Modeling and Thermal Performance Evaluation of a Phase Change Material based Passive Safety System for the Passive Molten Salt Fast Reactor using the GAMMA+ Code

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1. Introduction

The development of fast spectrum reactors capable of closing the fuel cycle is essential to ensure the sustainability of nuclear energy. Among potential candidates, Molten Salt Fast Reactors (MSFR) are highly promising due to their ability to combine high-temperature, low-pressure operation with the operational flexibility of liquid fuel. In this context, a Passive Molten Salt Fast Reactor (PMFR) concept has been designed targeting a long-life core to ensure continuous operation for over twenty years. The PMFR operates without online fuel replacement and is designed to maintain high safety margins without relying on a drain tank.

The absence of a drain tank imposes a strict requirement for a highly reliable and robust system to remove decay heat during postulated transient scenarios, such as a Loss of Heat Sink (LOHS) event. To address this, a passive safety system based on a Phase Change Material (PCM) is considered. Positioned around the reactor vessel, this system aims to minimize heat loss acting as a thermal insulator during normal operation, while seamlessly transitioning into a high-capacity heat sink to ensure safe decay heat removal during accidents. Preliminary studies by Im et al. [1] have demonstrated the theoretical feasibility of this concept.

To rigorously evaluate the thermal performance of this system, the GAMMA+ systems analysis code is employed. Because GAMMA+ does not natively resolve the moving-boundary physics of the melting front of the PCM, a specific modeling strategy was developed. The PCM, Reactor Vessel (RV), and Containment Vessel (CV) are modeled as a multi-layer radial wall. Within this framework, natural convection and latent heat are accurately represented by defining an effective thermal conductivity and an effective specific heat capacity, enabling real-time adjustment of thermal properties during the transient.

The primary objective of this study is to confirm the effectiveness of the PCM system in mitigating LOHS accidents. Furthermore, to verify the robustness of the numerical approach and guide future design choices, this paper introduces sensitivity analyses. These include an assessment of mesh discretization to ensure the stability of the numerical solution, and an evaluation of the containment vessel's surface emissivity to characterize its critical impact on radiative decay heat removal.

2. Design of the PCM passive safety system

The proposed passive safety system is integrated into the annular space between the reactor vessel and the containment vessel of the PMFR, organized into multiple vertical cells. According to Im et al. [1], the structures utilize Hastelloy-N, while the PCM employs a NaCl-KCl eutectic salt.

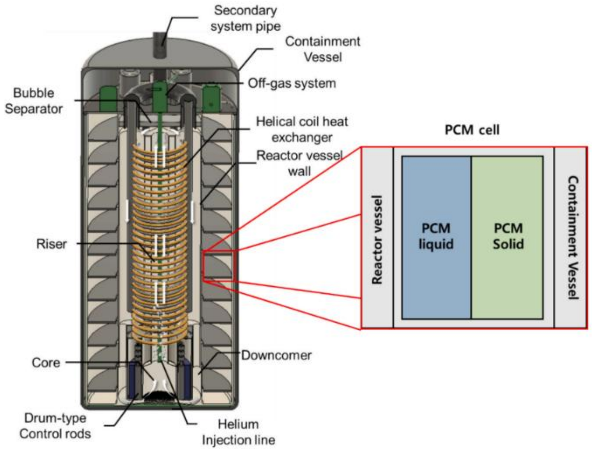

Fig. 1 Schematic of the PMFR and the PCM-based Passive Safety System. Im et al [1].

The system operates based on the state-dependent thermal properties of the Phase Change Material :

Normal Operation (Solid State): The PCM remains solid, acting as a thermal insulator. Heat transfer occurs solely via low-conductivity conduction, minimizing parasitic heat losses and preserving overall plant efficiency.

Accident Conditions (LOHS): As temperatures rise, the PCM melts. The phase change not only absorbs latent heat but also triggers natural convection within the liquid phase. This significantly enhances the heat transfer rate from the RV to the environment, ensuring efficient passive decay heat removal.

The PCM properties are the same as described in Im et al [1].

Table 1: Properties of the materials

Materials & parameters	**Values**
PCM salt properties	NaCl-KCl Eutectics
Heat of fusion	308 kJ/kg
Melting point	656 °C
Heat capacity	894 J/kg.K
Viscosity	1.5 mPa.s
Density	1507 kg/m3
Thermal conductivity	1.35 W/m.K (solid), 0.45 W/m.K (liquid)
Structural material	Hastelloy-N
Maximum allowable temperature	1000 °C (linear extrapolation)
Heat capacity	871 J/kg.K
Density	8860 kg/m3
Thermal conductivity	20 W/m.K
Emissivity	0.5

3. Modeling Strategy in GAMMA+

The thermal-hydraulic analysis is performed using the GAMMA+ systems analysis code. A significant limitation of the code is the absence of a freezing model within the fluid block module, meaning it cannot natively resolve the moving-boundary Stefan problem associated with phase transitions. Consequently, modeling the Phase Change Material as a fluid block is unfeasible. To overcome this, the PCM is modeled as a continuous, multi-layered solid wall block, enabling the specification of temperature-dependent physical properties. However, because the code calculates heat transfer in solid walls purely by conduction, this static representation neglects the natural convection currents that develop once the PCM melts. To realistically capture this convective enhancement, a quasi-steady approach is employed. The complex geometry of the actual melt front is simplified by assuming heat transfer is governed by the average length of the molten layer. This treats the irregular liquid zone as a uniform vertical enclosure subject to 1-D radial heat transfer. An effective thermal conductivity is then introduced for the liquid phase, derived from standard Nusselt number correlations. A remaining challenge is that the melt front evolves continuously, yet GAMMA+ cannot track the melt front position. Therefore, a closure relation was formulated by linking the melt front to the local material temperature. Based on the analytical solution of the one-dimensional Stefan problem which states that melt front propagation is proportional to the square root of time, a temperature-dependent square-root relationship was implemented. This ensures the effective thermal conductivity increases realistically, mimicking the progressive expansion of the convective zone.

3.1 Latent Heat of Fusion

The energy absorption associated with the phase transition is represented by defining an effective specific heat capacity [2]. This approach enables the real-time adjustment of the material's thermal properties during transient simulations, successfully capturing the thermal inertia as the PCM reaches its melting point.

$$(1)\quad c_{p,eff} = \begin{cases} c_{p,sol} & T < T_m - \Delta T \\ c_{p,sol} + \frac{L}{2\Delta T} & T_m - \Delta T \le T \le T_m + \Delta T \\ c_{p,liq} & T > T_m + \Delta T \end{cases}$$

3.2 Natural Convection

An important modeling issue occurs in the liquid phase: the code structure treats the PCM as a static solid wall, inherently neglecting the natural convection currents that develop upon melting. Because convection significantly enhances heat transfer compared to pure conduction, an effective thermal conductivity is introduced for the liquid phase [3]. This effective property relies on the Nusselt number correlation for a vertical enclosure [4] (with coefficients set to C=0.046, m=1/3, and n=0). In this model, the relevant temperature difference is evaluated between the varying hot wall (T1) and the cold boundary at the solid-liquid interface (T2), which is fixed at the melting temperature.

$$(2)\qquad \frac{k_{eff}}{k} = C\,(Gr * Pr)^m \left(\frac{L}{\delta}\right)^n$$

$$(3)\qquad Gr = \frac{g\beta(T1 - T2)\delta^3}{\nu^2}$$

$$(4)\qquad \mathrm{Pr} = \frac{c_p \mu}{k_{liq}}$$

3.3 Closure Relation (Stefan Problem)

A fundamental limitation in GAMMA+ is that the characteristic length evolves continuously, yet the code cannot track the position of the melt front. Therefore, a closure relation linking it to the local material temperature was formulated. This relation is based on the analytical solution of the one-dimensional Stefan problem (Neumann solution) [5][6], which states that the propagation of the melt front follows a diffusion law proportional to the square root of time. Implementing this square-root relationship ensures that the effective thermal conductivity increases realistically from the phase change interface up to the peak accident temperature, thereby mimicking the progressive expansion of the convective zone within the static mesh.

$$(5)\qquad \delta(t) \propto \sqrt{t}$$

$$(6)\qquad \delta(T) \propto \sqrt{T}$$

To formalize this substitution and implement it into the code, a scaling law was introduced to map the theoretical expansion of the liquid layer onto the expected operating temperature range of the LOHS event. This scaling law effectively normalizes the melt front propagation. By bounding the problem between the onset of melting and the maximum predicted fuel temperature (Tmax), the instantaneous liquid thickness can be expressed as a function of the local temperature:

$$\delta(T) = \delta_{max} * \left(\frac{T-T_m}{T_{max}-T_m}\right)^{0.5} \quad (7)$$

3.4 Gamma+ nodalization and geometric assumptions

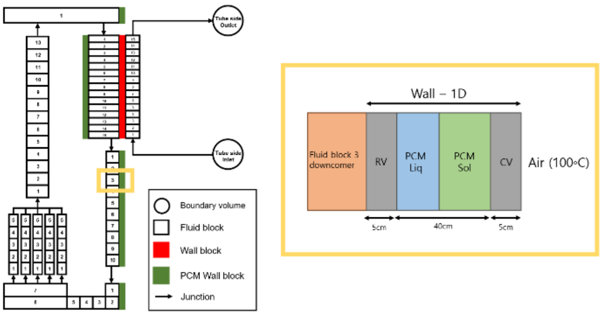

Fig. 2 Nodalization of the PMFR and the PCM-based Passive Safety System in GAMMA+.

In the numerical model, a multi-layered wall structure is thermally coupled to each fluid block along the primary circuit. To ensure accurate heat transfer calculations, the axial discretization of the wall structure strictly matches the nodalization of the adjacent fluid blocks.

The radial domain is discretized into 10 nodes to capture the temperature gradients and the phase change propagation. The layers are arranged from the inner to the outer surface as follows:

- 1 mesh representing the Reactor Vessel, 5cm.
- 8 meshes representing the Phase Change Material, 40cm.
- 1 mesh representing the Containment Vessel, 5cm.

Consistent with the 1-D wall modeling capability of GAMMA+ used in this section, heat transfer within these solid structures is assumed to be exclusively radial. Finally, the external boundary condition applied to the outer surface of the Containment Vessel simulates combined heat transfer via radiation and natural convection to a constant ambient air heat sink maintained at 100°C. The emissivity of the Hastelloy-N is taken as 0.5 to be in the same condition as Im et al [1].

For this transient analysis, the initial steady-state conditions were established assuming a baseline operating thermal power of 200 MWth. Following the LOHS event, the internal heat source is strictly dictated by the decay power transient, which was modeled according to the ANS73 standard.

3.5 Sensitivity cases

To validate the proposed modeling strategy and rigorously assess the thermal-hydraulic robustness of the passive safety system, sensitivity analyses were conducted on two parameters.

First, a PCM Mesh Sensitivity analysis was performed to evaluate how the transient thermal response calculated by the GAMMA+ code is dependent of the radial spatial discretization applied to the PCM wall.

Second, an CV Emissivity Sensitivity analysis was conducted to evaluate the physical impact of the reactor vessel's surface conditions. Given that radiative heat transfer constitutes the dominant decay heat removal mechanism at elevated temperatures during a LOHS event, this analysis quantifies how variations in the Hastelloy-N emissivity influence the overall cooling efficiency.

Table 2: Sensitivity cases

PCM Mesh Sensitivity	**CV Emissivity Sensitivity**
4	0.15
8 (reference)	0.30
18	0.50 (reference)
28	0.65
X	0.85

4. Results and discussions

Figure 3 represents the temperature in the exchanger over time of each mesh sensitivity case during a LOHS. The radial spatial discretization of the Phase Change Material significantly influences the transient thermal response calculated by the GAMMA+ code. As illustrated in the mesh sensitivity results, a notable discrepancy of more than 70°C in the peak fluid temperature is observed between the coarsest configuration (4 mesh) and the finer configurations (18 and 28 mesh).

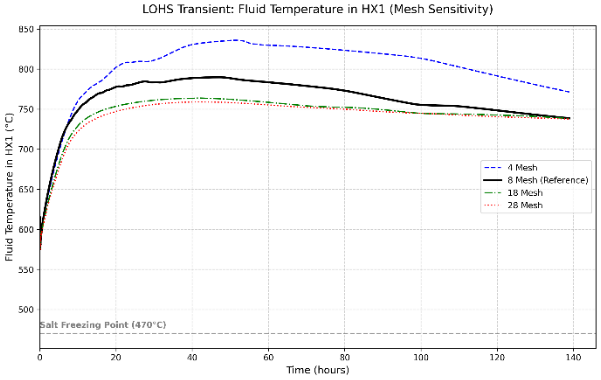

Fig. 3 Temperature in the exchanger over time of each mesh sensitivity case during a LOHS

Figure 4 expresses the temperature in the exchanger over time of each CV emissivity sensitivity case during a LOHS. The sensitivity of the thermal response to the containment Vessel's surface emissivity was analyzed using values ranging from 0.15 to 0.85. The transient results indicate that the initial heating phase and the resulting peak fluid temperature are uniform across all tested configurations; the curves are superposed during the temperature rise. A small divergence among the cases only becomes apparent during the subsequent cooling phase. As the 140-hour transient progresses, the spread between the curves gradually narrows, with all configurations continuously trending toward similar temperature ranges.

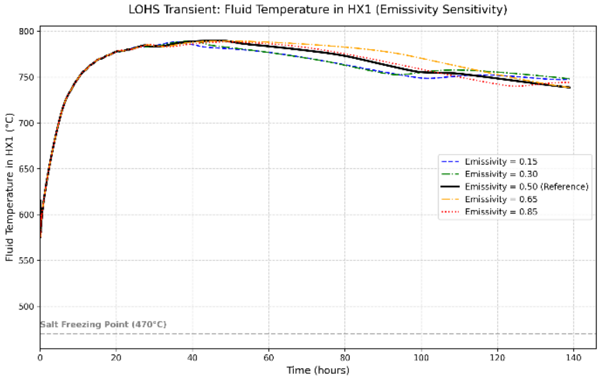

Fig. 4 Temperature in the exchanger over time of each CV emissivity sensitivity case during a LOHS

Despite the variations observed in the peak temperatures and the subsequent cooling rates across the different sensitivity cases, a fundamental safety conclusion can be drawn from these results. In all simulated configurations, the Phase Change Material-based passive safety system successfully limits and controls the initial temperature surge. The maximum fluid temperature consistently remains well below the allowable structural limits of the Hastelloy-N vessel. The PCM remains partially molten during the entire transient, indicating that the latent heat reservoir is not exhausted and the system retains additional safety margins. Furthermore, the results demonstrate that the decay heat is effectively and continuously evacuated to the ultimate heat sink. This confirms that the passive cooling mechanism is robust, ensuring that the reactor is maintained in a safe and stable state throughout the entire long-term LOHS transient.

5. Conclusions

This study investigated the feasibility of a Phase Change Material–based passive safety system for decay heat removal in a Passive Molten Salt Fast Reactor during a Loss of Heat Sink event.

Because the GAMMA+ code cannot directly model phase change with moving boundaries, a dedicated modeling strategy was developed using temperature-dependent effective thermal properties and a closure relation inspired by the Stefan solution. This approach enabled the representation of latent heat absorption and the convective enhancement occurring in the molten PCM within a static wall framework.

The simulation results demonstrate that the PCM system effectively mitigates the LOHS transient. The high thermal inertia of the melting PCM successfully buffers the initial temperature surge, maintaining the reactor vessel well below its structural limits and ensuring safe long-term decay heat removal. Sensitivity analyses revealed that a sufficiently refined mesh is necessary to avoid numerical thermal resistance and accurately capture the melt front propagation. Furthermore, the vessel's surface emissivity has a marginal impact on the peak temperature. Overall, the PCM-based system proves to be a robust and reliable passive safety solution for the PMFR during a LOHS without relying on a drain tank.

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REFERENCES

[1]. J. Im et al., Thermal performance evaluation of passive safety systems adopting phase change material applicable for passive molten salt fast reactor, Nuclear Engineering and Design 445 (2025) 114497.

[2]. K. Peippo et al., A multicomponent PCM wall optimized for passive solar heating, Energy and Buildings, 17 (1991) 259-270.

[3]. Z. Liao et al., A novel effective thermal conductivity correlation of the PCM melting in spherical PCM encapsulation for the packed bed TES system, Applied Thermal Engineering 135 (2018) 116–122

[4]. J.P. Holman, Heat Transfer, McGraw-Hill, 2010.
[5]. Carslaw, H.S. and Jaeger, J.C. (1959) Conduction of Heat in Solids. Clarendon Press, Oxford.
[6]. P. Jany and A. Bejan, Scaling theory of melting with natural convection in an enclosure, Int. J. Heat Mass Transfer. Vol. 31, No. 6, pp. 1221-1235, 1988