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Combined Safety Analysis on Gallium-based Passive Decay Heat Removal System of Ultra-long Cycle Fast Reactor

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1. Introduction

As one of the most promising types of Gen IV reactors, the sodium fast reactor (SFR) offers various concepts that reinforce the advantages and suppress the disadvantages of the sodium-cooled reactors. The long cycle fast reactor is one of the SFR designs operating in a long cycle without refueling. As one of the long cycle fast reactors, the Ultra-long Cycle Fast Reactor with a power rating of 1000 MWe (UCFR-1000) was firstly proposed for the purpose of 60-year operation, and modified small-size UCFR with the power rating of 100 MWe (UCFR-100) was developed by decreasing a power load of each rod.

One of the most important designs of SFRs, including UCFR, is the decay heat removal system (DHRS). The currently designed DHRS of PGSFR has two different types of loop: one is actively operated type (ADHRS) and the other is passively operated type (PDHRS). Each loop is composed of a sodium to sodium decay heat exchanger (DHX), a sodium to air heat exchanger (AHX) as an ultimate heat sink, a sodium expansion tank, and an intermediate sodium pipe connecting the DHX and AHX. The fundamental heat transfer mode of DHRS is global natural circulation of the primary heat transport system (PHTS) sodium leading to natural circulation of sodium in DHRS loop. This confirms the fully passive concept of DHRS, especially of PDHRS.

Previous studies in both deterministic safety analysis and probabilistic safety analysis confirmed the thermal and safety performance of PDHRS of KALIMER and PGSFR. The deterministic safety analysis utilized mainly MARS-LMR code for the postulated accidents at the steady-state and transient-state conditions [1]. The probabilistic safety analysis utilized PSA level-1 to evaluate the safety degree of overall system and specific system like PDHRS only itself [2].

The unique characteristics of proposed PDHRS of UCFR-100 is that gallium instead of sodium is used as heat transport medium in the PDHRS loop. Several nuclear applications are considering gallium as one of the various candidates for liquid-metallic coolants [3]. In this study, the use of gallium as heat transfer medium in PDHRS is analyzed in the aspect of safety performance through both deterministic and probabilistic approaches. Finally, the combined safety analysis ensures the safety of gallium-based PDHRS of UCFR and compares the safety performance of gallium-based PDHRS with sodium-based PDHRS.

2. Design consideration

Previous studies proposed the types of accidents involving the release of sodium into the air side of AHX. The occurrence of sodium-air reaction by leak, or even by rupture of heat exchanger tube, can cause the additional damage on the heat exchanger and further concern on overall system, in the form of fire itself or shock wave. It can violate the unique feature of UCFR-100 which is long and safe operation without refueling. In this study, we suggested two different design concepts satisfying the unique features of UCFR-100. One is the use of liquid gallium as a heat transfer medium in DHX loop, and, consequently, the other is the use of water as ultimate heat sink design.

2.1.Gallium-based PDHRS

The prominent feature of gallium is its melting and boiling temperatures, which facilitate convenient and simple handling. The melting temperature of liquid gallium is close to room temperature, whereas its boiling temperature is approximately 2477 K. In other words, gallium in the DHX loop exists in a liquid state in both normal operation and accident conditions, without the need for any other supporting system, while sodium DHX loop needs an additional electrical heater to prevent sodium freezing. Another prominent feature of gallium is its stability when it is exposed to air and water environments. Even at room temperature, the oxygen forms an oxide bond to the gallium surface, which provides stability to the gallium in both the air and the water environments. Therefore, if leakages or ruptures in the PDHRS occur, no further damage would be inflicted and no safety concerns would arise related to the chemical reaction between the gallium and the heat sink medium. Finally, the gallium-based PDHRS would secure the safety of the UCFR-100 for long-term operation, even when a severe accident related to the DHRS occurs.

2.2. Ultimate heat sink design

In contrast with the decay heat removal system of the light-water reactors (LWRs), most of the SFRs, including the PGSFR, adopt air-cooled heat exchangers as the ultimate heat sink because of safety concerns related to the sodium-water reaction. The air-cooled heat exchanger could reduce the safety concerns related to the sodium-water reaction. However, the air-cooled heat exchanger deteriorates the heat transfer performance through the heat exchanger and requires the installation of a long chimney, which, in turn, gives rise to another safety concern related to possible airplane crash. In comparison with the sodium-based PDHRS, liquid gallium as a heat transfer medium in the DHX loop enables the use of a water heat sink without any safety concern related to the gallium-water reaction. Consequently, an additional layout for the PDHRS, with a water heat sink, was designed for a gallium-based PDHRS.

3. Deterministic safety analysis

3.1.MARS-Ga modeling

The MARS-LMR code developed by KAERI was utilized for a transient safety analysis of the UCFR-100. In a previous work, the properties of gallium were implemented to enhance the modeling capability of the MARS-LMR code for a gallium-cooled system. Figure 1 shows the designed nodalization of the entire UCFR-100 system, including PHTS, IHX, PDHRS with DHX, and the heat sink. The initial conditions used in the analysis are listed in table 1.

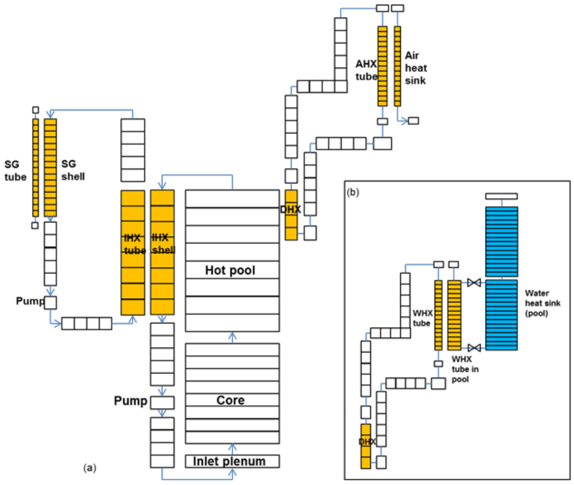

Figure 1. Nodalization of UCFR-100 adopted for MARS-Ga: (a) air-cooled heat sink (b) water-cooled heat sink

3.2. Transient analysis for TOP scenario

The transient analysis was performed for the representative DBA, a TOP scenario. It is assumed that all the events were accompanied by loss of offsite power (LOOP) and started at normal operating power with hot channel factor of UCFR-100. The ANS-73 model was used as a core decay power after a reactor shutdown. At five seconds after a reactor trip, the feedwater lines were isolated and the primary and secondary pumps were tripped, corresponding with the LOOP condition. For the conservative analysis, the AHX damper and the water pool valve were open at 30 minutes after a reactor trip. It was assumed that only one PDHRS was available to evaluate the safety performance of each PDHRS design.

Table 1. Initial conditions of UCFR-100

Design Parameters	**UCFR-100**
Normal Power (MW_{th})	260
Core Inlet Temperature (K)	663.0
Core Outlet Temperature (K)	811.0
Inlet Mas Flow Rate (kg/s)	1384.0
Steam Flow Rate (kg/s)	320.1
Feed Water Flow Rate (kg/s)	320.1
Feed Water Temperature (K)	503.15
Steam Pressure (MPa)	16.5
Required Decay Heat removal (MW_{th})	2.6

The TOP accident was assumed as initiated by the insertion of 0.3$ positivity reactivity at 10 seconds, and the reactor trip by a high power/flow trip occurred at 22.6 seconds. The power peaked after the insertion of the positive reactivity, and, subsequently, decreased drastically because of the reactor trip. Figure 2 shows the analysis results of the TOP accident for each design. The peak cladding temperature was calculated as 747 °C.

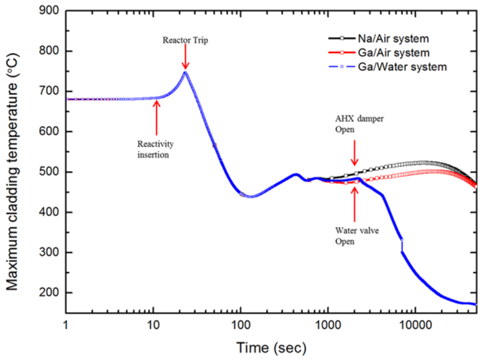

Figure 2. Maximum cladding temperature at TOP accident for each PDHRS design

The cladding temperature and the coolant temperature would continuously increase until the AHX heat removal exceeds the core power, and would subsequently decrease. The AHX heat removal of the sodium-air design exceeded the core power at 12725 sec, while that of the gallium-air design exceeded the core power at 16972 sec. On the other hand, in the instance of the water-cooled heat sink, the PCT and coolant temperature drastically decreased after the water pool valve had opened. As a result, the PCT and coolant temperature drastically decreased at the early state of the accident, and, subsequently, became steady after all the water in the pool had been saturated. In conclusion, any type of design could meet the safety criteria, while only a water-cooled heat sink could provide rapid cooling of the UCFR-100 system at TOP. If we consider that the rapid cooling at the initial state of the accident ensured a significant safety margin and additional time to manage the accident, the water-cooled heat sink provides an effective and prominent safety feature to the UCFR-100.

4. Probabilistic safety analysis

4.1.Level-1 PSA models for UCFR-100

The probabilistic safety analysis, using the level-1 PSA method, was performed for each design of the UCFR-100. The analysis adopted a conventional event tree and fault tree method. The considered initiating events were General Transients (GT), Loss of Offsite Power (LOOP), Station Blackout (SBO), Loss of Flow (LOFW), Loss of all Residual Heat Removal system (LOHR), and Sodium-Water Reaction in SG (SWR), based on the PSA experiences of the domestic SFR [4]. The reliability data for the initiating event frequencies and component failure rates were obtained from the available sources for the SFR design report and the current LWR PSA reports. The reliability data unobtainable from the available sources were assumed based on domestic LWR experiences or expert opinion. The fault trees for UCFR-100, including DHRS, were developed taking into account the domestic SFR reports, LWR experiences, and conceptual design information. The AIMS-PSA tool developed by KAERI was utilized to quantify the core damage frequency. The described event sequences for each event were obtained from the previous PRA report. The fault tree of the DHRS includes two trains of PDHRS and two trains of ADHRS. The failure modes considered for the PDHRS system with the sodium/air were as follows: unavailability because of phenomenological uncertainty, pipe leak, and sodium solidification because of temperature sensing failure, and heating failure by heat tracing [2]. The use of gallium instead of sodium could eliminate the solidification failure mode because of the aforementioned thermal properties of gallium. In addition, the water-cooled heat sink could replace the failure of the air damper opening with the failure of the valve, which has a lower failure probability.

4.2.Level-1 PSA results of UCFR-100

The accident sequence quantification was assessed as the value of the core damage frequency (CDF) for each sequence. In addition, the analysis also generated the minimal cut sets for each sequence. Table 2 shows the results of the level-1 PSA for each initiating event and table 3 shows the results specifically for the PDHRS system. As shown in table 3, the gallium-based PDHRS system provided only 0.27% less CDF and the water-cooled heat sink facilitated an additional 0.2% decrease in CDF. However, the generated minimal cut sets were halved compared with the sodium-based PDHRS with the air-cooled heat sink system. Although the change in the total CDF was negligible, the significant decrease in the minimal cut sets was important. That is to say, since the decrease in the minimal cut sets meant that the scenarios leading to core damage became restricted and simple, preventing and managing the accidents became more convenient, easy, and effective. In addition, as shown in table 3, the failure probability of the PDHRS was significantly reduced by the use of gallium and a water-cooling system to about 1% of that of a sodium-based PDHRS with an air-cooled heat sink. Therefore, it is reasonable to state that the gallium-based PDHRS with a water-cooled heat sink secured or even enhanced the safety of the UCFR-100.

Table 2. Level 1 PSA results of each design

IE		**Case 1**	**Case 2**	**Case 3**
Overall	**CDF**	2.782E-6	2.512E-6	2.509E-6
	MCS	252	154	126
GT	**CDF**	1.362E-8	9.228E-9	7.482E-9
	MCS	69	21	7
LOHR	**CDF**	1.187E-7	1.187E-7	1.187E-7
	MCS	92	92	92
LOFW	**CDF**	9.06E-9	6.164E-9	4.988E-9
	MCS	63	21	7
LOOP	**CDF**	2.378E-6	2.378E-6	2.378E-6
	MCS	20	20	20
SWR	**CDF**	2.624E-7	0	0
	MCS	8	0	0

*Case 1 : sodium-based PDHRS with air-cooled heat sink
Case 2 : gallium-based PDHRS with air-cooled heat sink
Case 3 : gallium-based PDHRS with water-cooled heat sink

Table 3. Comparison between sodium-based PDHRS and gallium-based PDHRS

Design Parameters	**Case 1**	**Case 2**	**Case 3**
Failure probability	8.633E-7	2.525E-7	1.023E-8
MCS	56	17	5

5. Conclusions

In this study, the gallium-based passive decay heat removal system (PDHRS) was suggested for the UCFR-100. Two different concepts were designed, namely, the use of liquid gallium as a heat transfer medium in the DHX loop, and the use of water as an ultimate heat sink design. For the evaluation of the safety performance of each design, three PDHRS designs, including sodium-air, gallium-air, and gallium-water PDHRS, were analyzed by employing both deterministic and probabilistic analysis methods. The transient analysis for the TOP showed that only the gallium-based PDHRS, with a water-cooled heat sink design, could provide rapid cooling of the UCFR-100 system. This system ensured a significant safety margin and additional time to manage the accident, representing an effective and prominent safety feature for the UCFR-100. In addition, the probabilistic safety analysis using the level-1 PSA method showed a significant decrease in the minimal cut sets and the significant reduction of the failure probability of the gallium-based PDHRS of the UCFR-100, compared with the sodium-based PDHRS. In conclusion, the use of the gallium-based PDHRS, with a water-cooled heat sink, secured or even enhanced the safety of the UCFR-100.

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