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Safety Analysis of One Pump Seizure Accident for 2017 PGSFR related to Effect of Pump Seizure Time and Loss of Off-site Power

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1. Introduction

The PGSFR which has thermal power of 392.2MW has been developed in Korea Atomic Energy Research Institute (KAERI) under a National Nuclear R&D program since 2012 to reduce a high-level waste and use a uranium resource efficiently [1]. The PGSFR consists of Reactor Vessel (RV), Primary Heat Transport System (PHTS), Intermediate Heat Transport System (IHTS), Decay Heat Removal System (DHRS) and Steam Generators (SGs) [1, 2]. The PGSFR has inherent safety features accord with the goal of generation-IV nuclear power plant. PGSFR has inherent negative reactivity during the plant operation time. Also, it has passive safety system to prevent the loss of power in operation time by utilizing a natural circulation in DHRS.

The One Pump Seizure (OPS) accident in PGSFR had been classified in Design Basis Accident (DBA) Class-1 until last year but further studying of SFR type nuclear power plant in many countries suggest that classifying the OPS into DBA Class-2 is more reasonable. According to regulation guide of Korea Institute of Nuclear Safety (KINS), safety analysis of accident under more sever condition is recommended [2]. Therefore, the analysis of OPS accident for many seizure delay time cases and Loss Of Off-site Power (LOOP) delay case was performed to find the most serious accident condition. Safety analysis of OPS accident for PGSFR with the most severe accident condition was implemented by using MARS-LMR code.

2. Modeling of PGSFR and Case Study for Seizure time.

2.1 PGSFR Input Modeling

Fig. 1 shows the nodalization of 2017 PGSFR for MARS-LMR input [3, 4]. The nodalization of 2017 PGSFR is changed to increase the accuracy of safety analysis result. Almost all the components of PGSFR are located in large pool to slow down the system transient [1]. Intermediate Heat eXchanger (IHX) is located in hot pool. Heat generated by reactor core is transferred hot pool to IHX. Then, IHTS transport the reactor generated heat from IHX to SGs. IHTS consists of two loops. Each loop has two IHX, one Electro-Magnetic (EM) pump, one expansion tank and one SG. Two units of IHTS exist in PGSFR. SG converts the sub-cooled feedwater to super-heated steam by transferring the heat from the intermediate sodium in IHTS to feedwater in SG. Four units of DHRS with 2.5 MWt heat removal capacity are installed in PGSFR. Two units are Active Decay Heat Removal System (ADHRS) with Forced-draft sodium-to-air Heat eXchanger (FHX) and two units are Passive Decay Heat Removal System (PDHRS) with nAtural-draft sodium-to-air Heat eXchanger (AHX). Each loop of DHRS remove the reactor generated heat by natural circulation of sodium in each loop. In normal operation condition, air damper is closed but in transient operation condition, air damper is open by emergency power supply when the core inlet and outlet temperature exceeds the trip set point. Node No. 170, 175, 180, 185, 190, 195, 200, 205, 210 represent the hottest fuel assembly on each flow group of reactor core. The rest of derivers fuel assemblies, control rod assemblies, IVS assemblies, reflector assemblies, shield assemblies and flow leakage are also considered in MARS-LMR nodalization.

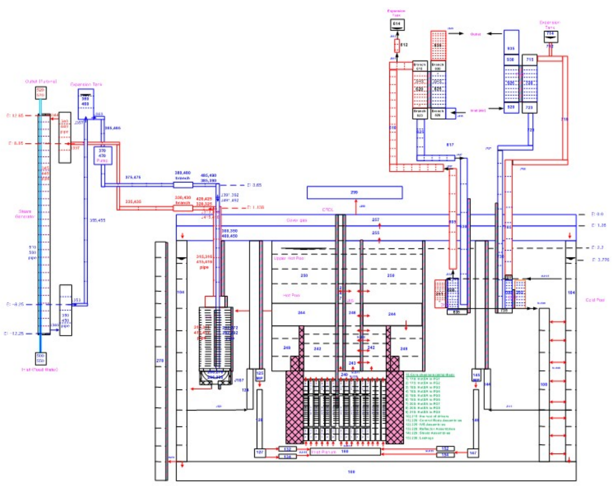

Fig. 1. Nodalization of 2017 PGSFR for MARS-LMR.

The reactor power includes 2% of uncertainty. For the conservative point of view, 102% of reactor power with Hot Channel Factor (HCF) and ANS-79 decay heat model [5] is used in OPS accident safety analysis. Also, the situation that one PDHRS and one ADHRS are unavailable due to single failure and single maintenance with LOOP is assumed to make more severe accident condition.

2.2 Safety Acceptance Criteria

The accident of PGSFR is classified by the occurrence frequency and its consequence. The safety acceptance criteria of Anticipated Operational Occurrence (AOO) and DBA-Class-1 are based on Cumulative Damage Function (CDF) which represents the measure of cladding rupture due to thermal creep. CDF is function of time, temperature and stress.

The safety acceptance criteria of DBA Class-2 and Design Extended Condition (DEC) event is based on the integrity of reactor core. Melting of fuel, rupture of cladding, and boiling of coolant are not allowed in safety acceptance criteria of DBA Class-2 and DEC [6]. OPS accident in PGSFR is representative accident in DBA Class-2. Safety acceptance criteria for DBA Class-2 are shown in Table I. In this study, peak cladding and coolant temperature were calculated considering HCF of variable uncertainties.

Table I: Safety Acceptance Criteria for DBA Class-2

Event Category	**DBA Class 2**
Fuel/ Cladding	Pin Coolable Geometry with No Pin Failure Propagation
	Fuel Temperature (T) < Solidus T Clad T < 1075℃ Coolant T < Boiling T
Reactor Vessel/ Primary System	ASME Service Level D Limits
Design pressure and temperature not exceeded	

2.3 One Pump Seizure Accident Scenario

The OPS accident is initiated by one PHTS pump seizure caused by mechanical failure of bearing or electric pump at 10 sec. LOOP occurs followed by reactor shut down signal with delay time. Power supply to the pumps in PHTS and IHTS is stop since electric power from off-site is lost. The SG feedwater valves are closed, one PHTS pump starts coast down which lead abrupt decrease of mass flow rate in reactor core due to LOOP. Halving time of coast down pump in PHTS is 8sec. The PHTS pump seizure time of 0.1, 0.5, 1.0, 3.0, 5.0 sec and LOOP occur delay time of 0.0, 0.4, 1.0, 3.0, 5.0 sec was simulated for OPS accident using MARS-LMR code. Due to the low mass flow rate in reactor core, high power to flow rate ratio set point signal is generated. This signal makes reactor trip signal which cause the reactor stop by inserting control rod assemblies. Table II, III show the specific scenario of OPS accident for different seizure delay time and LOOP delay time.

Table II: Sequence of OPS accident for different seizure delay time with LOOP occurs at 10.0 sec.

Sequence	**Time (sec)**					**Set-point**
	0.1sec	**0.5sec**	**1.0sec**	**3.0sec**	**5.0sec**	
One PHTS pump seizure	10.00	10.00	10.00	10.00	10.00	
High power to flow-rate ratio signal generation	10.04	10.12	10.20	10.54	10.89	110%
Reactor Trip Signal Generation	10.84	10.92	11.01	11.34	11.69	
LOOP occur	10.84	10.92	11.01	11.34	11.69	
Control rod insertion	11.40	11.47	11.56	11.89	12.24	

Table III: Sequence of OPS accident for different LOOP delay time with one PHTS pump seizure at 0.1 sec

Sequence	**Time (sec)**					**Set-point**
	0sec	**0.4sec**	**1.0sec**	**3.0sec**	**5.0sec**	
One PHTS pump seizure	10.00	10.00	10.00	10.00	10.00	
High power to flow-rate ratio signal generation	10.04	10.04	10.04	10.04	10.04	110%
Reactor Trip Signal Generation	10.84	10.84	10.84	10.84	10.84	
LOOP occur	10.84	11.24	11.84	13.84	15.84	
Control rod insertion	11.40	11.40	11.40	11.40	11.40	

2.4 Effect of Seizure delay time for One Pump Seizure Accident.

Many cases of seizure delay time and for OPS accident is conducted to find most severe accident condition for conservative point of view. The analysis results are evaluated based on the DBA Class-2 safety acceptance criteria. Table IV, V show the maximum peak temperature of cladding and coolant in hottest fuel assembly in reactor core. The analysis results for effect of seizure delay time suggest that OPS accident with seizure delay time of 0.1sec is most severe accident condition.

Table IV: Maximum peak cladding temperature on each seizure delay time case.

delay time	**0.1 sec**	**0.5 sec**	**1.0 sec**	**3.0 sec**	**5.0 sec**
Temperature	786.55℃	781.65℃	772.95℃	737.55℃	734.75℃

Table V: Maximum peak coolant temperature on each seizure delay time case.

delay time	**0.1 sec**	**0.5 sec**	**1.0 sec**	**3.0 sec**	**5.0 sec**
Temperature	782.75℃	778.25℃	770.05℃	733.75℃	734.25℃

PHTS pump seizure delay time affect the mass flow rate in reactor core directly. Mass flow rate behavior in reactor core is shown in Fig. 2. Mass flow rate in reactor core closely related to heat removal capacity. Therefore, abrupt decrease of mass flow rate in reactor core at 10 sec lead temperature increase of cladding and coolant in reactor core. Seizure delay time of 0.1 sec shows the most rapid mass flow rate change behavior. The cladding and coolant temperature behaviors in reactor core are shown in Fig 3 and 4.

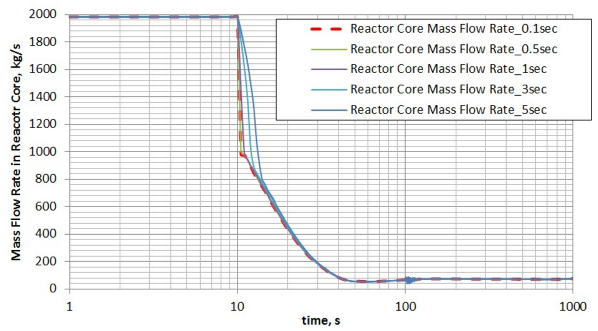

Fig. 2. Mass flow rate behavior of OPS accident for different seizure delay time.

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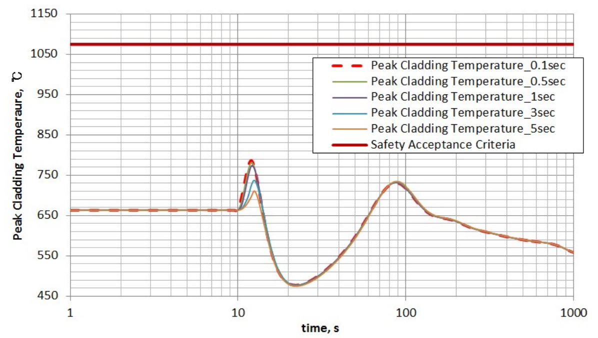

Fig. 3. Peak cladding temperature behavior of OPS accident for different seizure delay time.

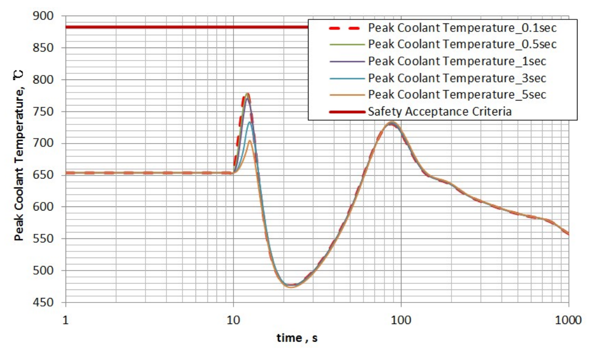

Fig. 4. Peak coolant temperature behavior for of OPS accident for different seizure delay time.

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2.5 Effect of LOOP time for One Pump Seizure Accident.

The effect of LOOP occurrence time is evaluated based on the case of 0.1 sec PHTS pump delay time since section 2.4 shows that the OPS accident with 0.1 sec PHTS pump seizure delay time is most severe case. To simulate the effect of LOOP in MARS-LMR, one un-stalled PHTS pump and both IHTS pump are tripped after the reactor shut down signal with delay time.

Many cases for LOOP delay time between reactor shut down signal and LOOP occurrence are conducted to find most severe accident condition. The analysis results are evaluated based on the DBA Class-2 safety acceptance criteria. Table Ⅵ, Ⅶ show the maximum peak cladding and coolant temperature in hottest fuel assembly in reactor core. The results from analysis suggest that OPS accident with LOOP delay time of 0.0 sec exhibit most severe accident condition. For the case of LOOP delay time lager than 1sec, LOOP occurs after the maximum cladding/coolant temperature is reached. Therefore, the values of maximum temperature are not varied accord with LOOP delay time.

LOOP delay time affect the amount of mass flow rate in reactor core since after the LOOP, electric power supplied to pumps in PHTS and IHTS is stop. Temperature behaviors of cladding and coolant for different LOOP delay time are shown in Fig 5 and 6.

Table VI: Maximum peak cladding temperature on each LOOP delay time case.

delay time	**0 sec**	**0.4 sec**	**1.0 sec**	**3.0 sec**	**5.0 sec**
Temperature	751.85℃	749.35℃	747.85℃	747.85℃	747.85℃

Table VII: Maximum peak coolant temperature on each LOOP delay time case.

delay time	**0 sec**	**0.4 sec**	**1.0 sec**	**3.0 sec**	**5.0 sec**
Temperature	748.05℃	745.15℃	743.15℃	743.15℃	743.15℃

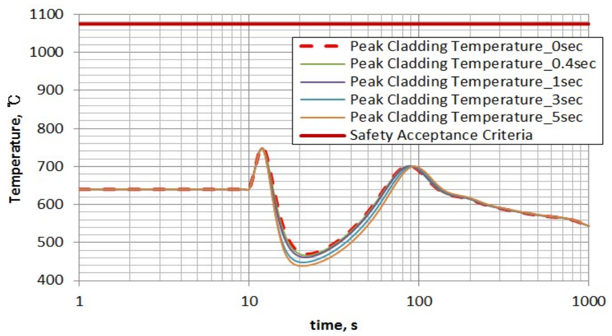

Fig. 5. Peak cladding temperature behavior of OPS accident for different LOOP delay time.

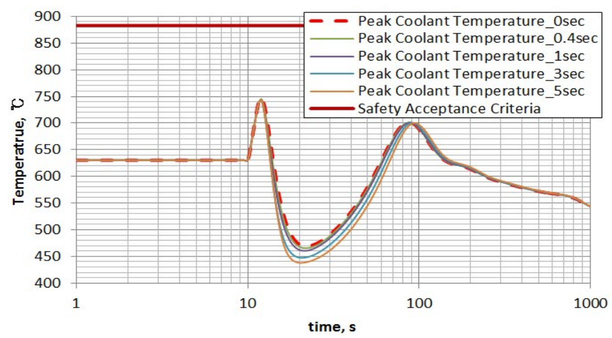

Fig. 6. Peak coolant temperature behavior of OPS accident for different LOOP delay time.

3. Results

3.1 One pump Seizure Accident Result for severe pump seizure delay time and LOOP delay time.

The cladding and coolant temperatures are most important variables in DBA Class-2 accident. The behavior of cladding and coolant temperature for OPS accident with case of 0.1 sec seizure delay time and LOOP delay time of 0.0 sec is shown in Fig.7. The OPS accident is divided into 5 stages. The first stage of accident is 10.0 sec to 12.0 sec. In the first stage of accident, reactor of PGSFR is not tripped but mass flow rate of reactor core decrease since one PHTS pump is stalled and the other PHTS pump is operating with coast down of 8 sec halving time. The cladding and coolant temperatures increase since heat generated from reactor core is not removed properly. The second stage of accident is 12.0 sec to 22.5 sec. In the second stage of accident, reactor power decrease exponentially due to insertion of control rod assemblies. Mass flow rate in reactor core is enough to remove the decay heat since coast down of one PHTS Pump is still valid. Decay power is less than heat removal by coolant. Cladding and coolant temperature decrease. The third stage of accident is 22.5 sec to 88.5 sec. In the third stage of accident, coast down of one PHTS pump is stop. Cladding and coolant temperature increase. Decay heat is removed properly due to lack of mass flow rate in reactor core. The fourth stage of accident is 88.5 sec to 4,116.5 sec. In the fourth stage of accident, reactor core is cooled down by natural circulation made by IHTS. The sodium in IHTS is relatively cooler than sodium in hot pool. Hot sodium from reactor core transports the heat to IHTS and made natural circulation. After the sodium in IHTS heated up, cladding and coolant temperature in reactor core increase again. The fifth stage of accident is 4,116.5 sec to 10,000 sec. The dampers of DHRS open at 4116.5 sec by high core inlet temperature signal. DHRS start to remove the decay heat from reactor core. At 4,879 sec, heat removal of DHRS exceeds the decay power. PGSFR cooled down as shown in Fig. 8.

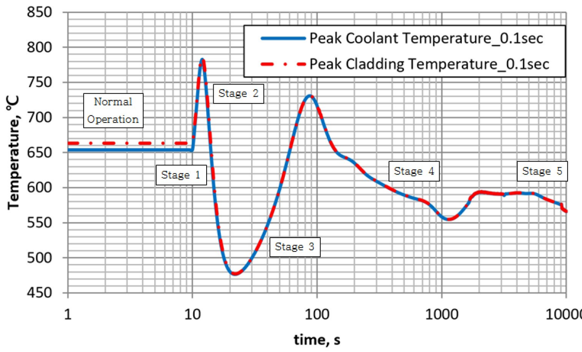

Fig. 7. Temperature behavior for case of 0.1 sec seizure delay time and LOOP delay time of 0.0 sec

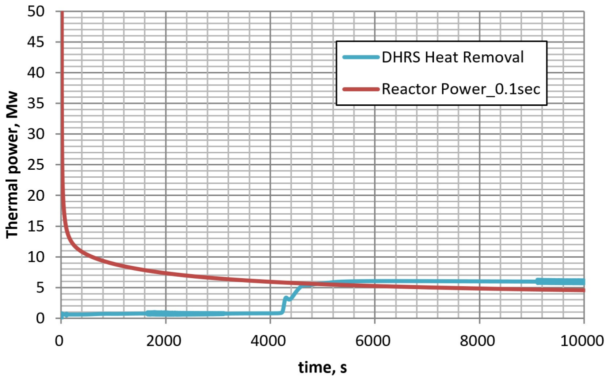

Fig. 8. Decay power and heat removal of DHRS

4. Conclusions

PHTS pump seizure delay time of 0.1 sec and LOOP delay time of 0.0 sec in OPS accident is the most severe condition. From a conservative point of view, safety analysis for OPS accident with 0.1 sec seizure delay time and LOOP with 0.0 sec delay time was implemented using MARS-LMR.

As a result, cladding and coolant temperatures in reactor core didn't exceed the safety acceptance criteria for all cases including seizure delay time and LOOP delay time. In the case of 0.1 sec seizure delay time and LOOP with 0.0 sec delay time, heat removal of DHRS exceeds the decay power around 4,879 sec. After this phenomenon, reactor cooled down continuously to shut down the reactor safely.

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