Evaluation of the Main Steam Line Break Accident for the APR+ Standard Design using MARS-KS

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1. Introduction

As a part of licensing evaluation of the APR+ (Advanced Power Reactor +) standard design, Korea Institute of Nuclear Safety(KINS) performed safety evaluation of the APR+ Standard Safety Analysis Report(SSAR)[1]. The results of the safety evaluation of the APR+ Main Steam Line Break(MSLB) accident is presented for the most limiting post-trip return-to-power case with the single failure assumption of the Loss Of Offsite Power(LOOP). MARS-KS regulatory safety analysis code[2] has been used to evaluate safety as well as the system behavior during MSLB accident.

The MARS-KS analysis results are compared with the results of the MSLB safety analysis presented in the SSAR of the APR+.

2. MARS-KS MSLB Accident Analysis of the APR+ Standard Design

MSLB accident has been selected to evaluate the APR+ Design Basis MSLB Accident with respect to the return-to-power after trip due to asymmetric core cooling by the MSLB. Most limiting case of the post-trip return-to-power MSLB inside containment at full power has been simulated using conservative initial conditions and assumptions. The safety evaluation is performed by comparing the results of the MARS-KS analysis with the corresponding results of the APR+ SSAR MSLB safety analysis.

2.1 APR+ Standard Design Safety Features

APR+ standard design has been evolved from the APR1400[3] currently under construction in Korea and United Arab Emirates(UAE) through upgrading the power and improving the safety systems. Total power was increased to 4,290 MWt and thus the Nuclear Steam Supply System(NSSS) design has been upgraded accordingly. Due to the safety concerns of the Station Black-Out(SBO) after Fukushima nuclear power plant accident in March 2011, Passive Auxiliary Feedwater System(PAFS) has been adapted as new safety feature for the ultimate heat sink to remove the core decay heat after the reactor trip by natural circulation replacing the Active FWS(AFWS) of the APR1400. Electrically and mechanically separated independent four train Safety Injection System(SIS) has been implemented as new safety feature using four Direct vessel Injection(DVI) nozzles with Emergency Core Cooling(ECC) Barrel Ducts(ECBD) to reduce the ECC bypass to the break.

APR+ standard design has received Standard Design Approval(SDA) in September 2014 from the Nuclear Safety and Security Commission(NSSC).

2.2 Main Steam Line Break Accident Scenario

MSLB is defined as a pipe failure in a main steam piping of the secondary system. In this analysis, Double Ended Guillotine(DEG) break of the main steam line pipe inside containment is assumed to maximize potential for a post-trip return-to-power due to Reactor Coolant System(RCS) cooldown and positive reactivity insertion by the negative Moderator and Fuel Temperature Coefficients(MTC, FTC). Concurrent LOOP was assumed as a single failure and thus the low RCS pump shaft speed trip was credited for the reactor trip. To maximize the cooldown of the RCS system and thus maximize return-to power after the reactor trip, PAFS is assumed to actuate after the Main Steam Isolation Valve(MSIV) completely closes. Power and reactivity behaviors were investigated with respect to the return-to-power after the reactor trip. Since the MSLB is an inherently asymmetric transient, asymmetric system behaviors were also investigated in this study.

2.3 Analysis Method

MARS-KS regulatory system code was used to simulate the MSLB accident inside containment at full power. DEG break was assumed to maximize the heat removal from the secondary system and thus the RCS cooldown. Following conservative assumptions were used to maximize the potential for the return-to-power after the trip;

- Technical Specification Limiting Conditions for Operation(LCO) at full power
- Concurrent LOOP as a single failure
- Safety system actuation : PAFS and SIS
- Most negative MTC and FTC with one most worth stuck CEA
- Decay heat : 1.2 * ANS(1979) Decay heat
- Break size : 0.39275 m^2

Independent safety evaluation of the APR+ MSLB accident was performed by comparing the MARS-KS MSLB analysis results with corresponding MSLB safety analysis results presented in the APR+ SSAR.

2.4 MARS-KS APR+ Nodalization

APR+ NSSS has been simulated using MARS-KS for the MSLB accident analysis as shown in Figure 1. Each PAFS is simulated and linked to the secondary feedwater and steam pipings at upstream of the MSIV and MFIV for each steam generators. Core decay heat is removed by the heat exchangers in the Passive Condensation Cooling Tank(PCCT) of the PAFS. Four train SIS is also simulated as shown in Figure 1.

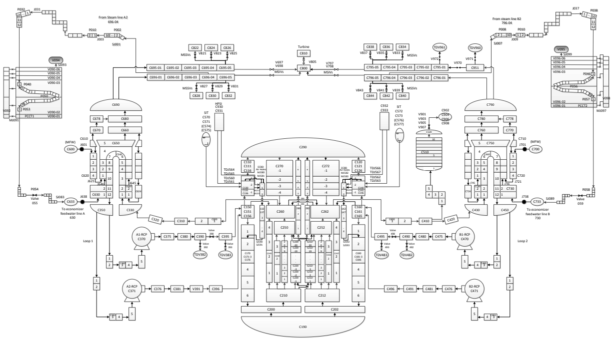

Figure 1. MARS-KS APR+ Nodalization.

2.5 Analysis Results

Conservative full power initial conditions were used to maximize post-trip return-to-power during the MSLB accident inside containment. As shown in Table 1, Technical Specification LCOs at full power were used to simulate the limiting case of MSLB inside containment.

Table 1. Initial Conditions of MSLB Safety Analysis

Parameter	**Unit**	**SSAR**	**MARS-KS**
Total Core Power	MWt	4375.8	4375.8
Core Inlet Temperature	^oC	299.44	298.26
Core Outlet Temperature	^oC		334.54
Core Mass Flow Rate	Kg/s	19950.0	19846.0
Pressurizer Pressure	MPa		16.03
Pressurizer Water Volume	m^3	47.4	47.4
Feed Water Mass Flow Rate	Kg/s	-	2483.6
Feed water Temperature	^oC	-	232.22
Steam Flow rate	Kg/s	-	2484.3
SG Liquid Inventory	Kg	124,049.0	124,049.0
Steam Temperature	^oC	-	286.35
SG Pressure	MPa	-	7.059

The limiting case of the post-trip return-to-power MSLB accident inside containment was simulated using MARS-KS code. Henry-Fauske critical flow model[4] was used for the break flow from the affected SG to the break. LOOP was simultaneously assumed at the time of the main steam line pipe break. Reactor trip signal is generated by the low RCS pump shaft speed trip at 0.63 second after the break and reactor trip was initiated at 0.98 second after signal delay time. PAFS was actuated after complete closure of the MSIV of the intact SG at 6.07 seconds followed by the complete closure of the MFIV. Table 2 shows the sequence of the event during the MARS-KS MSLB accident analysis as well as the APR+ SSAR analysis results.

Table 2. Sequence of the Event of MSLB Analysis

Time (sec)		Event	Set point (SSAR/MARS)
SSAR	MARS-KS		
0.00	0.00	Main Steam Pipe Break and LOOP	0.397259 m^2
0.63	0.63	Low RCP Shaft Speed Trip Signal generated	94.83 %
0.98	0.98	Reactor trip initiated, MSIV/MFIV starts to close	
1.08	1.08	Reactor Trip	
6.18	6.07	MSIV Closure and PAFS actuated to Intact SG	
11.18	11.00	MFIV Closure	
38.20	54.10	RPV Upper Head void generation	
341.16	339.02	Pressurizer dryout	
413.90	326.01	Maximum Total Reactivity	-0.242 / -0.1346 %$\Delta\rho$
		Maximum Core Power	No r-t-p

As shown in Table 2, the MARS-KS MSLB analysis results show similar trend as the SSAR results up to the time of the MFIV closure. However, MARS-KS steam flow of the broken side of the SG shows higher break flow than the SSAR analysis as shown in Figure 2. The differences in the break steam flow are due to different critical flow models used for the MARS-KS and APR+ SSAR analysis. However, the time of void generation in the upper head of the MARS-KS analysis is about 14 second later than the SSAR analysis. This earlier void generation in the upper plenum of the SSAR analysis is due to larger PAFS flow of the SSAR analysis than the MARS-KS as shown in Figure 3.

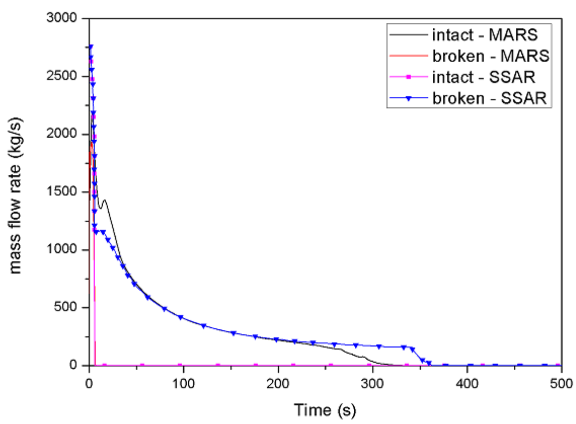

Figure 2. Steam flows of Intact and Broken SGs

For the MARS-KS analysis, PAFS natural circulation flow is calculated by the code, but, for the case of SSAR, PAFS flow was input as a boundary condition. More PAFS natural circulation flow of the SSAR analysis drives more RCS cooldown. Total heat removal, however, is greater for the MARS-KS analysis than the SSAR analysis and thus more positive reactivity insertion into the core due to negative MTC than the SSAR analysis. Thus, as shown in Figure 4, total positive reactivity insertion by the MTC is higher for the MARS-KS analysis than the SSAR mostly due to moderator temperature reactivity insertion.

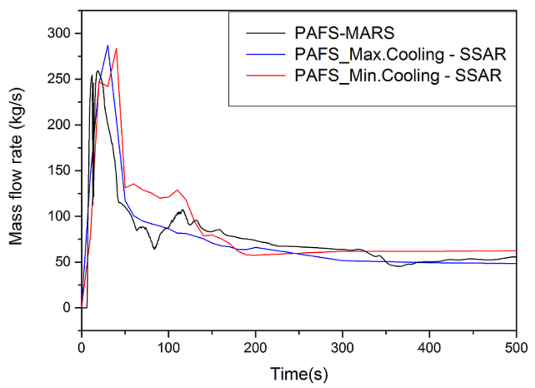

Figure 3. PAFS and SIS Flows

Figures 5 and 6 show the core temperatures and RCS pressure, respectively.

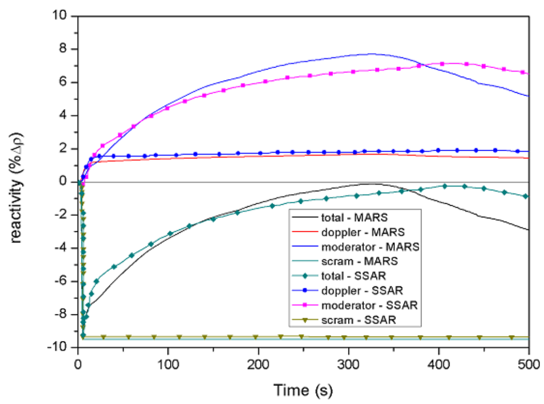

Figure 4. Reactivity Insertion

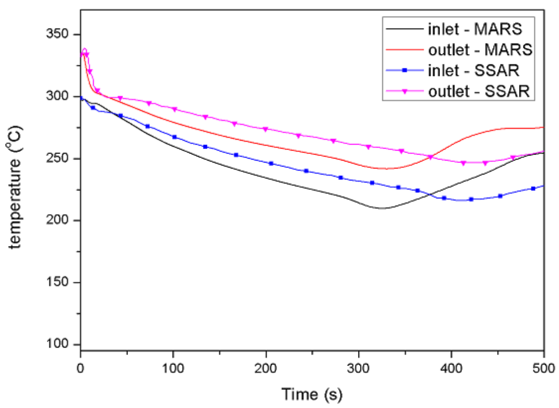

Figure 5. Core Temperatures

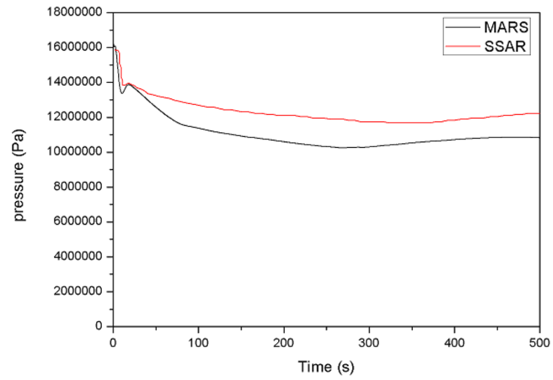

Figure 6. RCS Pressure

Core Temperatures of the SSAR analysis are higher than the core temperatures of the MARS-KS analysis due to more RCS cooldown than the SSAR analysis caused by more PAFS and steam flows. Earlier generation of the voids in the upper plenum for the SSAR analysis is caused by these higher core temperatures of the SSAR analysis than those of the MARS-KS analysis. This effect is also shown in Figure 6 for the RCS pressure, where SSAR RCS pressure is higher than the MARS-KS RCS pressure due to higher temperature and earlier void generation in the upper plenum.

Maximum total reactivity insertion during the MSLB accident was -0.242 %Δρ and -0.1346 %Δρ for the SSAR and MARS-KS analysis, respectively. As shown in Figure 4, the difference in total reactivity insertion is mostly due to the moderator reactivity insertion. It should be also noted, however, that the SSAR analysis used moderator reactivity insertion based on the moderator temperature contrary to the MARS-KS analysis which used moderator reactivity insertion based on the moderator density instead. Thus, APR+ SSAR moderator reactivity insertion should be evaluated by more fundamental MARS-KS moderator cooldown density reactivity insertion.

Figure 7 shows the core power behavior during the MSLB accident. APR+ SSAR analysis shows higher power during the MSLB accident than the MARS-KS analysis, but no return-to power.

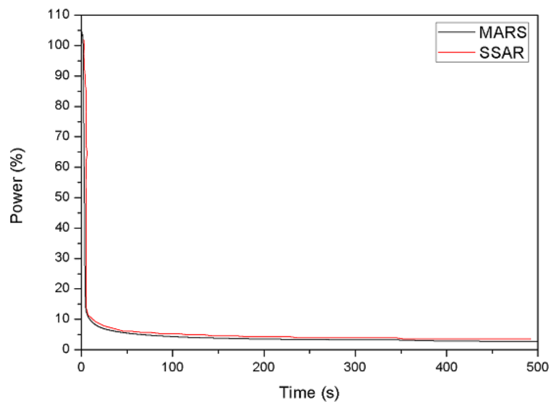

Figure 7. Core Power

MSLB accident is inherently asymmetric cooldown of the RCS due to the asymmetric steam line break at one side of the affected SG as well as the PAFS actuation only at the intact side of the SG. These asymmetric factors all contribute to the asymmetric phenomena in the RCS loop, downcomer and the core during the MSLB accident. Figures 8 and 9 are the MARS-KS analysis results of the asymmetric natural circulation flows in the downcomer and show that the natural circulation flows of the broken side nodes are higher than the intact side nodes of the loops and the temperatures of the intact side nodes are higher than the broken side nodes of the loop at the downcomer.

The asymmetric phenomena in the core are rather minimal as shown in Figures 10 and 11 for the core flows and temperatures of the intact and affected sides. These asymmetric thermal hydraulic phenomena of the MSLB accident should be evaluated for the excore neutron flux detector signal calibration during the transients.

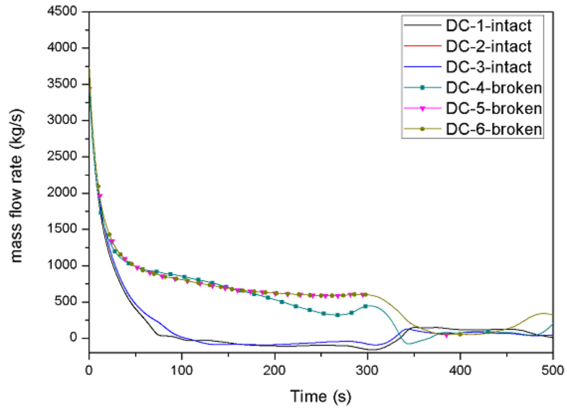

Figure 8. Asymmetric Natural Circulation Flows Of Downcomer Nodes

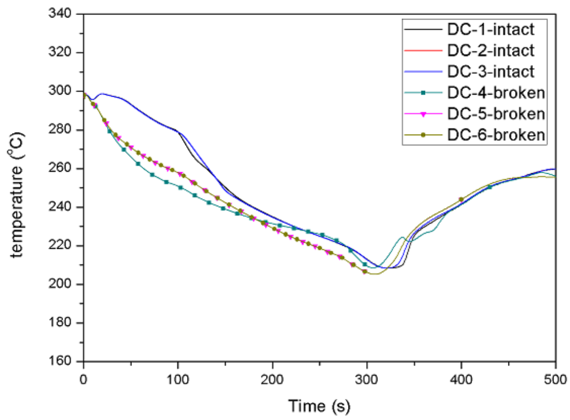

Figure 9. Asymmetric Temperatures of Downcomer Nodes

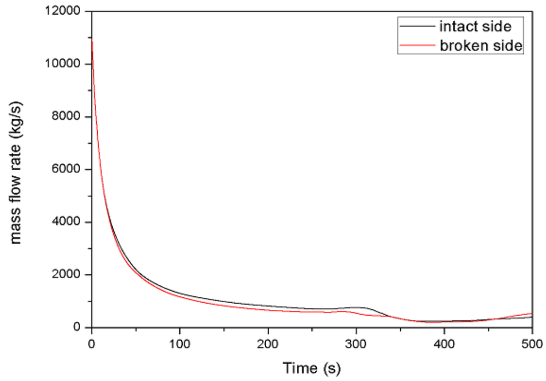

Figure 10. Asymmetric Core Flows

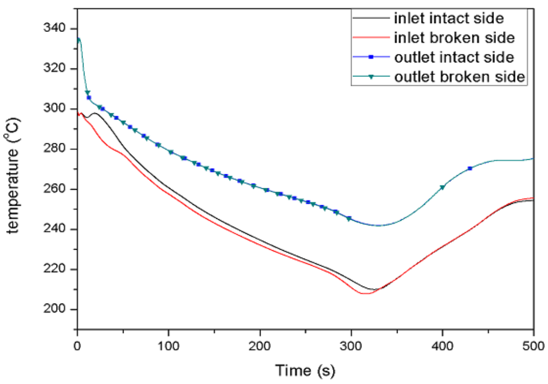

Figure 11. Asymmetric Core Temperatures

3. Conclusions

Independent safety evaluation has been performed using MARS-KS regulatory safety analysis code for the APR+ MSLB accident inside containment for the limiting case of the full power post-trip return-to-power. The results of MARS-KS analysis were compared with the results of the MSLB safety analysis presented in the APR+ SSAR. Due to higher cooldown of the MARS-KS analysis, the MARS-KS analysis results in a higher positive reactivity insertion into the core by the negative moderator and fuel temperature reactivity coefficients than the APR+ SSAR analysis. Both results show no return-to-power during the limiting case of the MSLB inside containment. However, APR+ SSAR moderator temperature reactivity insertion should be evaluated against the MARS-KS moderator density reactivity insertion for is conservatism.

This study also clearly shows asymmetric thermal hydraulic behavior during the MSLB accident at intact and affected sides of the downcomer and the core. These asymmetric phenomena should be further investigated for the effects on the system design.

REFERENCES

[1] APR+ SSAR, Korea Hydro and Nuclear Power, 2012.
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[4] R. H. Henry and H. H. Fauske, The Two-phase Critical Flow of one component mixtures in nozzle orifices and steam tubes, J. Heat Transfer, Trans. 93, 724-737, 1971.