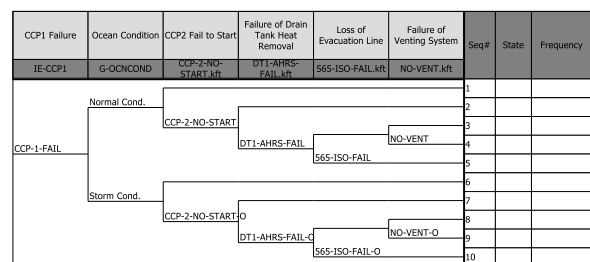


Fig. 6. Revised Event Tree for CCP-1 Failure

The third step is the re-estimation of human error probabilities (HEPs). The PSA supporting analyses show that the available times for some human actions, such as the available time to start CCP-2, are similar to those in the original MSRE PSA. However, the necessary human actions under a 45-degree heel condition are expected to be more difficult than the same actions on land. Therefore, the existing HEP values were multiplied by a factor of five, similar to a simplified sensitivity treatment used in some external-event PSA applications. The

modified HEP values are shown in Table I. The factor-of-five increase in HEP is used only as an illustrative sensitivity assumption to demonstrate how degraded human performance under severe heel conditions can be reflected in PSA quantification. For a more realistic HRA, ocean motion should be treated as a performance shaping factor that separately affects alarm diagnosis, decision-making, communication, local accessibility, manual dexterity, and action execution time. Therefore, HRA for marine MSR PSA should be based on the comparison between action-specific available time obtained from supporting analyses and the required diagnosis and execution time under marine conditions.

Table I: Modified HEP Values for the Storm Condition

Item	Base HEP → Storm HEP	Action
EV3-O	1.0E-3→5.0E-3	Operator fails to successfully start CCP-2
EV7-O	1.0E-3→5.0E-3	Operator fails to initiate closing of drain line valves
EV43-O	1.0E-3→5.0E-3	Operator fails to close HCV-565-A1 on demand
EV57-O	1.0E-3→5.0E-3	Operator fails to maintain operation of stack fan 2
EV126-O	1.0E-2→5.0E-2	Operator fails to open 03HCV-882-C1 on demand

In this illustrative quantification, the storm branch affects only the HEPs listed in Table I; changes in mechanical and electrical equipment failure probabilities are identified as an important topic for future work. Regarding SSC reliability data, the reliability of SSCs used on marine MSRs may be lower than that of the same SSCs used in onshore facilities because marine environmental conditions may affect component reliability through corrosion, humidity, salt deposition, vibration, acceleration, and repeated mechanical loading. Shipboard and offshore reliability databases such as OREDA [10] may provide useful reference data, but their applicability to MSR-specific components should be evaluated with respect to operating temperature, salt chemistry, radiation environment, and safety function. A practical data analysis approach may combine land-based MSR component data with marine environment correction factors derived from shipboard operating experience, qualification tests, and condition monitoring data.

The PSA quantification results are summarized in Table II. In this illustrative quantification, the storm condition is assigned an illustrative probability of 0.05, and the resulting sequence frequencies should be interpreted only as an example of how marine conditions can be propagated through the PSA model. This value should be replaced by a plant- and mission-specific operational profile in a full-scope PSA. The present numerical results are not intended to be definitive because they are based on several simplifying assumptions. The numerical results in Table II should therefore be interpreted as a demonstration of the proposed framework rather than as

a validated estimate of the risk of a specific marine MSR design.

Table II: Quantification Results of the CCP-1 Failure Event Tree

Seq. No.	Freq. (/year)	Condition
1	1.29e-1	Normal Condition
2	1.77e-2	
3	9.54e-5	
4	2.81e-7	
5	2.11e-7	
6	6.80e-3	Storm Condition
7	9.59e-4	
8	5.17e-6	
9	1.51e-8	
10	1.13e-8	

Nevertheless, the objective of this example is to establish a basic framework for marine MSR PSA, and the results are meaningful in that they demonstrate the applicability of the proposed framework. Even in this simplified example, effects of ocean motion propagate through major PSA elements by modifying component failure probabilities, altering event-tree branch probabilities, changing thermal-hydraulic success criteria, and affecting human error probabilities.

3. Conclusions

This paper proposes a preliminary approach for developing a marine MSR PSA framework within a RIPBTI licensing process. Existing MSRE and MSR PSA studies provide useful starting points for initiating-event analysis, component failure-rate development, and event-sequence modeling. However, shipboard MSR applications require explicit treatment of ocean motion. The MSRE CCP failure event tree shows that ocean motion can influence standby equipment start, freeze valve thawing time, gravity drain success, drain-tank heat removal, containment isolation, ventilation performance, and operator action reliability.

The key conclusion is that ocean motion should not be treated as a simple environmental multiplier or secondary correction factor. It can alter accident progression, safety function success criteria, operator response, and the structure of the PSA model itself. The present study should be regarded as an initial framework demonstration. Further work is required to develop validated marine-condition models, component reliability adjustment methods, and HRA guidance for shipboard MSR applications.

ACKNOWLEDGMENTS

This work was supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (RS-2024-

00439210), and the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. RS-2022-NR067165).

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