Predictability Evaluation of Korea Thermal Hydraulic Safety Analysis Codes for Multiple SGTR-PAFS Test with ATLAS Experimental Facility

Hyunjoon Jeong*, Kyungho Nam
Korea Hydro & Nuclear Power Co., LTD. Central Research Institute
70, Yuseong-daero, 1312 beon-gil, Yuseong-gu, Daejeon, Republic of Korea

**Corresponding Author: hyunjoon.jeong@khnp.co.kr*

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1. Introduction

After Fukushima nuclear power plant accident, it has been became of importance to secure the safety under multiple failure condition. The multiple failure accident which concept of design extension conditions to cover beyond design basis accident such as MSGTR (Multiple Steam Generator Tube Rupture), SBLOCA (Small Break Loss of Coolant Accident) with LSI (Loss of Safety Injection), SBO (Station Black Out), and additional sever accident scenarios were introduced. Among them, the MSGTR is an accident which two or more u-tubes of steam generator are ruptured simultaneously in a single steam generator. In Korea, five u-tubes rupture is considered as MSGTR accident by regulatory guideline [1]. The characteristics of the MSGTR accident is which the break flow and the radioactive materials released from the RCS (Reactor Coolant System) are relatively larger compared to SGTR. Therefore, the MSGTR accident progresses more rapidly compared to single tube rupture. In Korea, the PAFS (Passive Auxiliary Feedwater System) had been development to replace the conventional active AFWS (Auxiliary Feedwater System). It is important to investigate the conventional accident mitigation strategies and assess whether it could be effectively applied to multiple failure accident using passive safety system. Especially, the PAFS is adopted as one of the cooling system i-SMR (innovative Small Modular Reactor) as well as passive cooling system to replace the conventional active AFWS.

KAERI (Korea Atomic Energy Research Institute) has been operated an integral effect test facility, the ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simulation), with reference to the APR 1400 (Advanced Power Reactor 1400) for experiments for transient and DBAs [2]. In addition, KAERI has operated the domestic standard problem (DSP) program using the experimental data from the selected experiments at ATLAS in order to encourage the verification of system codes. The fifth DSP (DSP-05) aims at evaluating the cooling ability of the PAFS during MSGTR with loss of conventional active AFWS.

In this study, the analysis of the MGSTR with PAFS operation has been performed using the MARS-KS [3] and SPACE [4]. The main topic in this paper is the investigation of thermal hydraulic phenomena during an MSGTR with failure of all active AFWS as well as the assessment of the codes for the accident with PAFS.

2. Test Condition

The initial heater power was controlled to be 1.627 MW and decay heat was implemented by using the ANS-73 curve with a multiplier of 1.2 from the conservative point of view. The break model of the MSGTR accident consist of piping connected the primary side (Point A) to the secondary side (Point B), five break tubes with a break nozzle, a break valve, and break pipe, as shown in Figure 1 [4]. In the test, only two safety injection pumps (SIPs) were injected through the DVI line by the assumption of a single failure condition.

The safety system in secondary system such as the main steam safety valves (MSSVs) were assumed to be available, but the active AFWS was not operated to consider the multiple failure accident which MSGTR accident under the PAFS operation condition. When the collapsed water level in the SG becomes lower than 25% of the wide range of the water level transmitter during the transient state, an actuation valve at the return-water line is opened, initiating the natural convection flow of the PAFS. The detail information of test condition can be found in the reference [5]

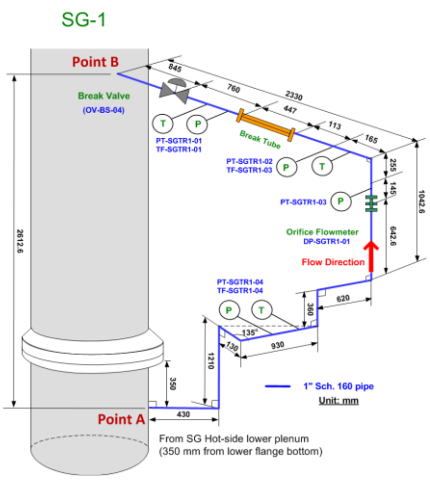

Fig.1. Pipe arrangement of SGTR simulation [5]

3. Modeling Information

The thermal hydraulic model to analyze the MSGTR accident under PAFS operation at ATLAS has been developed on the basis of a reference input provided KAERI [6]. The reference model has been modified on the basis of the facility design report in order to have the correct geometry and boundary conditions. Especially, a new heat loss correlation for the secondary system was suggested by fitting the result of the heat loss tests because of the heat loss of secondary system is closely related to the time when PAFS is activated, as shown in Figure 2. The detailed review information can be found in the reference [7].

In order to simulate the MSGTR accident at the SG-1, break system was modeled from C330 to C640, as shown in Figure 1. The break system should describe the test configuration as realistic as possible to predict the characteristics of the transient appropriately. The break model of MSGTR accident consist of piping connecting the primary side (Point A) to the secondary side (Point B), five break tubes with a break nozzle, a break valve, and break pipe. The MSGTR break system is implemented as same as the test specification aforementioned. The critical flow model of both codes was applied as a default model. The default model of MARS KS is the Henry-Fauske critical flow model [8]. In case of the SPACE, the Ransom-Trapp critical flow model [9], was applied.

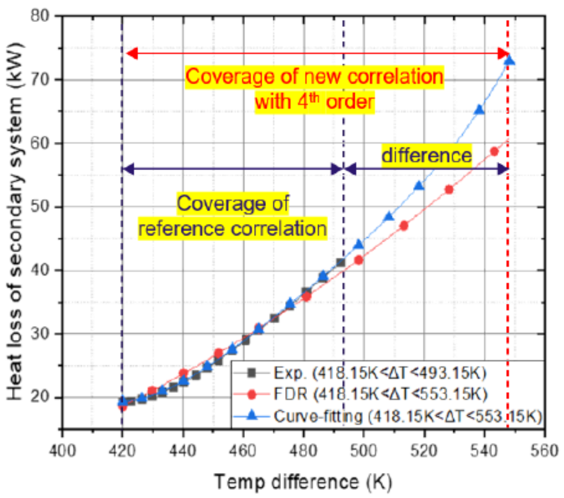

Fig.2. Heat loss of secondary system

4. Analysis Results

4.1. Steady-state calculation

A steady state calculation has been conducted for 5,000 second in problem time to achieve the initial conditions for postulated accident. The results of steady state calculations are summarized in Table I. All major parameters except for the SG pressure were well predicted within the error bands of the experimental values. The secondary system parameters indicated that the saturation pressure corresponding to the steam temperature was different from measured SG pressure. The preliminary analysis confirmed that the utilization of the SG pressure as a parameter for the steady state calculation prevented the system from reaching the desired steady state condition [7]. Thus, it was decided to achieve the steady state conditions of the secondary system based on the SG temperature. The resulted SG pressure was exactly same as the saturation pressure corresponding to the steam temperature of each SG and all system parameters were predicted within acceptable error range, as aforementioned. The steady state results for the heat loss also confirmed that the new heat loss correlation applied to this study predicted the heat loss appropriately.

Table I. Steady-state calculation result of MARS-KS

Parameter	Exp.	MARS-KS [Cal.]	SPACE [Cal.]
Primary System			
Core Power (MW)	1.627	1.627	1.627
Heat Loss (kW)	97.1	97.0	97.7
PZR Pressure (MPa)	15.5	15.5	15.5
PZR Level (m)	3.71	3.71	3.71
Core Inlet Temp. (K)	565.15	564.45	564.08
Core Outlet Temp. (K)	600.65	600.95	599.65
Secondary System			
Feed Water Flow Rate (kg/s)	SG 1:0.410 SG 2:0.420	SG 1:0.416 SG 2:0.416	SG 1:0.416 SG 2:0.416
Feed Water Temp. (K)	506.45	506.45	506.45
Steam Pressure (MPa)	7.83	8.079	8.078
Steam Temp. (K)	SG 1:569.35 SG 2:568.35	SG 1:568.85 SG 2:568.85	SG 1:568.52 SG 2:568.52
Secondary Side Level (m)	4.97	4.97	4.97
Heat Loss (kW)	70.0	69.9	69.9
PAFS			
PCCT LVL (m)	3.8	3.8	3.8
PCCT Temp. (K)	301.95	301.95	301.95

4.2. Transient-state calculation

Table II shows the chronology of main sequence of postulated accident occurred comparing the results from the test and both codes. Both codes predicted the overall trends of the major sequence observed in the ATALS test successfully.

Table II. Chronology of the transient main event

Event	Exp. (s)	MARS-KS (s)	SPACE (s)	Remarks
Break	0	0	0	@t=0
HSGL	11	10	12	SG 1 LVL > 5.05m
Reactor Trip	11	10	12	Coincidence with HSGL
Turbine Trip	11	10	12	
MSIV close	15	14	16	
MFIV close	18	17	19	
Decay heat	23	22	24	LPP+12.07 sec delay
LPP signal	248	278	235	PZR P < 10.72MPa
SIP injection	276	306	263	LPP +28.28 sec delay
PAFS operation	7204	7233	7217	SG 2 LVL < 25%

The accident was initiated by opening the break valve at 0.0 seconds. The break flow into the rupture side SG (SG-1) through the break line. This led to increased collapsed water level of SG-1 continuously, and that generated high steam generator signal (HSGL) when the collapsed water level of SG-1 exceeds 5.05m. The HSGL signal generates a reactor trip signal and turbine trip signal, so that reactor trip. In addition, secondary system was blocked by the main feedwater isolation signal (MFIS) and main steam isolation signal (MSIS) activated with pre-define from the reactor trip signal. Figure 3 shows the core heater power that indicates the decay heat curve of both codes simulated. Figure 4 shows the overall pressure behavior of the primary and secondary systems. Both codes and experimental results, the rapid depressurization of primary system occurred during initial period, and the LPP signal generated at around 250 seconds. The SIP operation signal is occurred after 28.28 seconds of delay time, and safety injection is supplied as shown in Figure 5.

In this study, considering the characteristics of the single failure of emergency diesel generators (EDGs), only two SIPs out of four SIPs were activated. After SIPs operation, the pressure of primary system maintains constant in both the ATLAS test and code results, and the both codes properly predict the pressure behavior of the primary system. The liquid inventory of the primary system is released to the broken SG u-tubes through the break line, as shown in Figure 6. Because of the continuous release, the collapsed water level and pressure of the broken SG u-tubes continue to rise, and the pressure of the intact SG increase owing to the decay heat of the primary system. The main steam safety valves (MSSVs), one of the safety systems of the SG that has hysteresis open/ close characteristics was simulated so that when the pressure of the SG rises above 8.1MPa, the MSSVs operate to release steam, and when it decreases below 7.7MPa, the MSSVs closed.

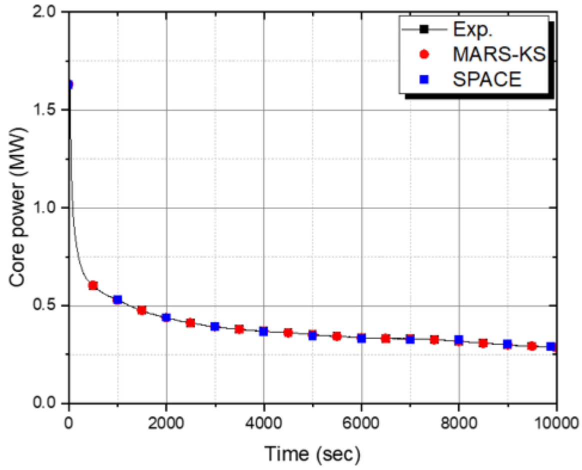

Fig.3. Core power

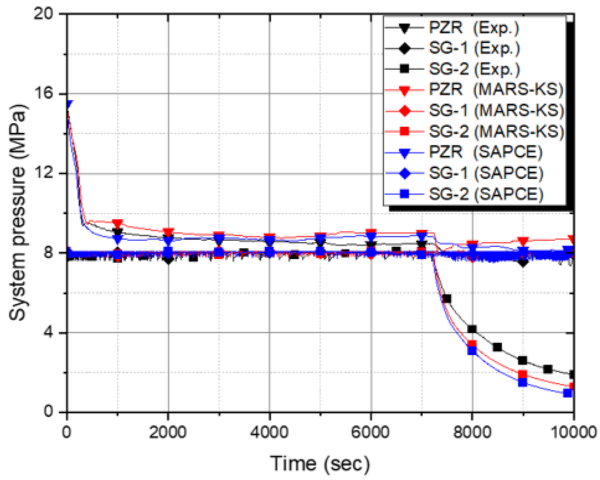

Fig.4. Pressure of system

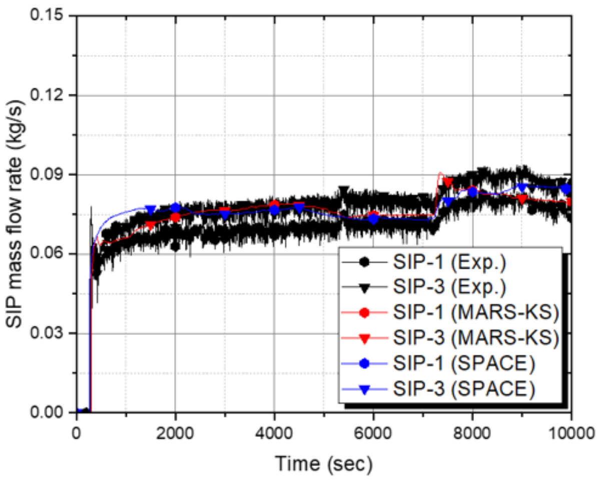

Fig.5. SIP mass flow rate

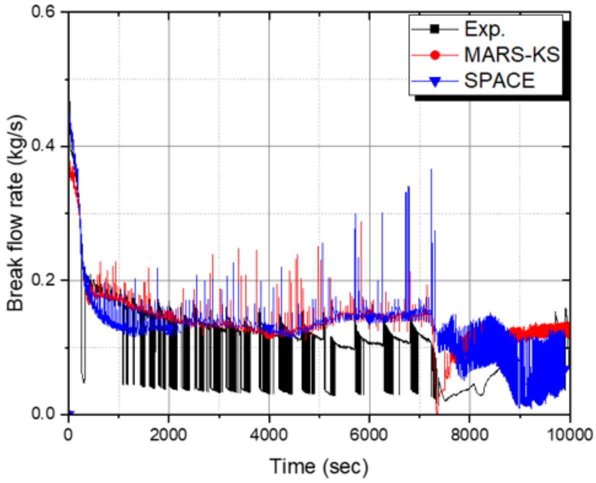

Fig.6. Break flow rate

Figure 7 shows the collapsed water level of the SG. The collapsed water level of the SG on broken u-tubes (SG-1) continuously increases because of the break flow rate and reaches the highest collapsed water level. During the initial period, the rate of increase of SG liquid level on the broken u-tubes of both codes under predicted the experimental value, but after about 4,000 seconds, the both codes calculated a lager value, so the highest collapsed water level of the SG was reached early. The collapsed water level of the intact SG gradually decreased owing to continuous operation of the MSSVs, as shown in Figure 8. The SG collapsed water level reached 25% at the 7,204 seconds in the experimental and approximately 7,233 seconds for the MARS-KS and 7,217 seconds for SPACE, respectively, it lead to open the PAFS valve.

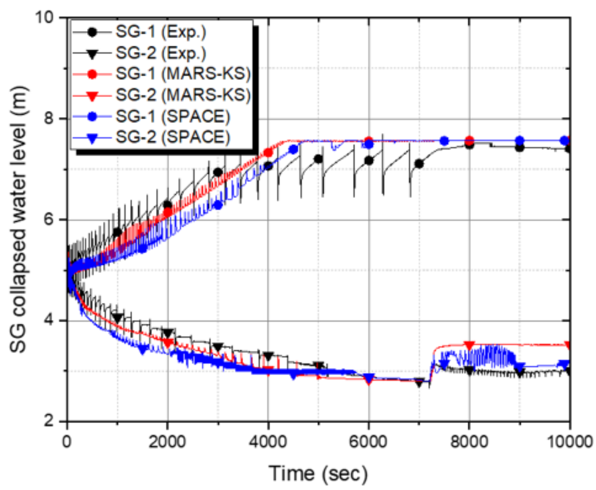

Fig.7. Collapsed water level of SG

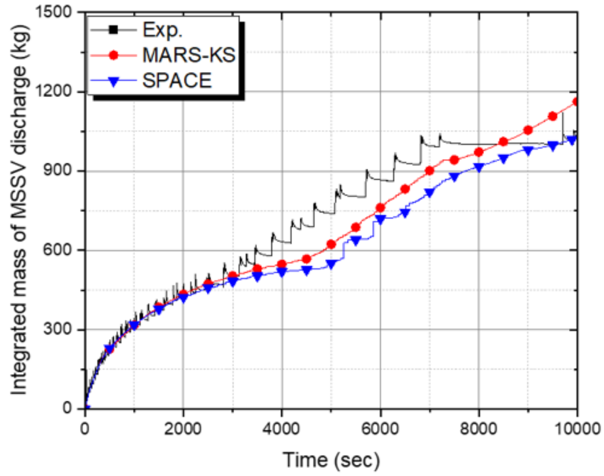

Fig.8. Integrated of MSSV discharge

Figure 9 show the behavior of the core inlet and outlet temperatures. After the accident, the results of the experiment and the codes does not differ significantly after the accident. In addition, the both results show a decrease in temperature owing to activation of the PAFS. Both the experimental and the analysis results confirmed that the temperature of passive condensate cooling tank (PCCT) increases due to heat transfer through the passive condensation heat exchanger, as shown in Figure 10.

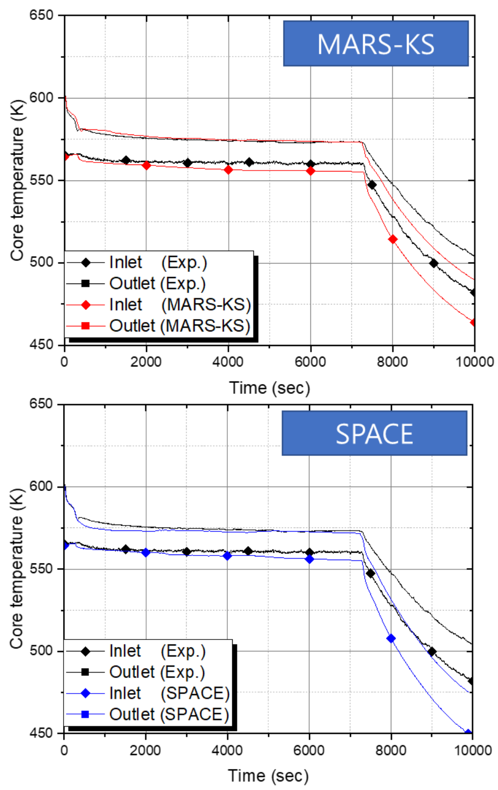

Fig.9. Core inlet/outlet temperature

This substantiated that residual heat generated in the primary system is cooled through the passive system connected to the secondary system, and the core inlet and outlet temperatures are cooled, respectively. As a result, it means that the physical phenomenon shown in the experiment is also appropriately represented in the both codes, and the integrity and cooling capability of the passive safety are proven. In addition, the both codes appropriately predicted the activation time as well as cooling capability of the PAFS, which is judge to be an appropriate reflection of the secondary system heat loss model.

5. Conclusion

In this study, the MSGTR-PAFS postulated accident at the ATLAS experimental facility was simulated using the MARS-KS and SAPCE to analyze the main physical phenomena occurring during the postulated accident and to evaluate the cooling capability of the PAFS. The information of geometry and heat structure of overall systems were verified by referring to the technical report of the ATALS to reflect accurate design information. In addition, the heat loss correlation equation of the secondary system did not include the actual experimental temperature range, which resulted in a low heat loss value of the secondary system.

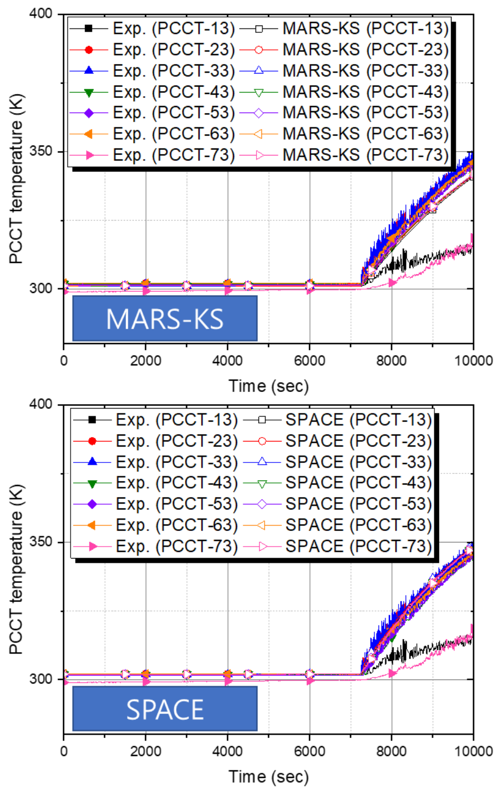

Fig.10. Temperature of PCCT

In order to solve the above problem, the secondary system heat loss was newly calculated and applied by deriving a new heat loss correlation in the form of a 4th order polynomial based on the heat loss experimental value. As a result, the overall physical behavior was appropriately predicted. In particular, the valve opening time of the PAFS in both codes is similar to the experimental, and the temperature of the PCCT shows similar behavior to the experiment, the prediction ability of the both codes is judged to be reasonable.

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