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Preliminary Study of Conceptual Design of Passive Residual Heat Removal System for PMFR Safety

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1. Introduction

Small Modular Reactors (SMRs) have been aggressively developed to make nuclear energy utility more flexible and safer than large reactors. However, small power of SMRs have limited early commercialization due to the diseconomies of scale. Therefore, SMR developers have been focusing on improving the economic feasibility of SMR through modular design.

Application of generation IV (GEN IV) reactor technology is also one of the powerful economical improve drivers as well as safety. The Generation IV International Forum, launched by the U.S Department of Energy, designated six advanced reactors under development as Gen IV reactors. The common goals of Gen IV reactors were improving power generation efficiency and reducing spent nuclear fuel compared to the current nuclear reactor system. According to the IAEA report [1], about 55% of currently developing or developed SMRs are advanced GEN IV reactors such as molten salt reactors (MSRs) or high temperature gas-cooled reactors (HTGRs).

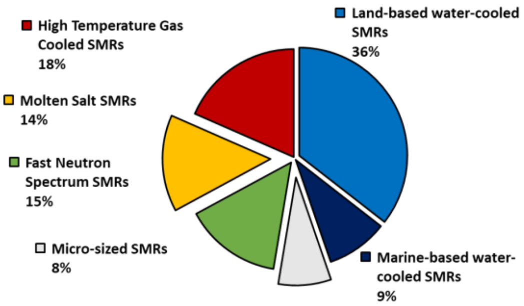

Figure 1. Types of under developing or developed SMRs (2020)

Passive molten salt fast reactor (PMFR) is also a kind of these advanced SMRs, especially MSRs. Currently, the association of the universities has been conducting research on the technology of reactor physics, thermohydraulics and materials for PMFR.

The unique feature of the MSRs is fissile materials are dissolved with the coolant. Thus, the fuel salt can be drained into tanks connected to the cooling system when the abnormal situations. However, in the case of PMFR, there may be not enough space to place the drain tank at the bottom of the reactor because PMFR is designed as a compact modular containment vessel. Therefore, a dedicated safety concept and system design is required.

The purpose of this study is to investigate the safety requirements for PMFR and to derive a suitable conceptual design. In this study, the containment cooling capacity for PMFR is preliminary estimated and the new concept of the safety system based on the results are introduced.

2. Safety requirements for PMFR

7.1. Preliminary design of PMFR

Figure 2 shows the layout of the primary system of PMFR. The main components of the PMFR are a core and a riser, six helical-coil heat exchangers, and downcomers. A two-phase flow occurs from the core to the riser as helium is injected from the bottom of the core. The helium bubbles are released by the separator and moves through the upper gas region to the off-gas system and the helium circulation system.

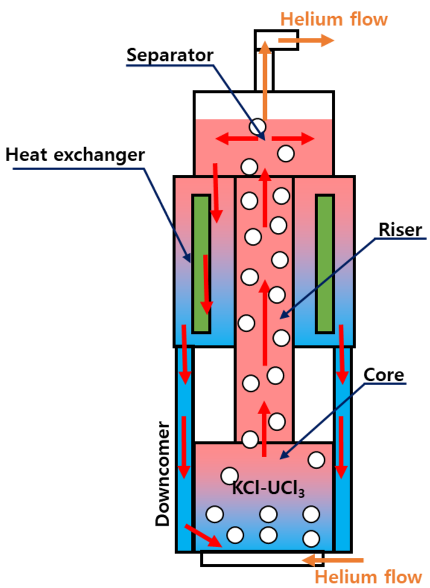

Figure 2. A schematic of the PMFR primary system

The PMFR has a modulated metal containment filled with a clean salt (KCl-NaCl), as illustrated in figure 3. The salt act as a radionuclide release barrier such as fuel salt to accumulate the fissile materials and fission products by dissolving. The melting point of KCl-NaCl eutectic compound is 657°C at 1 atm. Due to the temperature difference between the melting point and ambient air the salt may solidify and form a crust layer at the interface of the containment vessel.

The output power of PMFR can be determined by the natural circulation force by the temperature difference and the helium injection [2]. 250MWt was assumed in this study.

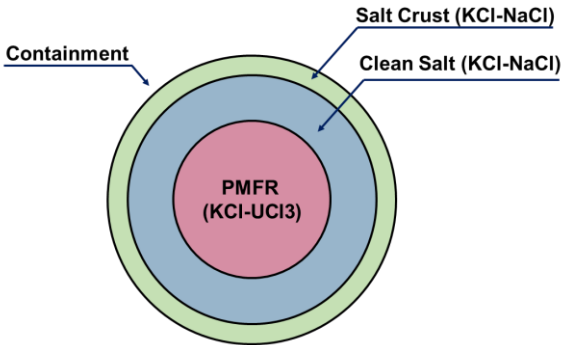

Figure 3. A schematic of the radial view of PMFR

7.2. Safety requirements for PMFR

The goal of reactor safety is to limit the release of radioactive materials to the environment. The containment vessel of the PMFR is the important final barriers of radionuclide release. Therefore, the integrity of the containment vessel must be guaranteed firstly.

The internal factors that threaten the integrity of the containment vessel can be divided into overheating and overpressure. Boiling of the molten salt can pressurize the reactor system and the containment vessel. Therefore, the role of the decay heat removal function that prevent boiling of molten salt is expected to be significantly important to maintain the containment vessel, which is the ultimate barrier of PMFR.

When the secondary system pump and primary system helium injection are not available, decay heat could be only removed by surrounding air through the metal containment in current PMFR design. This type of cooling system is commonly found called as reactor vessel auxiliary cooling system (RVACS) in high-temperature reactors such as HTGR. However, in the case of PMFR, the difference is that the system cools the containment vessel, not the reactor vessel.

7.3. Cooling capacity estimation for PMFR containment

Depending on the performance of direct air cooling of the containment vessel, it is possible to evaluate whether the decay heat is removed, and the integrity of the containment vessel. The decay heat removal performance was evaluated with a simplified one-dimensional modeling of PMFR.

As illustrated in figure 4, PMFR system was modeled 4 nodes: PMFR reactor layer, clean salt layer, salt crust layer. Because of higher conductivity of the metallic materials, Temperature distribution of reactor and containment vessel was neglected.

The salt mass of PMFR reactor layer was found based on the geometric structure. However, it was assumed to be an arbitrary value of the mass of the formed crust and the clean salt. Because only conduction heat transfer exists in the crust layer, high thermal resistance is expected at the layer. It means this crust layer assumption may act as a dominant uncertainty factor in this preliminary analysis. Thus, to confirm the difference in the amount of heat removal according to the thickness of the crust, additional analysis was performed on the case without the crust layer.

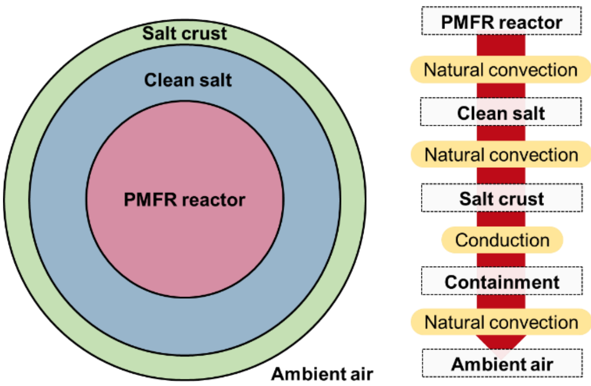

Figure 4. Nodalization for cooling capacity estimation

Table 1 Parameters for cooling capacity estimation

Parameters	Values
Reactor	
Thermal power	250 MW_t
Fuel salt mass	130.7 ton
Clean salt mass	564.23 ton (Assumed)
Salt crust mass	120.64 ton (Assumed)
Initial fuel temp.	700°C
Salt properties	
Salt composition	
$UCl_3 – UCl_4 – KCl$	36.03%-9.1%-54.9% (mol)
KCl-NaCl	56%-44% (mol)
Heat capacity	
UCl_3 [3]	129.7 J/mol·K
UCl_4	Assumed (129.7 J/mol·K)
KCl [4]	73.6 J/mol·K
NaCl [4]	67 J/mol·K

Figures 5 and 6 show heat removal rate (figure 5) and fuel salt temperature (figure 6) of this preliminary estimation. At the beginning, the amount of decay heat rate was higher than the amount of heat removed for each case, so the fuel salt temperature rises rapidly. The amount of heat removed also increases rapidly due to the heating of the salt inside the containment vessel.

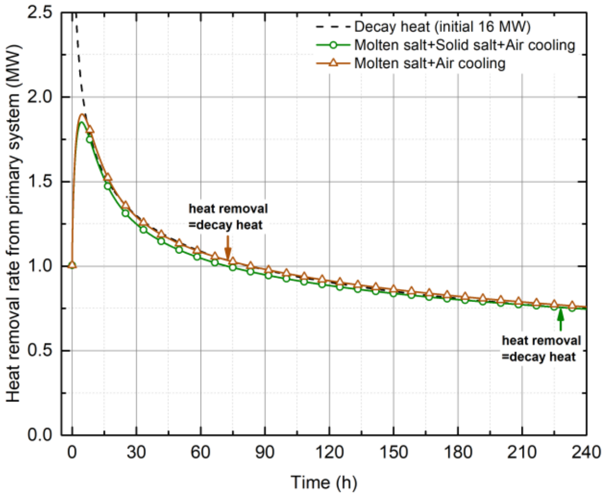

Figure 5. Cooling capacity of PMFR with or without solid salt crust

The cooling of the fuel salt was delayed due to the low thermal conductivity of the solid crust, but the maximum fuel salt temperature was 1430K, which was kept lower than the boiling point of the fuel salt (~1700K).

On the other hand, if there is no solid salt layer inside the initial containment, the fuel salt temperature reaches 1184K and then cools. The results of this analysis suggested that the internal temperature of the reactor vessel can be maintained below the boiling point of fuel salt only with passively air-cooled containment. However, these results are derived from the assumed crust buildup mass. If the crust built-up is underestimated, it may not cool the reactor sufficiently.

4. Alternative passive safety system triggered by helium decompression

From the results of preliminary analysis, the effect of the built-up crust on the heat removal of containment was confirmed in an accident. In this study, a new concept of safety system is proposed to overcome this limitation of containment cooling capacity. The purpose of this conceptual design is to ensure the long-term passive residual heat removal capacity of the containment vessel by rapidly removing the crust in the vessel at the early stage of an accident.

One alternative is to transfer the decay heat directly to the crust. Furthermore, if decay heat can be directly removed by the containment vessel, not through the crust layer, it will be significantly efficient as illustrated in figure 5 and 6. For this, the fuel salt must be guided to the crust or the containment wall for heat transfer.

A conceptual design using the helium circulation system of PMFR was carried out to satisfy these requirements. Figure 7 shows the schematics of the system. In normal conditions (a), the helium injection piping maintains a continuous supply of helium to the bottom of the reactor. To maintain this helium circulation, the helium is pressurized by the compressor. Thus, the check valves are placed to prevent the helium flow into the separator in the normal operation.

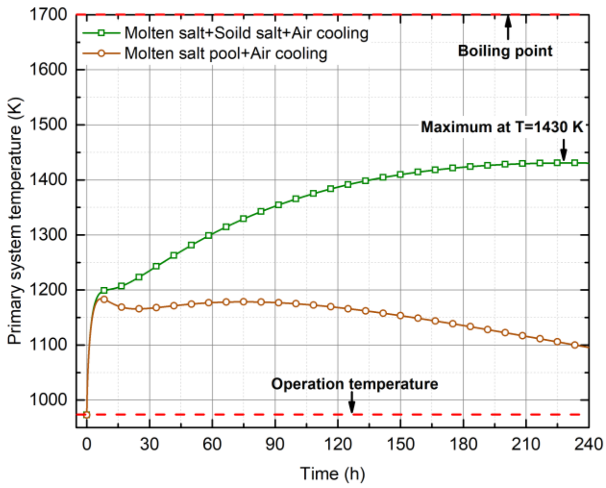

Figure 6. PMFR reactor temperature with or without solid salt crust

The pressurized helium injection system can be depressurized by the compressor shutdown (b). Due to helium decompression, the helium injection line connected to the bottom of the reactor can act as a flow path for the molten salt driven by gravity. The main function of the proposed passive safety system is to provide a heat exchange space that can directly cool the source of decay heat when the helium circulation is shutdown.

As the fuel salt backflow level in the helium injection line reaches the pipe connected to the separator tank, the gravity-induced flow weakens. However, the natural circulation caused by the cooled salt will continue the salt circulation.

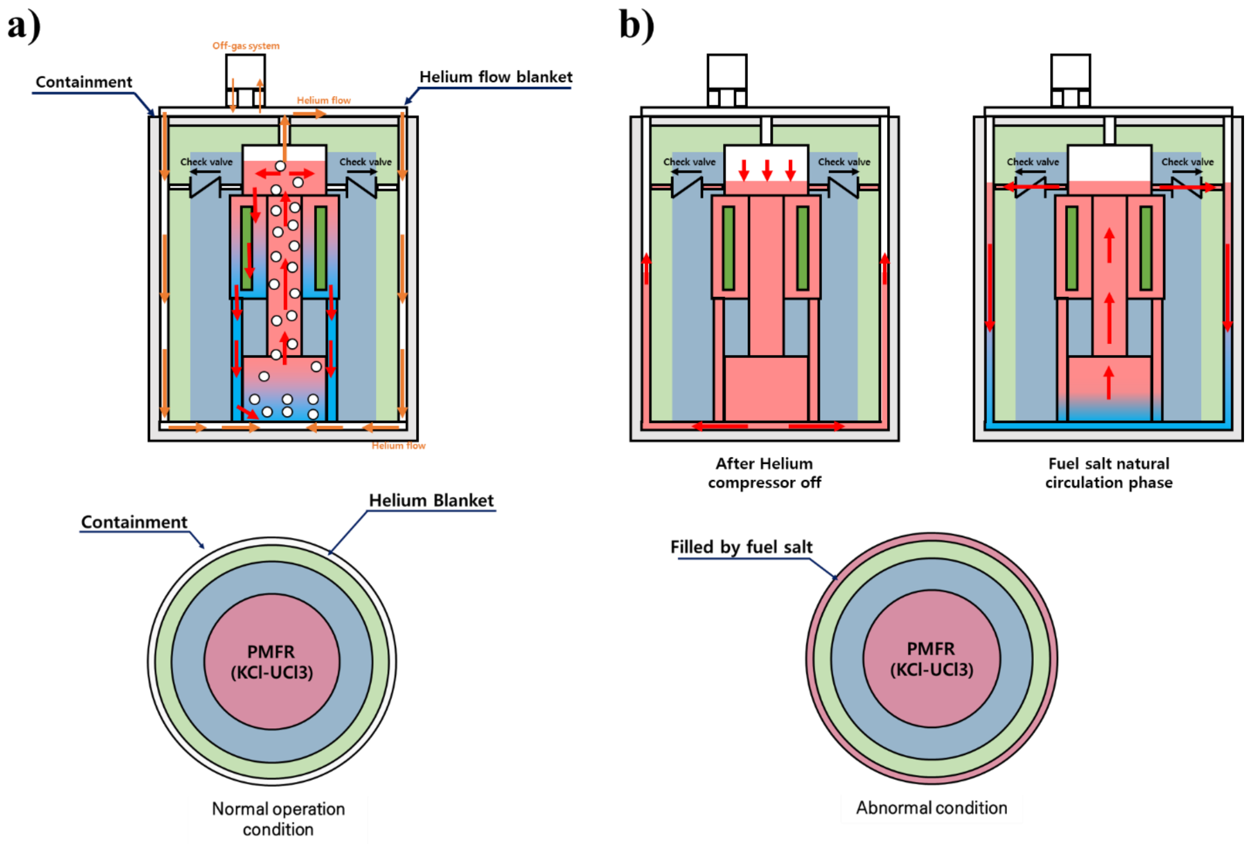

Figure 7 Schematics of Alternative passive safety system a) normal operation condition b) abnormal condition

5. Conclusion

This study investigated the safety systems of PMFR, which is conceptual SMR enhanced by the technology of the molten salt reactor. As a first step, a preliminary analysis of the cooling capacity was performed based on the PMFR geometry. The results showed that the cooling capacity could be deteriorated due to the solid salt crust existing in the containment. As a solution to this, a conceptual safety system triggered by helium decompression was presented. We will proceed with preliminary analysis to investigate the feasibility of the conceptual safety system.

Acknowledgments

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