GAMMA+ Simulation for Pre-conceptual MSR Emergency Shutdown

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1. Introduction

GAMMA+ (General Analyzer for Multi-component and Multi-dimensional Transient Application) code [1] is continually being developed to enhance safety analysis of Non-Light Water Reactors (non-LWRs). Recent advancements for molten salt reactors (MSRs) include:

1) Nuclide groups transport kinetics (NTK): In 2022-2023, GAMMA+ implemented and validated NTK modeling for circulating delayed neutron precursors and decay heat nuclides [2, 3]. This capability has been further refined since its initial implementation for an accident scenario involving drainage.

2) Gas-liquid and freezing models: Models for simulating gas-liquid phase and freezing phenomena within MSR systems were implemented and verified in 2024, though they are not yet publicly available.

This paper presents simulations of emergency shutdown scenarios without drain for a conceptual MSR design. We analyze the temperature behavior of fuel salt and solid structures. The impact of pony pumps on primary side mass flow during such accidents is also investigated, considering their potential effectiveness in designs where natural circulation is not reliable.

2. Methods and Results

Fig. 1. schematically depicts the reference MSR. This three-loop system circulates fuel salt, coolant salt, and gas. The chosen fuel and coolant salts are KCl-UCl_3 and $NaCl$-$MgCl_2$, respectively. The core structure comprises top-bottom plenums, a reactor vessel, reflectors, shielding material, an absorber, and control drums, and insulators.

The primary loop includes pumps, piping, HX1 (hot side), an expansion tank, and a drain tank. The secondary loop also has pumps, piping, HX1 (cold side), HX2 (hot side), expansion tanks, and a drain tank. Finally, the tertiary loop has HX2 (cold side) and power conversion components utilizing gas.

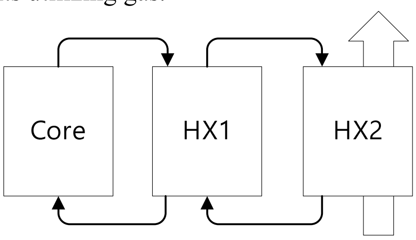

Fig. 1. Schematic diagram for reference reactor.

Major operating conditions are presented as ranges in Table I. A GAMMA+ input model was developed for system components, with steady-state values showing agreement within 0.70% of the operating conditions.

Table I: Operating conditions of reference MSR

Parameters	Nominal value
Reactor power (MWth)	< 10
Fuel salt temperature in primary loop (°C)	> 600
1st loop mass flow rate (kg/s)	> 400
2nd, 3rd loop mass flow rate (kg/s)	< 100
Heat loss (%)	0.4% of reactor power

2.1 Shutdown procedure

The accident scenario assumes that upon trip signal activation, negative reactivity of 5000 pcm is inserted over 5 seconds with a 0.1-second signal delay. The fuel and coolant salt pumps are tripped at 0.1 seconds after shutdown over 5 seconds, following homologous curves. Gas flow stops at 0.1 seconds after shutdown over 3 seconds. Primary loop pony pumps begin operation at 5.1 seconds, achieving full pump head within 3 seconds.

2.2 Nominal case

GAMMA+ simulation results for the 7-day (168-hour) post-shutdown period under nominal conditions are presented in Figs. 2-7. Heat values in Figs. 3 and 8 are normalized against nominal operating conditions. In the legend, "DP" represents the pressure rise due to the pony pump, where "DP0" indicates no pony pump operation and "DP100" denotes a 100 Pa pump head.

As illustrated in Fig. 2, the primary loop mass flow rate approaches zero (below 0.1%) at 0.39 hours post-shutdown. Natural convection fails to establish due to the minimal elevation difference between the core and HX1, coupled with negligible heat transfer through the HX1. The primary loop mass flow rate recovers to a few kg/s at approximately 24.9 hours, when heat loss surpasses total generated power, as shown in Fig. 3. Fig. 4 depicts the maximum and minimum temperatures of fuel salt and solid wall. Until 24.9 hours, insufficient heat removal capability and stagnant fluid cause maximum temperatures to rise in both fuel salt and solid walls. After 24.9 hours, limited fuel salt circulation equilibrates temperatures between the core and loop regions. Temperature differences of tens of degrees Celsius persist between maximum and minimum temperatures in both core and loop regions throughout the simulation.

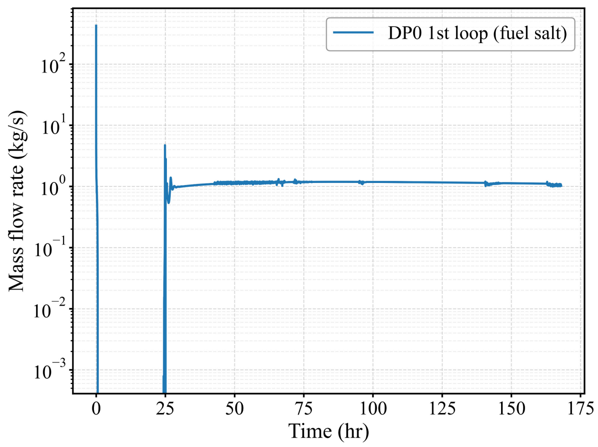

Fig. 2. Mass flow rate vs. time in primary loop.

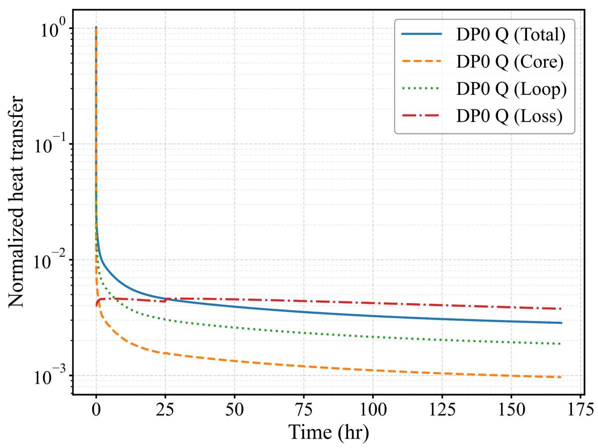

Fig. 3. Normalized heat transfer vs. time.

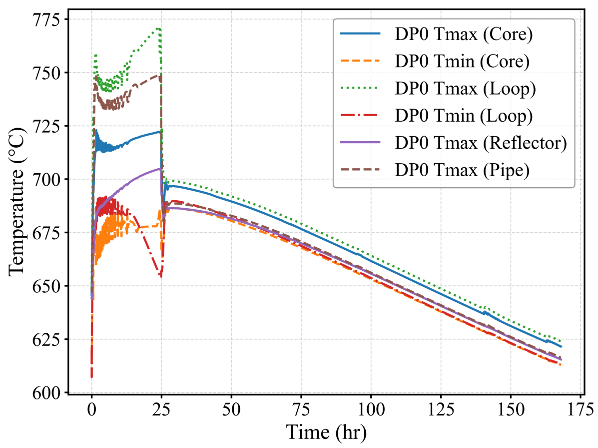

Fig. 4. Temperature vs. time in primary loop.

The operation of the primary loop pony pump maintains a mass flow rate in tens of kg/s when the head is greater than 300 Pa, as demonstrated in Fig. 5. Higher mass flow rates correlate with lower maximum fuel salt loop temperatures, as shown in Fig. 6. Increased pump head reduces temperature differences between maximum and minimum fuel salt temperatures in the loop.

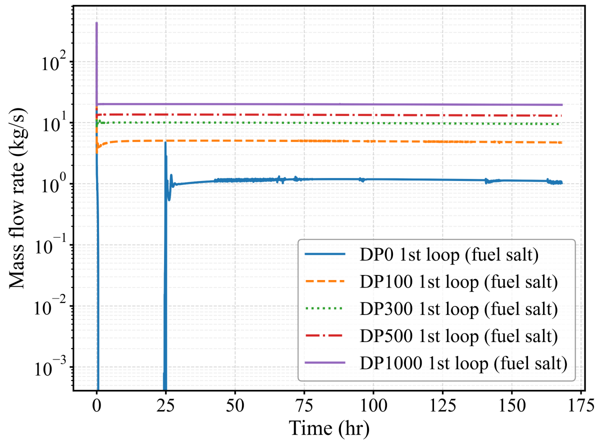

Fig. 5. Mass flow rate vs. time in primary loop with/without pony pump operation.

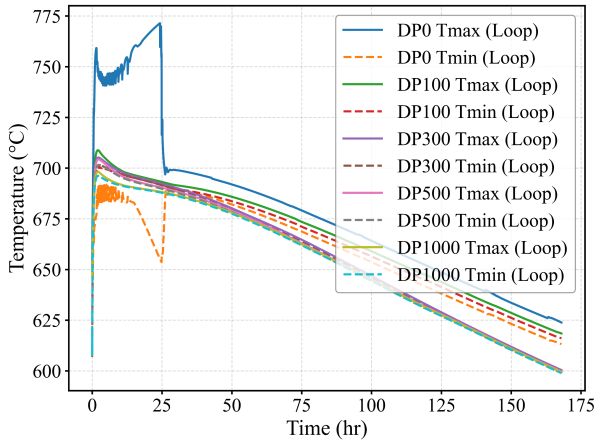

Fig. 6. Temperature of fuel salt vs. time in primary loop with/without pony pump operation for nominal cases.

Fig. 7 illustrates temperature behaviors of fuel salts, reflectors, and insulators for the "DP500" case. Mass and heat capacity of structures, combined with circulation, facilitate fuel salt temperature reduction. Consequently, fuel salt temperature peaks occur 2.3 hours post-shutdown, while reflector and insulator temperature peaks appear approximately 24.9 hours post-shutdown.

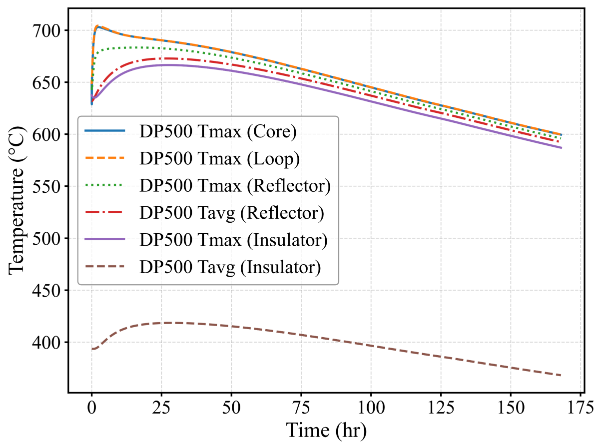

Fig. 7. Temperature of fuel salt and solid vs. time for "DP500" nominal case.

2.3 Conservative case

For conservative safety analysis, reactor power and three-loop mass flow rates were set to 102% of nominal values, with a decay heat multiplier of 1.2. Table II presents temperature increases relative to the nominal case steady-state conditions.

Table II: Operating conditions of reference MSR

Parameters	Conservative value compared to nominal value
Reactor power (MWth)	1.02
1st ,2nd ,3rd loop mass flow rate (kg/s)	1.02
Core exit temperature (°C)	+ 4.0 °C
Maximum reflector temperature (°C)	+ 4.0 °C
HX1 exit temperature in 2nd loop (°C)	+ 3.9 °C
Gas exit temperature in 3rd loop (°C)	+ 4.1 °C

As shown in Fig. 8, heat loss in the conservative case exceeds total generated power at 41.5 hours post-shutdown, representing a 16.6-hour delay compared to the nominal case (24.9 hours). This delay results in distinct fuel salt temperature behavior patterns in conservative cases, as illustrated in Fig. 9. Conservative case fuel salt temperatures continue rising again until 28.2 and 31.4 hours for "DP500" and "DP1000" cases, respectively. Conservative cases maintain approximately 20-50 K higher temperatures than nominal cases.

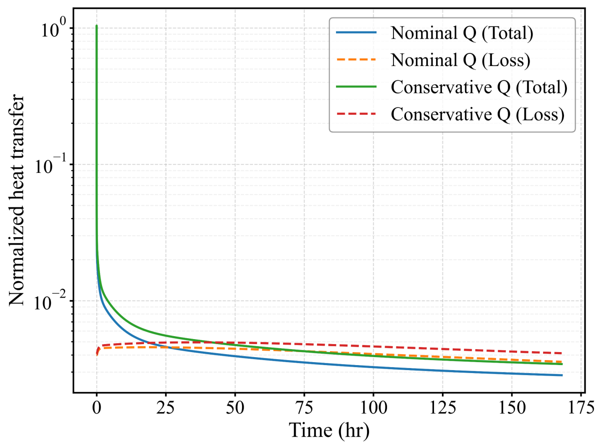

Fig. 8. Normalized heat transfer vs. time for nominal and conservative cases.

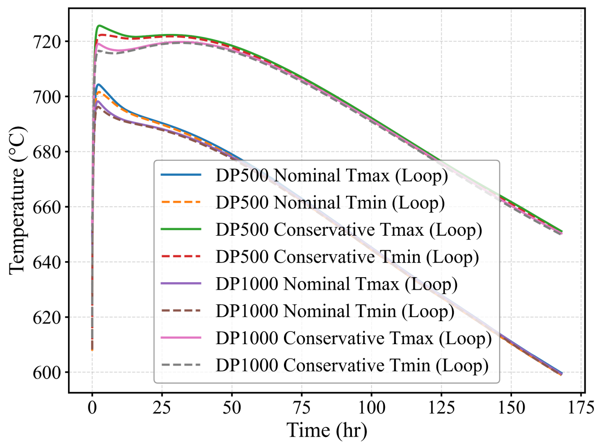

Fig. 9. Temperature of fuel salt vs. time in primary loop with pony pump operation for nominal and conservative cases.

3. Conclusions

We conducted simulations of pre-conceptual MSR emergency shutdown, incorporating reactor scram and pump trips. Results indicate that primary loop pony pump installation and operation benefits maximum fuel salt temperature management in systems lacking natural circulation capability during accidents. Conservative case (102%) analyses reveal maximum fuel temperature increases of approximately 20-50 K compared to nominal case (100%) conditions.

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REFERENCES

[1] H.S. Lim and H.C. No, GAMMA Multidimensional Multicomponent Mixture Analysis to Predict Air Ingress Phenomena in an HTGR, Nuclear Science and Engineering, Vol. 152, pp. 87-97, 2006.

[2] H.S. Lim, "핵종-이송 동특성 모델 장착", 과제회의 발표자료 (2022).

[3] S.H. Yoon, N.I. Tak, and H.S. Lim, "Validation of GAMMA+ Code Using Reactivity Insertion Tests of MSRE", Transactions of the Korean Nuclear Society Spring Meeting, 2023.