Analysis of SBLOCA for CRDM Nozzle Rupture with Loss of Safety Injection at the ATLAS Experimental Facility using the MARS-KS 1.5 and TRACE V5.0 Patch 6

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1. Introduction

After the Fukushima accident, it has become of importance to secure the safety under multiple failure conditions. The total failure of safety injection could be considered as a multiple failure condition that can lead to the core damage when a proper accident management (AM) action is not provided.

Korea Atomic Energy Research Institute (KAERI) has operated an integral effect test facility, the Advanced Thermal-Hydraulic Test Loop for Accident Simulation (ATLAS), with reference to the APR1400 (Advanced Power Reactor 1400) for transient and design basis accident (DBA) simulations [1]. 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 and validation of system codes. The sixth DSP (DSP-06) aims at evaluating the importance of the accident management (AM) action during a small-break loss-of-coolant-accident (SBLOCA) with loss of safety injection (LSI). The CRDM nozzle rupture at the upper head of the reactor pressure vessel (RPV) was selected as a postulated accident for DSP-06.

In this study, the analysis of the SBLOCA with LSI has been performed using MARS-KS 1.5 [2] and TRACE V5.0 Patch 6 [3]. The main topic in this paper is the investigation of the thermal-hydraulic phenomena during an SBLOCA at RPV upper head with a failure of all safety injection pumps(SIPs) as well as the assessment of the codes for the accident with AM actions.

2. Test Condition

In the test, four safety injection tanks (SITs) were utilized as a safety injection system during the test period. However, four SIPs were not operated to consider the total failure of the SIP. The safety systems in the secondary system such as the main steam safety valves (MSSVs) and auxiliary feedwater (AFW) system were assumed to be available. In addition, the atmospheric dump valve (ADV) was employed for the AM action, which opened 50% when the maximum surface temperature of the heater rods in the core is higher than 623.15 K. The initial heater power was controlled to be 1.664 MW and the decay heat was modeled by using the ANS-73 curve with a multiplier of 1.2. Detailed test condition information of DSP-06 can be found in the reference [4].

3. Modeling Information

The thermal hydraulic model to simulate the CRDM SBLOCA at ATLAS have been developed for MARS-KS and TRACE based on reference input distributed by KAERI. 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. The detailed model information as well as heat loss correlation of secondary system can be found in the references [5-6].

In order to predict the behavior of break flow against the experiment data correctly, it was necessary to renodalized the upper head volume in order to take into account the effect of the stratification. The reference upper head volume has been renodalized with 14 subvolumes. The node sensitivity for the upper head volume is additionally discussed in section 4.3.

The break system consisted of a break nozzle, a break valve, sink volume, and break pipes. Among those components, the modeling of the break nozzle is very important in this simulation since chocking in the break line occurs at the smallest area section. In this break line, the break nozzle has the smallest inner diameter of 7.12 mm, whereas the inner diameter of the break pipe is 33.99 mm Thus, the Henry-Fauske critical flow model [7], the default model of MARS-KS, was applied at the break nozzle with a discharge coefficient of 0.9. In case of the TRACE, the Ransom-Trapp critical flow model [8] with discharge coefficient of 0.5 and 0.8 for subcooled and two-phase conditions, respectively.

4. Analysis Results

4.1 Steady-state Calculation

A steady-state calculation has been performed for 5,000 sec in problem time to achieve the initial conditions for the postulated accident. The result of steady-state calculations by both codes steady state calculations are summarized in Table I-II. All major parameters except for the steam generator (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 the 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 conditions [5]. 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 results of MARS-KS

Parameter	Exp.	Cal.	Error [%]
Primary System			
Core power [MW]	1.66	1.66	0.00
Heat loss [kW]	98.4	98.0	-0.41
PZR pressure [MPa]	15.5	15.5	0.00
PZR level [m]	3.62	3.62	0.00
Core inlet temp. [K]	565.35	564.45	-0.16
Core outlet temp. [K]	600.95	600.95	0.00
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 1:1.46 SG 2:-0.95
Feed water temp. [K]	506.45	506.45	0.00
Steam pressure [MPa]	7.83	8.07	3.18
Steam temp. [K]	SG 1:569.35 SG 2:568.35	SG 1:568.85 SG 2:568.85	SG 1:-0.09 SG 2:0.09
SG level [m]	4.99	4.99	0.00
Heat loss [kW]	70.0	69.9	0.01
Primary Piping			
Cold leg flow [kg/s]	2.0	1.91	-0.09

Table II: Steady-state calculation results of TRACE

Parameter	Exp.	Cal.	Error [%]
Primary System			
Core power [MW]	1.66	1.66	0.00
Heat loss [kW]	98.4	98.4	0.00
PZR pressure [MPa]	15.5	15.5	0.00
PZR level [m]	3.62	3.62	0.00
Core inlet temp. [K]	565.35	565.31	-0.001
Core outlet temp. [K]	600.95	600.37	0.01
Secondary System			
Feed water flow rate [kg/s]	SG 1:0.410 SG 2:0.420	SG 1:0.420 SG 2:0.420	SG 1:2.10 SG 2:0.00
Feed water temp. [K]	506.45	506.45	0.00
Steam pressure [Mpa]	7.83	8.07	3.18
Steam temp. [K]	SG 1:569.35 SG 2:568.35	SG 1:568.85 SG 2:568.85	SG 1:-0.09 SG 2:0.09
SG level [m]	4.99	5.05	0.06
Heat loss [kW]	70.0	70.0	0.00
Primary Piping			
Cold leg flow [kg/s]	2.0	1.999	-0.001

Table III: Chronology of the transient main events

Event	Exp. (s)	MARS-KS (s)	TRACE (s)	Remarks
Break	0	0	0	@t=0
LPP (Rx, RCP trip)	68	66	72	PZR P < 10.72Mpa
MSIS	72	70	76	LPP +3.54s delay
MFIS	75	73	79	LPP+7.07s delay
Decay Heat	80	78	84	LPP+12.07s delay
AM Action	2181	2206	2208	PCT > 623.15K
ADV Open	2181	2206	2208	ADV 50% open
SIT Injection	2301	2279	2272	D.C P < 4.03Mpa
SIT FD (Low flow)	2671	2600	2547	SIT Level < 2.0m
SIT Termination	2998	2987	2983	SIT Level < 0.1m

4.2 Transient-state Calculation

The analysis of the CRDM SBLOCA with LSI has been conducted from the steady-state conditions. Table III shows the sequence of major events occurred during the accident, comparing the results from experiment and both codes. Both codes predicted the overall trends of the major sequence observed in the ATLAS test successfully.

The CRDM penetration nozzle break accident was initiated by opening the break valve at 0.0 seconds. At the beginning of the accident, the primary system was rapidly depressurized and the reactor trip signals were generated by the low pressurizer pressure (LPP). Also, the main steam isolation signal (MSIS) and main feedwater isolation signal (MFIS) occurred in some delay time after the LPP signal. The decay heat curve was implemented by using measured power described in the test specifications and it was activated with a delay of 12.07 seconds from the reactor trip considering the scaled nominal power of ATLAS, as shown in Fig. 1.

The behavior of the primary pressure is depicted in Fig. 2. During the initial rapid depressurization, the safety injection should be started when the setpoint of the SIP is reached. However, the SIP was not operated in this test because of LSI. Thus, the primary system kept depressurized slowly until the ADV opened. Figure 3 shows the behavior of the integrated break flow through the break valve. During the initial blowdown phase, single phase liquid was expelled through the break line.

Afterwards, a less steep depressurization region was formed both experiment and calculation up to approximately 2200 seconds because of the two-phase flow at the break. Subsequently, the void fraction of the break modules increased and the break flow switched from two phase to single phase vapor.

Figures 4 and 5 show the active core collapsed water level and peak cladding temperature (PCT), respectively. It was found that the behavior of overall level and temperature in the calculations were similar to those in the experiment. When the PCT exceeded 623.15 K, the AM action to open 50% of the ADV was performed to increase cooling by the secondary system. Thus, the pressure of the primary system was decreased, and the SITs were actuated when the primary system was depressurized to the setpoint as shown in Figs. 6 and 7. It was confirmed that the core collapsed water level was recovered and the PCT was stabilized after the injection of the SIT in both experiment and calculations.

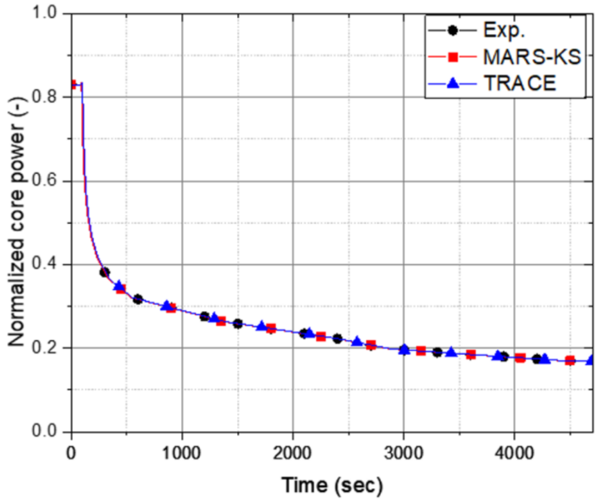

Fig.1. Power of core heater

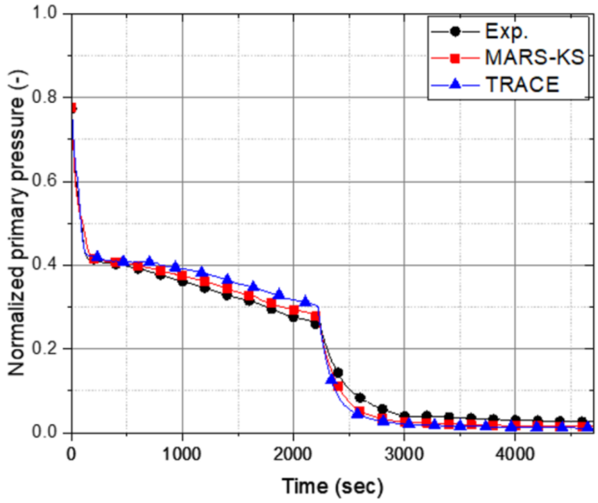

Fig.2. Pressure of primary system

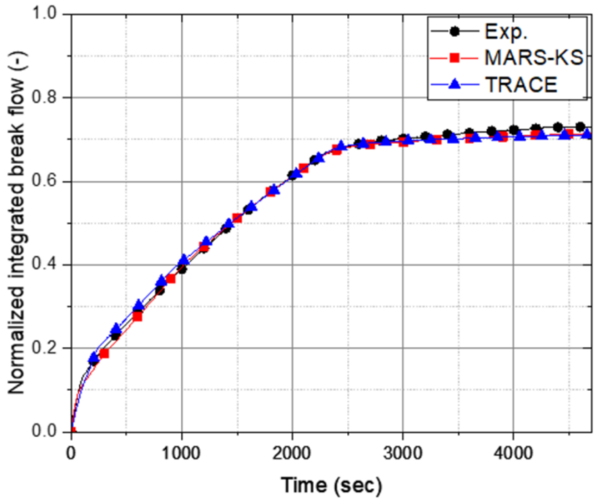

Fig.3. Integrated break flow

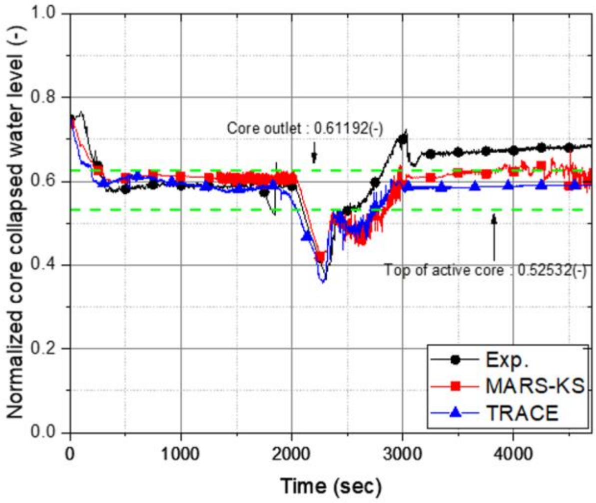

Fig.4. Active core collapsed water level

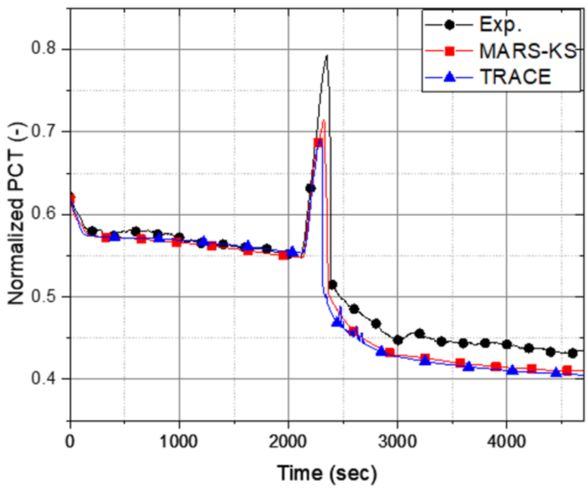

Fig.5. Peak cladding temperature

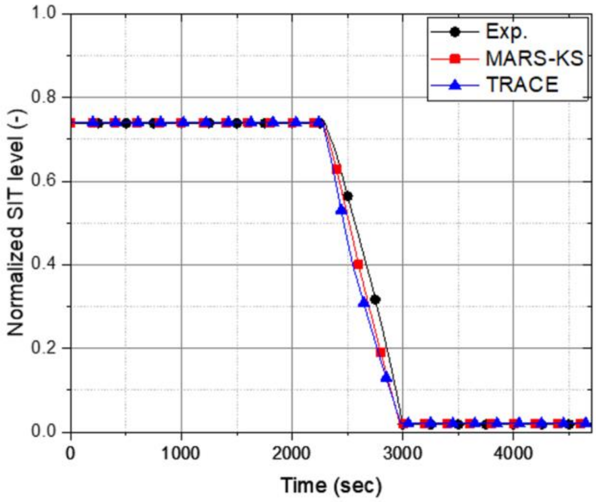

Fig.6. SIT collapsed water level

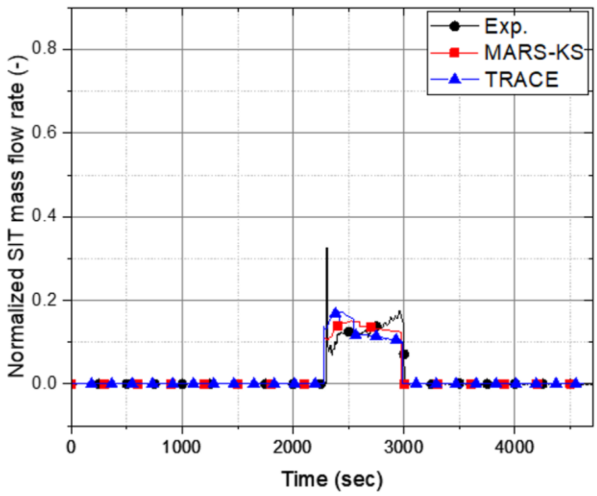

Fig.7. SIT mass flow rate

4.3 Sensitivity Analysis

In this study, the nodalization of upper head becomes especially important as the break module is located at the top of RPV. The reference model for the upper head has been renodalized with 5,10,and 14 subvolumes to simulate the impact of the stratification occurred in the upper head. In order to figure out the effect of the upper head nodalization a sensitivity analysis was performed with cases listed in Table IV.

Figures 8 and 9 show the primary system pressure and the PCT with respect to the number of subvolumes. The figure indicates that more accurate behavior of the primary pressure was predicted with finer mesh. It is because finer nodalization allowed more accurate prediction of the void fraction at the break location in the upper head and this was directly connected to the break flow prediction. Since more accurate prediction of the break flow also influenced the inventory of the primary system, finer nodalization applied to the upper head helped the codes to predict the PCT more appropriately.

Table IV: Volume information of upper head nodalization

<table>
<tr><th></th><th>Case 1</th><th>Case 2</th><th>Case 3</th><th>Case 4</th></tr>
<tr><td>Subvolume</td><td>With 1</td><td>With 5</td><td>With 10</td><td>With 14</td></tr>
<tr><td rowspan="14">Volume Ratio</td><td>1</td><td>0.2</td><td>0.1</td><td>0.01</td></tr>
<tr><td rowspan="13">N/A</td><td>0.2</td><td>0.1</td><td>0.02</td></tr>
<tr><td>0.2</td><td>0.1</td><td>0.03</td></tr>
<tr><td>0.2</td><td>0.1</td><td>0.04</td></tr>
<tr><td>0.2</td><td>0.1</td><td>0.05</td></tr>
<tr><td rowspan="9">N/A</td><td>0.1</td><td>0.06</td></tr>
<tr><td>0.1</td><td>0.07</td></tr>
<tr><td>0.1</td><td>0.08</td></tr>
<tr><td>0.1</td><td>0.09</td></tr>
<tr><td>0.1</td><td>0.1</td></tr>
<tr><td rowspan="4">N/A</td><td>0.1</td></tr>
<tr><td>0.1</td></tr>
<tr><td>0.1</td></tr>
<tr><td>0.15</td></tr>
</table>

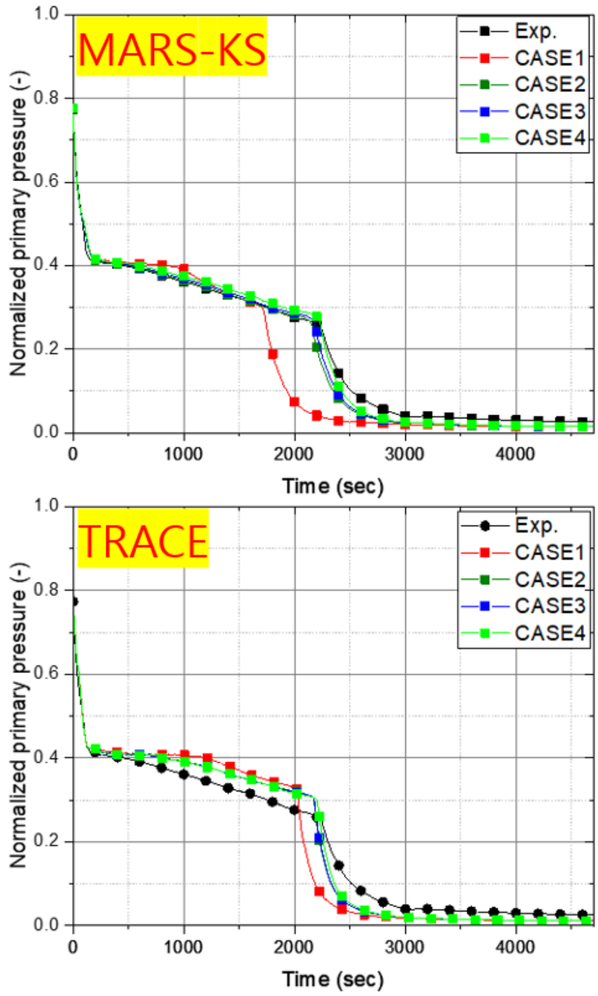

Fig.8. Primary system pressure according to node number

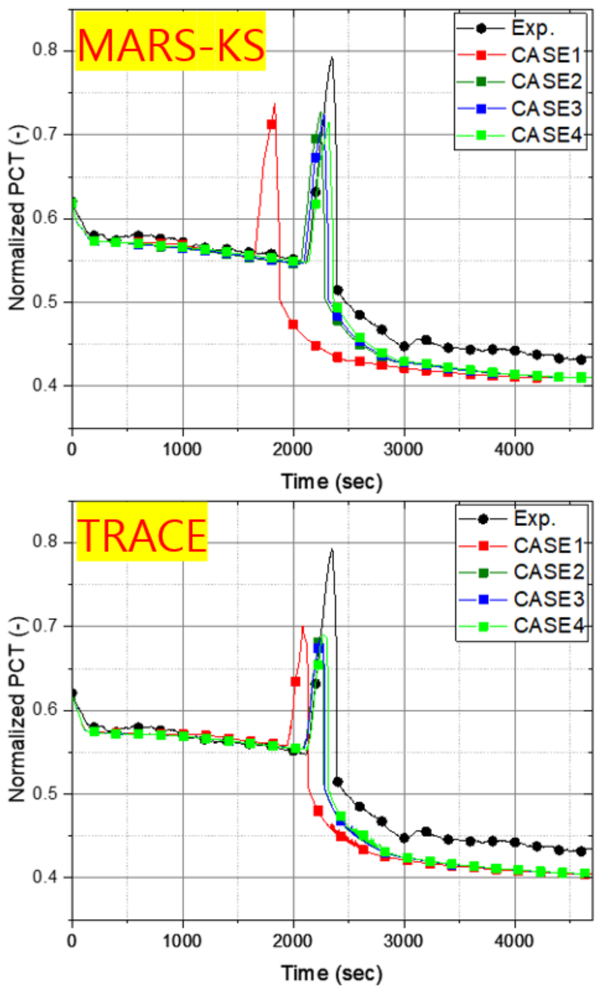

Fig.9. PCT according to node number

5. Conclusion

The ATLAS test for the SBLOCA with LSI was analyzed with the improve model using the MARS-KS and TRACE in order to validate the codes against the experiment with the multiple failures and AM action. Considering the break location and corresponding physical phenomena during the accident, the upper head of the RPV was refined with finer nodes. The results indicate that the revised model can predict the system behavior during the accident appropriately and, especially, the prediction of the break flow by both codes showed a good agreement with one in the experiment. The system response to the AM action was reasonably predicted by the calculations and, as a result, the PCT behavior was reproduced successfully. In addition, the experiment and calculations confirm that the suggested AM action could mitigate the SBLOCA with LSI accident without core damage.

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