

Considering Helium Bubble Behavior for Gaseous Fission Product Removal in Molten Salt Reactors: A Literature Review

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1. Introduction

Molten salt reactors (MSRs) are one of the advanced nuclear systems proposed within the Generation IV International Forum [1]. Unlike conventional light-water reactors that rely on solid fuel rods, MSRs employ molten alkali and actinide fluoride salts, either as a circulating fuel or as a coolant for solid fuel. This liquid-fueled concept enables high heat capacity, operation at low pressure, and compact system design, making MSRs fundamentally different from traditional reactor technologies. Due to these features, MSRs are considered well-suited for applications that demand enhanced safety, high energy density, and flexibility, including marine propulsion and ocean-based power generation. [2].

Although classified as a Generation IV reactor, research on molten salt reactors (MSRs) has been conducted since the mid-20th century. Early studies addressed Xenon transport and poisoning effects, leading to models that incorporated bubble and migration mechanisms to capture steady-state and transient behavior [3-7]. More recent work has expanded these efforts to system-level models, isotopic effects, alternative fuel cycles, and flow-dependent analyses [8-11].

Overall, Xenon modeling has evolved from simple graphite and bubble interactions toward more comprehensive and diverse approaches supporting modern MSR development [12].

Table I: Summary of the research subject of MSR.

Year	Research subject
1960s ~ 1970s	- Modeling of fission product behavior in molten salt. - Experimental study on a molten salt reactor.
2000s ~ 2025	- Investigation of fission product behavior via simulation. - Enhance the accuracy of the model reflecting the physical phenomena.

This study presents a literature review on fission product removal in molten salt systems to highlight the need for models that explicitly incorporate the behavior of injected helium. Whereas earlier research has primarily addressed removal mechanisms, the dynamics

of helium used for extracting gaseous fission products have received relatively little attention, despite their importance for developing more comprehensive models.

2. Literature Review

2.1 Fission products in molten salt Reactor

In molten salt reactors, the nuclear fuel is dissolved in the molten salt, and this mixed fuel circulates throughout the entire reactor system. Fission products are generated through the nuclear reactions occurring within this circulating fuel.

Based on previous MSR studies, four classes of fission products can be identified: gaseous, soluble, insoluble, and sometimes soluble [13].

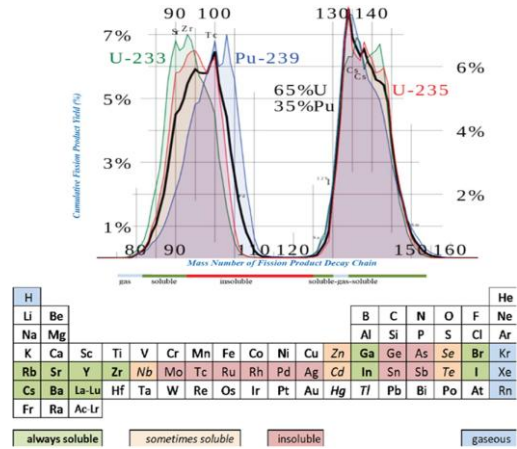


Fig. 1. Fission yield curve of the molten salt reactor [13]

In particular, among the four classes of fission products, extensive research has previously focused on gaseous fission products. This is because gaseous species, such as xenon and krypton, strongly absorb neutrons, cause significant reactivity fluctuations, and can be more readily removed from the circulating fuel salt compared to other fission product classes [14].

2.2 Effects of Gaseous Fission Products

Xenon-135, one of the major gaseous fission products (GFPs), is a strong parasitic neutron absorber with a thermal cross section of about 2.6 Mb while its

metastable form, Xe-135m, exhibits an even larger cross section of 10.17 Mb [12].

In molten salt reactors, the low solubility of gases in fuel salt leads to the formation of bubbles that circulate with the liquid fuel. These entrained gases arise from fission product generation, radiolysis, or mechanical agitation, and their presence can displace fuel, alter moderation.

Consequently, voids within the circulating salt influence system reactivity and dynamic response, making accurate prediction of gas behavior and its reactivity impact essential for reactor design and operation [15].

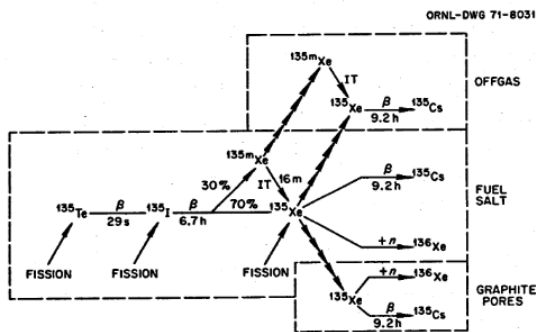


Fig. 2. Schematic of the decay chain of Xe-135 [7].

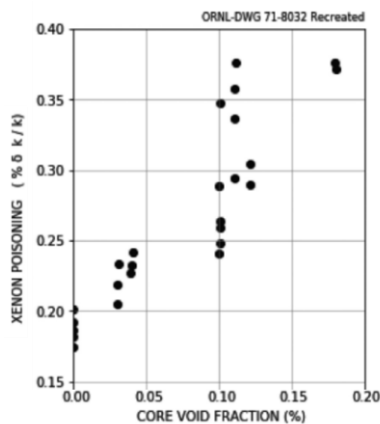


Fig. 3. Xenon poisoning according to the core void fraction in MSRE [12].

2.3 Helium injection for GFP removal

To enable the removal of fission products from the molten salt without shutting down reactor operation, the Molten Salt Reactor Experiment (MSRE) adopted a helium bubbling system, in which helium was injected into the fuel salt to capture gaseous fission products and subsequently removed from the salt stream [16].

The mechanism of the removal of GFPs is as follows:

1. Helium gas was injected into the circulating fuel salt to remove GFPs. Helium entered through an injection line and was dispersed into the molten salt, forming bubbles within the salt stream.

2. These bubbles acted as carriers, capturing GFPs with very low solubility in the molten salt. The frothy fuel salt then passed through the spray tower, where the entrained gases separated from the liquid phase.
3. The cleaned fuel salt rejoined the primary loop, while the off-gas stream containing helium and radioactive gases was discharged and treated through the off-gas system.

In this way, helium bubbling provided a continuous and effective mechanism for GFPs removal without interrupting reactor operation [17].

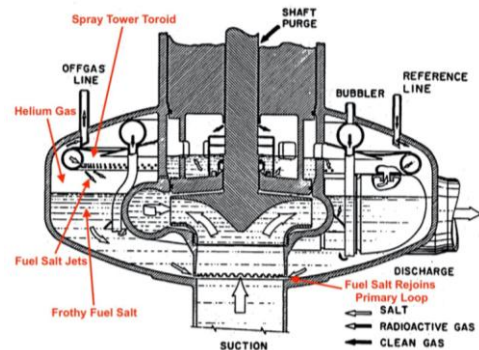


Fig. 4. Schematic of helium injection for gaseous fission product removal in MSRE [17]

Since the MSRE, this concept has been further investigated in various studies. More recently, research efforts, particularly in Europe, have focused on in-core helium bubbling, where helium is injected directly into the reactor core rather than externally as in the MSRE, and active computational analyses have been conducted to evaluate its effectiveness via a multi-physics framework to reflect the unique physical phenomena in molten salt [18].

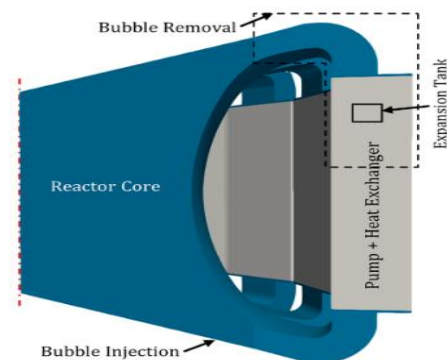


Fig. 5. Simple geometry of MSR with in-core helium bubbling system.[18]

2.4 Importance of Helium behavior consideration

In the MSRE, it was observed that the extent of Xenon removal was strongly influenced by the quantity of helium introduced into the system. [7] Beyond the void

fraction, a critical parameter governing Xenon removal is the ratio of interfacial area to void volume. The interfacial area, in combination with the mass transfer coefficient, dictates the rate of Xenon transfer from the molten salt to the bubbles. Although Xenon models for MSRs developed at Oak Ridge National Laboratory (ORNL) often assumed spherical bubble geometry for simplicity [12].

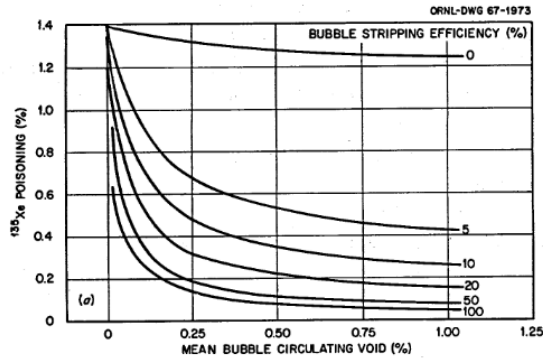


Fig. 6. Xenon poisoning changes as to removal rate and helium fraction [7]

Visualization studies of helium bubbles in molten salt, as shown in Fig. 7, revealed that the bubble shapes were not spherical but exhibited significant deformation during their rise. The bubbles were observed to oscillate and tilt while moving upward, and their trajectories deviated from straight vertical paths. These observations indicate that the interfacial area between the bubbles and the molten salt can differ considerably from that of idealized spherical bubbles. Consequently, careful consideration of bubble dynamics is a critical aspect in the fission product removal modeling [19].

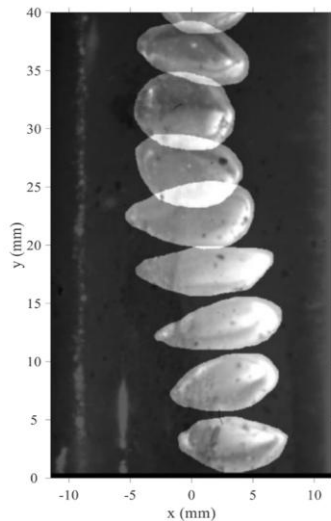


Fig. 7. Visualization data from single helium bubble rise experiment [19]

Building on these findings, the visualization results demonstrate that non-spherical deformations of bubbles

can significantly alter the effective interfacial area. Since Xenon removal is directly proportional to the available interfacial area, the observed variations in bubble shape and motion become decisive factors for accurately predicting removal efficiency.

Also, in a multi-physics analysis study of the Helium bubbling system, it was found that assuming a uniform distribution of injected helium within the molten salt resulted in significantly lower thermal power compared to the case where a non-uniform distribution, calculated from the simulation, was applied. [20]

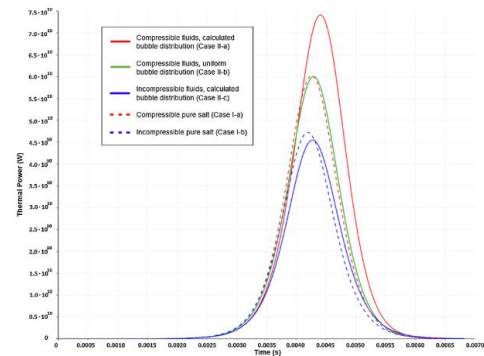


Fig. 8. Thermal power differences based on helium bubble distribution [20].

The helium bubble distribution was calculated without considering bubble behavior. However, coalescence and breakup must be included to accurately predict gas distribution, as they are the key mechanisms that alter bubble sizes. Figure 9 illustrates that, in a water–nitrogen system, small bubbles gradually disappear while larger ones become more prevalent, resulting in a bimodal size distribution that strongly affects interfacial area and mass transfer. Although this result is based on water, similar phenomena are expected in molten salt; therefore, incorporating bubble dynamics into the analysis is essential for capturing realistic bubble distributions and for accurately evaluating helium behavior in molten salt systems. [21].

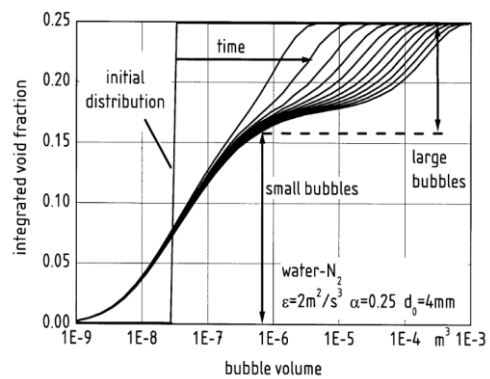


Fig. 9. Bimodal bubble-size distribution observed during nitrogen injection into water [21]

Taken together, these findings indicate that variations in helium bubbles within molten salt, driven by their dynamic behavior, can significantly influence not only the efficiency of fission product removal in the bubbling system but also the overall power generation of the molten salt reactor.

3. Conclusions

In this study, a literature review was conducted on GFPs removal in molten salt reactors, with particular focus on helium bubbling systems. The review covered historical experimental studies, such as the MSRE, as well as more recent computational and multi-physics analyses that examined xenon behavior, helium injection mechanisms, and the effects of helium bubbles distribution.

From these works, it is evident that helium quantity, distribution, and bubble geometry critically affect xenon removal efficiency and reactor power. Therefore, accurate modeling of helium bubble behavior, including void fraction, interfacial area, and non-uniform distribution, is essential for reliable performance assessment.

In this context, further development of solvers based on the Volume of Fluid (VOF) model, along with their integration into multi-physics frameworks for neutronics and fission product removal, is recommended to improve predictive capability and guide the design of helium bubbling systems in future molten salt reactors.

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