

Preliminary Study of Xe-135 Reactivity Transient Analysis in a Natural-Circulation Molten Salt Reactor Using a GAMMA+ Coupled Mass Transport Model

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***Keywords:** molten salt reactor, gas sparging, xenon poisoning, natural circulation

1. Introduction

Molten salt reactors (MSRs) have been researched worldwide for their exceptional merits, including higher thermal efficiency and enhanced safety. However, several technical issues remain to be resolved, including chemistry control, material corrosion, and limited operational experience. Among these, the buildup and transport of insoluble fission products (IFPs), including noble metals and noble gases, are technical topics for MSR research. In particular, noble gases, namely xenon (Xe) and krypton (Kr), have long been studied for their reactivity effects [1]. Xe has drawn particular attention owing to its especially large neutron absorption cross section.

Such effects have been thoroughly studied in pressurized water reactors, where Xe poisoning governs start-up and load-following transients [2]. For non-power reactors which typically have a shorter fuel cycle of about 1-2 months, Xe reactivity has a significant effect on core excess reactivity [3]. In MSRs, however, Xe exhibits more complex behavior since it can be transported along with the circulating liquid fuel and removed to the gas cleanup system either through diffusion or gas sparging. The reactivity effect of Xe may be particularly important in natural-circulation MSRs, such as the passive molten salt fast reactor (PMFR), where a change in reactor power alters the density-driven flow rate and feeds back into overall reactor performance [4].

Most MSRs employ helium sparging systems that inject helium bubbles into the primary fuel salt to remove fission product gases. This sparging strips Xe from the system and, simultaneously, the helium bubbles induce bubble-driven flow in the natural-circulation system. During steady-state operation, the gas sparging system should maintain a very low Xe gas concentration in the liquid fuel salt. The Xe removal and the accompanying bubble-driven flow should therefore be investigated to accurately capture their combined effect.

To date, however, no framework has been reported to study this integrated effect in a natural-circulation MSR. In this study, we developed a transient analysis framework that couples the GAMMA+ system code with a Xe bubble-interface mass transport model. In this proposed methodology, the void fraction calculated by

GAMMA+ is passed one-way into the Xe bubble-interface mass transport model to determine the Xe concentration. Xe reactivity worth is estimated based on neutronic constants obtained from the literature. Using this framework, we performed a preliminary sensitivity analysis to quantify Xe reactivity transient effects due to helium sparging operation.

2. Methodology

In this section, the methodology and numerical setup are introduced. GAMMA+ calculates the void fraction of the target system, PMFR. The Xe bubble-interface mass transport model subsequently uses this void fraction to calculate the Xe concentration and corresponding reactivity worth.

2.1. GAMMA+ code

GAMMA+ is a system-level multi-physics code developed by the Korea Atomic Energy Research Institute (KAERI), for the analysis of advanced reactors [5]. GAMMA+ solves one-dimensional mass, energy, and momentum conservation equations. GAMMA+ evaluates the two-phase flow field using a drift-flux model. The interfacial friction correlation is selected from a flow regime map based on the local void fraction and mass flux, distinguishing bubbly, slug, transition, and annular/mist flow. For the bubbly and slug regimes, a combined Kawanishi and Chexal-Lellouche drift-flux correlation is used. In this study, the core and riser void fractions were expected to remain low. The flow therefore stayed within the bubbly regime, with the interfacial coupling governed by this bubbly-branch correlation throughout the primary loop.

The PMFR nodalization, shown in Figure 1, was used to analyze its thermal-hydraulic parameters such as mass flow rate, pressure and temperature, and void fraction. The nodalization includes the lower plenum, the core, the riser, the upper plenum, the primary side of the heat exchanger, the secondary side of the heat exchanger, the downcomer, the helium inlet, and the helium outlet. The riser extends 13.05 m above the 1.95 m tall core, providing the elevation head that drives the natural-circulation flow. The helium injection nozzle is located at the bottom of the riser to keep the injected bubbles

from reaching the core and thereby altering its void fraction and reactivity. Table I summarizes the key design parameters of the PMFR modeled in this study.

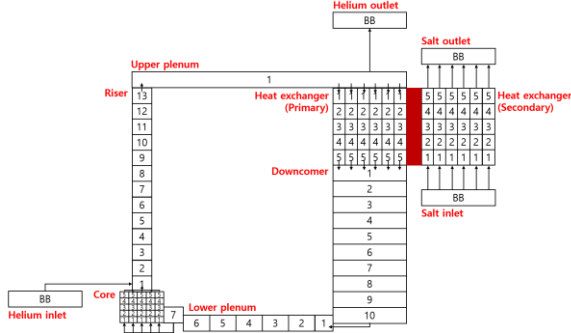


Figure 1. GAMMA+ nodalization for the PMFR analysis

Table I. Design parameters of the PMFR

Parameter	Value
Thermal power [MWth]	200
Primary fuel salt	NaCl-KCl-UCl ₃ (mol% 42.9-20.3-36.8)
Secondary coolant salt	NaCl-MgCl ₂ (mol% 57-43)
Working temperature [°C]	520-700
Working pressure [MPa]	0.1053
Mass flow rate of primary fuel salt [kg/s]	1,686
Mass flow rate of secondary coolant salt [kg/s]	1,500
Diameter of active core [m]	2
Height of active core [m]	1.95
Diameter of riser [m]	0.6
Height of riser [m]	13.05

2.2. Xenon bubble-interface mass transport model

Xe can be transported mainly by two mechanisms, spontaneous diffusion and bubble-interface mass transport [6]. The former is governed by the difference in equilibrium concentration, while the latter is governed by helium sparging. In this study, the spontaneous diffusion term was neglected, since it is not expected to be dominant once helium is continuously injected into the system. Only Xe-135 is considered among the xenon isotopes, given its exceptionally large thermal neutron absorption cross section of 2.6×10^6 barn (b).

The I-135 and Xe-135 inventories are calculated by the coupled balance equations shown in Eqs. (1) and (2). I-135 is produced by the fission chain reaction and removed by decay, as expressed in Eq. (1). Here, t is the time, γ_{I-135} is the fission yield of I-135, Σ_f is the macroscopic fission cross section, ϕ is the neutron flux, λ_{I-135} is the decay constant of I-135, and N_{I-135} is the I-135 number density.

$$\frac{dN_{I-135}}{dt} = \gamma_{I-135}\Sigma_f\phi - \lambda_{I-135}N_{I-135} \quad (1)$$

Xe-135 is produced directly by the fission chain reaction and by the decay of I-135, and removed by decay and neutron absorption, as expressed in Eq. (2). Here, γ_{Xe-135} is the direct fission yield of Xe-135, λ_{Xe-135} is the decay constant of Xe-135, σ_c^{Xe-135} is the microscopic absorption cross section of Xe-135, N_{Xe-135} is the Xe-135 number density.

$$\begin{aligned} \frac{dN_{Xe-135}}{dt} = & \gamma_{Xe-135}\Sigma_f\phi + \lambda_{I-135}N_{I-135} \\ & - \lambda_{Xe-135}N_{Xe-135} - \sigma_c^{Xe-135}N_{Xe-135}\phi - \dot{m}_{Xe-135} \end{aligned} \quad (2)$$

Notably, an additional removal mechanism, bubble-interface mass transport to the helium phase, is introduced as the last term on the right-hand side of Eq. (2). Here, $\dot{m}_{Xe-135}$ is the net mass transfer rate of Xe-135 into the gas phase. The net mass transfer rate is expressed in Eq. (3) as the product of a mass transfer coefficient (K_{Xe-135}), the interfacial exchange area per unit volume (a), and concentration difference ($C_{Xe-135} - C_{Xe-135}^*$). Here, C_{Xe-135}^* is the saturation concentration of Xe-135 at the interface.

$$\dot{m}_{Xe-135} = K_{Xe-135} a (C_{Xe-135} - C_{Xe-135}^*) \quad (3)$$

The interfacial exchange area per unit volume can be obtained from the void fraction (α) and the bubble diameter (d_b), as expressed in Eq. (4). In this study, K_{Xe-135} and d_b were both assumed to be representative constants of 1.0×10^{-4} m/s and 3.0×10^{-3} m, respectively. K_{Xe-135} is of the same order of magnitude as the estimate obtained from the Higbie penetration theory correlation summarized in [6]. The value of d_b follows Scioscioli et al. [7].

$$a = \frac{6\alpha}{d_b} \quad (4)$$

To illustrate the operational significance of the Xe-135 reactivity worth, the corresponding reactor power level was additionally estimated assuming that no corrective action, such as control rod movement, was taken to compensate for the reactivity change. The power level was estimated using the prompt jump approximation, which assumes that the reactivity change is instantaneously reflected in the reactor power, as expressed in Eq. (5).

$$P = P_0 \frac{\beta}{\beta - \Delta\rho(t)} \quad (5)$$

Here, P is the reactor power, P_0 is the reference power of 200 MWth, β is the total delayed neutron fraction, and $\Delta\rho(t)$ is the Xe-135 reactivity worth obtained from Eqs. (1) and (2). In this study, β was assumed to be 0.0065 (650 pcm), corresponding to the delayed neutron fraction of uranium-235 (U-235).

2.3. Simulation conditions and major assumptions

As this is a preliminary study, several simplifying assumptions were applied. Reactor thermal power was fixed at 200 MWth. Reactivity feedback effects, including the fuel temperature coefficient, the void coefficient, and even Xe poisoning itself, were not considered. Table II shows major assumptions employed in this study.

Table II. Major assumptions

Index	Assumption
1	No temperature feedback effect was considered
2	No void feedback effect was considered
3	Only Xe-135 was considered among the xenon isotopes
4	Validated thermal-spectrum nuclear data were used for the Xe-135 absorption cross section
5	Only one-way coupling between GAMMA+ and the Xe bubble-interface mass transport model was considered
6	Spontaneous diffusion of Xe-135 through the free liquid surface was neglected
7	The liquid-phase Xe-135 concentration in equilibrium with the bubble gas was assumed negligible
8	Advection and diffusion of Xe-135 through the circulating fuel salt were neglected

The validated nuclear data were taken from the Massachusetts Institute of Technology Research Reactor (MITR) thermal-spectrum database, since nuclear data for the CI-based fast-spectrum fuel of the PMFR are not readily available. Table III shows the nuclear data employed in this calculation. The resulting one-group Xe-135 microscopic absorption cross section is therefore a thermal-spectrum value, even though the PMFR is a fast-spectrum reactor. Nevertheless, this thermal-spectrum approximation is considered acceptable as a conservative approach. Future work will require a detailed analysis to utilize a 3D neutronic code, such as OpenMC, to generate PMFR-specific nuclear data.

Table III. Nuclear data

Parameter	Value
Σ_f [cm ⁻¹]	1.74
γ_{I-135} [-]	0.0639
γ_{Xe-135} [-]	0.00237
λ_{I-135} [s ⁻¹]	2.93×10^{-5}
λ_{Xe-135} [s ⁻¹]	2.11×10^{-5}
σ_c^{Xe-135} [b]	2.6×10^6

The balance equations, Eqs. (1) and (2), excluding the bubble-interface mass transport term, were validated against measured Xe-135 reactivity transients from the MITR literature. The ratio of the predicted to measured Xe-135 worth at the same simulation time was 0.976 for the startup transient and 0.973 for the shutdown transient.

This agreement indicates that the balance equations, together with the borrowed nuclear data, correctly reproduce the measured Xe-135 transients.

2.4. Test matrix

The test matrix was designed for a sensitivity analysis, consisting of four transient cases, as summarized in Table IV. In every case, the transient is initiated at $t = 10,000$ s (2.78 hr), at which point the helium sparging velocity is instantaneously changed to the value listed in Table IV. The low sparging velocity of 0.7442 m/s was selected to keep the core void fraction below the recommended limit of 1% [8]. The high sparging velocity of 7.442 m/s, a tenfold increase, was then selected as a comparison case.

Table IV. Test matrix

Case	Condition	Initial velocity [m/s]	Final velocity [m/s]
Case 01 (IN-LOW)	Sudden low-rate helium injection	0	0.7442
Case 02 (IN-HIGH)	Sudden high-rate helium injection	0	7.442
Case 03 (HA-LOW)	Sudden halt of low-rate helium injection	0.7442	0
Case 04 (HA-HIGH)	Sudden halt of high-rate helium injection	7.442	0

3. Results and discussion

3.1. Thermal-hydraulic behavior

Figures 2 (a) and (b) show the volume-averaged void fraction in the core and the riser, respectively, for all four transient cases. As intended by the design, the core void fraction remained low in all cases, since the helium injection nozzle is located at the bottom of the riser to prevent void-induced reactivity effects within the core. In Case 02 (IN-HIGH), however, a noticeably higher core void fraction of about 0.4% developed after the switch, compared with below 0.1% in the other three cases.

This behavior is presumed to result from a limitation in the vent model's flow area, rather than from physical migration of helium into the core. At the higher injection rate, the fixed vent area appears insufficient to fully evacuate the injected helium, and the retained gas is thought to recirculate within the loop. Future work should optimize the vent area to accommodate a range of helium injection rates.

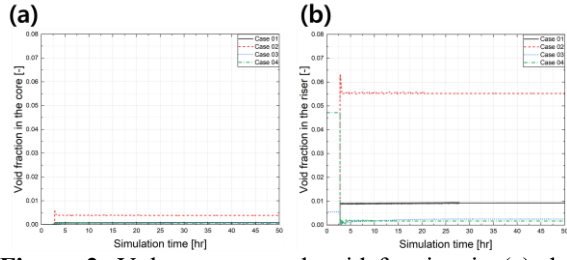


Figure 2. Volume-averaged void fraction in (a) the core and (b) the riser for the four transient cases

In contrast, the riser void fraction evolved differently depending on the transient scenarios. In Case 01 (IN-LOW) and Case 02 (IN-HIGH), the riser void fraction was initially at zero in the absence of helium injection. It increased to about 0.9% and 5.5%, respectively, after helium injection began ($t = 2.78$ hr). In Case 03 (HA-LOW) and Case 04 (HA-HIGH), the riser void fraction was initially maintained at about 0.56% and 4.72%, respectively, under continuous helium injection. Even though helium injection was halted ($t = 2.78$ hr), the void fraction did not return to exactly zero, settling instead to a small residual value of about 0.25% and 0.17%, respectively. This is consistent with the same retained-gas anomaly observed in the core, which is presumed to result from the same limitation in the vent model's flow area.

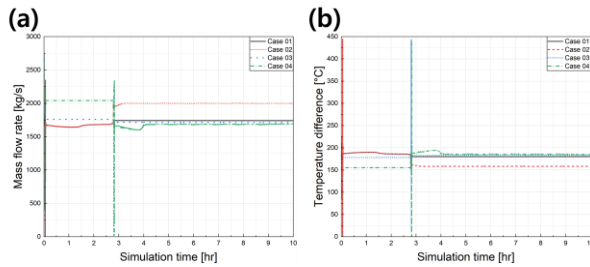


Figure 3. (a) Mass flow rate and (b) temperature difference for the four transient cases

The mass flow rate at the riser exit and the temperature difference between the core inlet and outlet were extracted, as shown in Figure 3. In Case 01 (IN-LOW) and Case 02 (IN-HIGH), the sudden injection of helium increased the natural-circulation flow rate due to the bubble-driven (gas-lift) effect. The mass flow rate increased from 1,686 kg/s to 1,738 kg/s in Case 01 (IN-LOW) and 1,997 kg/s in Case 02 (IN-HIGH). This corresponds to increases of 3.08% and 18.44% in the natural-circulation flow rate, respectively. The corresponding temperature difference decreased from about 185 °C to 180 °C in Case 01 (IN-LOW) and 158 °C in Case 02 (IN-HIGH), since the higher mass flow rate removed the fixed 200 MWth of thermal power over a smaller temperature rise.

In Case 03 (HA-LOW) and Case 04 (HA-HIGH), the sudden halt of helium injection produced the opposite trend, reducing the flow rate from 1,762 kg/s to 1,710 kg/s in Case 03 (HA-LOW) and from 2,043 kg/s to 1,692 kg/s in Case 04 (HA-HIGH), while the temperature

difference increased correspondingly, from 179 °C to 183 °C and from 155 °C to 185 °C, respectively.

3.2. Response of Xe-135 to helium sparging

The Xe-135 concentration and variations in reactivity worth were obtained for each transient case, as shown in Figures 4 (a) and (b). Following the onset of helium injection, the Xe-135 concentration decreased rapidly from $2.99 \times 10^{15} \text{ cm}^{-3}$ to $8.19 \times 10^{13} \text{ cm}^{-3}$ in Case 01 (IN-LOW) and $1.45 \times 10^{13} \text{ cm}^{-3}$ in Case 02 (IN-HIGH). In Case 03 (HA-LOW) and Case 04 (HA-HIGH), the pre-halt equilibrium Xe-135 concentration was $1.53 \times 10^{14} \text{ cm}^{-3}$ and $1.89 \times 10^{13} \text{ cm}^{-3}$, respectively, due to the different helium injection rates. After the helium injection was halted, the concentration slowly converged toward a common equilibrium value of $2.99 \times 10^{15} \text{ cm}^{-3}$, as governed by the coupled I-135 and Xe-135 balance model.

Upon the onset of helium injection, the removal of Xe-135 inserted a positive reactivity of 179 pcm in Case 01 (IN-LOW) and 183 pcm in Case 02 (IN-HIGH), corresponding to reductions of 97.3% and 99.5% in the magnitude of the Xe-135 reactivity worth, respectively. The larger reduction in Case 02 (IN-HIGH) confirms that a higher helium injection rate more effectively suppresses Xe-135 poisoning. Nevertheless, even at the lower injection rate, Xe-135 was already removed almost completely, indicating that the removal efficiency saturates quickly with increasing helium injection rate.

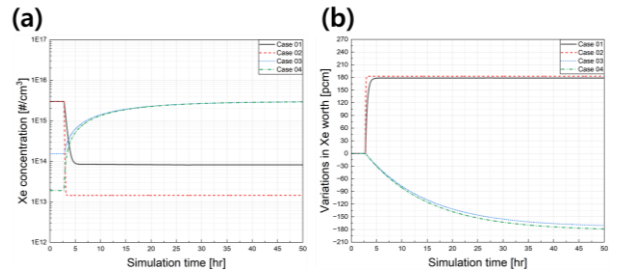


Figure 4. (a) Xe-135 concentration and (b) variations in Xe-135 reactivity worth for the four transient cases

Upon the halt of helium injection, the reduction in Xe-135 removal resulted in a reactivity effect of -172 pcm in Case 03 (HA-LOW) and -181 pcm in Case 04 (HA-HIGH). The slightly larger reactivity change in Case 04 (HA-HIGH) suggests that a higher helium injection rate produces a greater negative reactivity insertion rate. However, this equilibration process proceeds far more slowly than the injection transient, since accumulation of Xe-135 after the halt is governed only by radioactive decay and neutron absorption. As a result, the Xe reactivity requires more than 40 hours to reach a new equilibrium in Cases 03 (HA-LOW) and 04 (HA-HIGH), compared to only a few hours for the injection cases, namely Cases 01 (IN-LOW) and 02 (IN-HIGH).

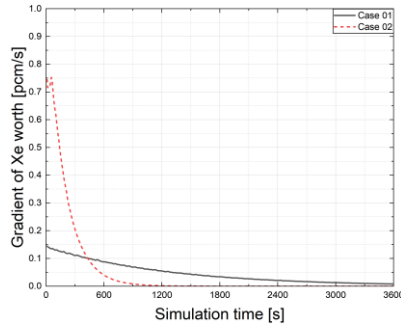


Figure 5. Gradient of the Xe-135 reactivity worth for Case 01 (IN-LOW) and Case 02 (IN-HIGH) during the first 3,600 s of the simulation

Even though the helium injection rate does not significantly affect the Xe-135 equilibrium concentration and worth, it can significantly affect the rate of Xe worth change, as shown in Figure 5. As the helium injection rate increases from 0.7442 m/s to 7.442 m/s, the peak gradient of the Xe worth increases drastically, from about 0.15 pcm/s to about 0.75 pcm/s. In other words, the Xe worth in Case 02 (IN-HIGH) changes much more rapidly immediately after the onset of injection due to its higher helium injection rate, exhibiting a sharp exponential attenuation. In contrast, the gradient of Xe worth in Case 01 (IN-LOW) decreases more gradually over the full 3,600 s window.

Figure 6 shows the reactor thermal power levels corresponding to the Xe-135 reactivity worth shown in Figure 4 (b). Within this 3,600 s window, the power level increased rapidly in Case 01 (IN-LOW) and Case 02 (IN-HIGH), approaching the eventual equilibrium values of about 276 MWth and 278 MWth, respectively. In Case 03 (HA-LOW) and Case 04 (HA-HIGH), the power level decreased only slightly and remained close to 200 MWth within this window, since the corresponding reactivity change develops much more slowly. The power level eventually reached equilibrium values of about 158 MWth and 157 MWth in Case 03 (HA-LOW) and Case 04 (HA-HIGH), respectively, only after about 44 hours. These results indicate that the reactivity effect of Xe-135 removal is large enough to substantially alter the reactor power level in the absence of operator corrective action. This effect also develops on markedly different timescales for the injection and halt transients.

It should be emphasized that these power levels are obtained under one-way coupling, in which the reactor power is fixed at 200 MWth and no reactivity feedback is applied. Since the PMFR fuel salt has a strongly negative temperature reactivity coefficient, the actual excursion would be substantially attenuated and the scram setpoint reached later than estimated here. Figure 6 should therefore be read as an upper bound of the power excursion rather than a prediction of the actual transient.

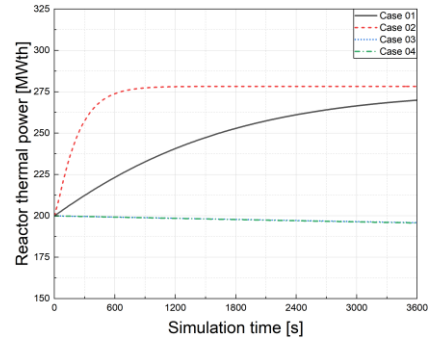


Figure 6. Reactor thermal power levels corresponding to the Xe-135 reactivity worth for the four transient cases during the first 3,600 s of the simulation, estimated using the prompt jump approximation in the absence of corrective action and reactivity feedback

4. Summary and conclusion

A new methodology coupling the GAMMA+ system code and bubble-interface mass transport model was developed to analyze Xe-135 reactivity transient. Using this framework, the thermal-hydraulic behavior of the PMFR and its Xe-135 response to helium sparging were investigated. The major findings of this study are summarized as follows:

- ✓ The mass flow rate increased from 1,686 kg/s to 1,738 kg/s and 1,997 kg/s upon injecting helium bubbles at 0.7442 m/s and 7.442 m/s, respectively.
- ✓ The Xe-135 concentration decreased rapidly from $2.99 \times 10^{15} \text{ cm}^{-3}$ to $8.19 \times 10^{13} \text{ cm}^{-3}$ and $1.45 \times 10^{13} \text{ cm}^{-3}$ upon injecting helium bubbles at 0.7442 m/s and 7.442 m/s, respectively.
- ✓ As the helium injection rate increases from 0.7442 m/s to 7.442 m/s, the peak Xe reactivity insertion rate increases significantly, from about 0.15 pcm/s to 0.75 pcm/s.
- ✓ The timescale to reach Xe equilibrium without gas sparging is on the order of 10's of hours, indicating a very slow transient similar to solid fuel light water reactors. Upon re-starting gas sparging, positive reactivity insertion due to Xe removal drives a power increase on the order of seconds in the absence of reactivity feedback.
- ✓ In the absence of corrective action and reactivity feedback, rapid reactor power level increase upon starting gas sparging system is predicted to exceed overpower scram setpoint, typically 110% of full power, within minutes. This represents an upper bound, but it highlights the practical significance of the Xe-135 reactivity effect on reactor operation.

These results confirm that the thermal-hydraulic performance and the Xe-135 response to helium sparging cannot be treated independently in a natural-circulation MSR. This study elucidates the importance of analyzing Xe-135 response in the operation of MSR and gas

sparging system. Several aspects of this preliminary analysis require further study. Future work will focus on obtaining MSR system design specific information such as nuclear data using OpenMC or Serpent, refining the mass transfer coefficient with detailed gas sparging system design, and improving the vent model to resolve the residual gas retention.

Beyond these, the present one-way coupling will be extended to a two-way scheme in which the Xe-135 reactivity worth is passed to a point kinetics solver and the resulting power is returned to GAMMA+ at each time step. The updated temperature and density fields then feed back into the void fraction and the Xe-135 transport, thereby accounting for the reactivity feedback neglected in this study.

ACKNOWLEDGMENTS

Funding support for W. Choi is provided by Korean Institute for Advancement of Technology (KIAT) grant funded by the Korea Government (MOTIE) (RS-2024-00435157, Human Resource Development Program for Industrial Innovation (Global)). Additionally, this work was also 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).

REFERENCES

- [1] Taylor, Z., Salko, R., Graham, A. M., Collins, B. S., & Maldonado, G. I. (2022). Implementation of two-phase gas transport into VERA for molten salt reactor analysis. *Annals of Nuclear Energy*, 165, 108672.
- [2] Roggenkamp, P. L. (2000). The influence of Xenon-135 on reactor operation. *Proc. 50 Years of Excellence in Science and Engineering at the Savannah River Site*, 49-56.
- [3] L. Tan, L. Hu, "Verification and Validation of the MITR Simulator for Xenon Transients", *Transactions of the American Nuclear Society*, vol. 133, November 2025.
- [4] Lee, J., Song, M. S., Jae, S., Yang, W. S., & Kim, S. J. (2025). Multiphysics Analysis of Natural Circulation-Driven Operation of Passive Molten Salt Fast Reactor and Effect of Guide Structure. *International Journal of Energy Research*, 2025(1), 6052359.
- [5] Tak, N. I., Lim, H. S., Hong, J., Yoon, J., Park, B. H., & Eoh, J. (2022). Improvement of GAMMA+ code for system transient and thermo-fluid safety analysis of sodium-cooled fast reactors. *Nuclear Engineering and Design*, 399, 112002.
- [6] Evans, A., Rakib, G. S., & Vergari, L. (2026). Physics and engineering review of gas sparging in molten salt reactors. *Nuclear Engineering and Design*, 446, 114624.
- [7] Scioscioli, F., Cammi, A., & Lorenzi, S. (2024). Analysis of the operational and safety features of the In-Core bubbling system of the Molten Salt Fast Reactor. *Nuclear Science and Engineering*, 198(6), 1288-1307.
- [8] Mochizuki, H. (2023). Study on start-up of molten salt fast modular reactor from shutdown based on two-phase flow CFD analysis. *Nuclear Engineering and Design*, 414, 112560.