VERIFICATION OF SEVERE ACCIDENT MANAGEMENT GUIDELINE (SAMG) ENTRY CONDITION FOR OPR1000

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ABSTRACT

The current severe accident prevention and mitigation strategies for OPR 1000 have emergency operating procedures (EOPs) and severe accident management guidelines (SAMGs), respectively. The main objective of SAMG is to prevent a release of radioactive materials from releasing into environment and mitigate severe accident phenomena during severe accident. The current SAMG entry condition is met when the core exit temperature (CET) reaches 650℃ in OPR 1000. Peak cladding temperature (PCT), which represents core integrity more precisely than CET does, cannot be used since it is not measurable in the main control room (MCR). Current SAMG entry condition for every kind of accident scenarios is not reasonable, since entry condition is determined without considering operator action time. Therefore, SAMG entry condition need to be verified with consider operator action time. Thus, an analysis methodology for SAMG entry condition was developed to verify the SAMG entry condition. A severe accident DB were also developed in order to analyze the SAMG entry condition. The analysis results of DB show that available operator action time from the SAMG entrance to RV fail is shorter than the required time in most cases. As a result, the proper SAMG entry condition was suggested through the results of DB analysis. When the SAMG entry condition is changed from CET to suggested condition, the available action time is increased about 350 to 4300 sec. Also, the suggested entry condition was verified through the simulation which considered operation action time and reflecting the suggested entry condition.

Key Words: Severe accident management guideline (SAMG), Entry condition, Operator action time, MAAP code

1 INTRODUCTION

Public concerns and worries about safety of nuclear power plants (NPPs) has risen since the Fukushima nuclear accident in 2011. The importance of severe accident management has been emphasized because severe accident management failed during the Fukushima accident. Thus, it is vitally important to develop proper severe accident management strategies for NPPs [1].

Design basis accidents (DBAs) are postulated accidents to which a nuclear plant, its systems, structures and components must be designed and built to withstand loads during accidents conditions. Normally, emergency operating procedures (EOPs) are critical for ensuring reactor safety and preventing severe accident during DBAs in NPPs. If the accident conditions become more severe than the DBA, then EOPs end. Such a scenario is called beyond DBA or severe accident. Therefore, severe accident management guidelines (SAMGs) have been developed to mitigate severe accident. The main objective of SAMG is to prevent a release of radioactive materials from releasing into the environment and mitigate severe accident phenomena during severe accident [2]. The EOPs are terminated when the mitigation process enters to the SAMGs, so the criteria of the process change from the EOPs to the SAMGs are an entry condition of the SAMGs. Therefore, the entry condition is very important for the operator action to have sufficient time to mitigate the severe accident. Table I shows the current SAMG entry condition [3].

Table I. Current SAMG entry condition

Reactor Type	SAMG entry condition
CE PWR	CET: 480℃
OPR 1000 (Korea)	CET: 650℃
Westinghouse PWR	CET: 650℃
APR 1400 (Korea)	CET: 650℃
Loviisa (Finland)	CET: 450℃
B&WOG	CET: 480℃
EDF PWR (France)	CET: 1100℃
CANDU	Loss of core cooling and either loss of moderator cooling to fuel channels or major release of fission products from the fuel

Currently, the Core Exit Temperature (CET) of over 650℃ is the only one SAMG entry condition for Korean Optimized Power Reactor (OPR) 1000. The Peak Cladding Temperature (PCT) can more precisely represents core integrity than the CET does; however, the PCT cannot be used because it is not measurable in the MCR of real NPPs. Fixed SAMG entry condition for every kind of accident scenarios is not reasonable, since current entry condition is determined without considering operator action time. In addition, if the major safety critical systems or components such as the high pressure safety injection (HPSI) system and low pressure safety injection (LPSI) system are unavailable, available operator action time becomes less because time between the SAMG entrance and reactor vessel failure is shortened. Therefore, the SAMG entry condition need to be reconsidered with operator action time.

To verify the SAMG entry condition, this study analyzed the level 1 and 2 probabilistic safety assessment (PSA) reports for OPR 1000 [4]. Four dominant accident events were selected as an analysis result: small break loss of coolant accident (SBLOCA), medium break loss of coolant accident (MBLOCA), large break loss of coolant accident (LBLOCA), and station blackout (SBO). These events contribute about 90 percent to Core Damage Frequency (CDF). The data were obtained by simulating selected scenarios using the modular accident analysis program (MAAP) version 5.01 [5].

2 OPERATOR TASK ANALYSIS

The SAMGs for OPR 1000 were developed by quantitative risk analysis through PSA analysis [6]. The SAMGs consist of an emergency strategy, a control strategy, a monitoring strategy, and seven mitigation strategies. Also, the SAMGs are implemented by the technical support center (TSC) and separated from EOPs. The seven mitigation strategies in SAMGs focus on two objectives: in-vessel and ex-vessel strategies.

The operator's task in EOPs and SAMGs can be classified into monitoring, control, and evaluation tasks. For examples, the monitoring task is to check the PRZ water level, the availability of SI pump, etc. For the control task, adjusting the PRZ pressure and opening the valve are the examples, and evaluating the adverse effect by adjusting the valve is for the example of the evaluation task. Table II shows analysis results of operator's task in SAMGs

Table II. Analysis results of operator's task in SAMGs

Strategy NO.	Minimum task amount			Maximum task amount		
	Monitoring	Control	Evaluation	Monitoring	Control	Evaluation
Emergency 01	4	1	0	26	39	4
Mitigation 01	56	6	9	91	29	11
Mitigation 02	42	3	3	59	24	8
Mitigation 03	65	1	6	96	32	8
Mitigation 04	28	12	15	36	22	17
Mitigation 05	60	39	25	118	70	38
Mitigation 06	76	30	21	79	30	24
Mitigation 07	27	11	11	110	31	27

Also, the operator action time was assumed based on ANSI-ANS-58.8 [7]. In this report, the acceptable methods for deriving analysis time estimates for individual task are as follows: operator interviews and surveys, operating experience reviews, use of control/display mockups, and expert judgment. Unfortunately, the OPR1000 could not conduct SAMG operation simulation. In this paper, the operator performance time was assumed to monitoring task 30 sec/a task, control task 40 sec/a task, and evaluation task 120 sec/a task based on expert judgment.

3 DEVELOPMENT OF AN ANALYSIS METHODOLOGY

3.1 Description

An analysis methodology for entry condition was developed to verify the SAMG entry condition. The required steps to develop the analysis methodology are as follows: selectin of reference plant, selection of initiating event, development of severe accident data base (DB) using a simulation tool, analysis of developed severe accident DB and suggest proper SAMG entry condition considering operator action time, and verification and validation. In this paper, OPR 1000 is selected as the reference plant. This plant is a South Korean two-loop 1000MWe PWR, developed as the first Korean Standard NPP. 12 units in total are operating in South Korea. To select the initiating events, level 1 and 2 PSA reports for OPR 1000 are analyzed. Four dominant initiating events: SBLOCAs, MBLOCAs, LBLOCAs, and SBO are selected based on level 1 and 2 PSA reports.

Since NPP accident data are merely available, the data were obtained by simulating selected scenarios from the simulation code. Through the review result for reliable severe accident code, since current SAMG and PSA reports have been developed based on MAAP code for OPR 1000, MAAP code was selected. This code is a computer code developed by EPRI that simulates the response of a PWR during NPP severe accidents. The latest MAAP code, MAAP 5, handles the full spectrum of important phenomena that could occur during an accident and simultaneously models thermal-hydraulics and fission products.

3.2 Development of Severe Accident DB

Using MAAP 5.01 code, severe accident sequences were simulated with the selected initiating events, SBLOCA, MBLOCA, LBLOCA, and SBO in OPR 1000. In the case of LOCA, to proceed with the code calculation, break location and break size need to be determined. In this study, the break is assumed to occur at the cold leg and the break size were only considered. The scenarios for each selected initiating event were explained in Table III to VI in more detail. Although Event Tree (ET) from the PSA report was referred to reduce the number of severe accident sequences to consider, many paths may still lead to the plants to severe accidents.

Table III. Explanation of selected scenarios for SBLOCA

Scenario	HPSIS injection	Deliver Aux. Feed-water	Steam removal via MSSVs	HPSIS recirculation	Depressurize RCS for LPSIS	LPSIS recirculation
#1	Success	Success	Success	Failure	Success	Failure
#2	Success	Success	Success	Failure	Failure	N/A
#3	Success	Failure	N/A	N/A	N/A	N/A

Table IV. Explanation of selected scenarios for MBLOCA

Scenario	HPSIS injection	HPSIS recirculation	HPSIS hot and cold leg recirculation	Recirculation cooling
#1	Success	Success	Failure	Failure
#2	Success	Failure	N/A	N/A
#3	Failure	N/A	N/A	N/A

Table V. Explanation of selected scenarios for LBLOCA

Scenario	Deliver Aux. feed-water using TDPs	Restore AC power (After 1 hr)	Steam removal via ADVs	Steam removal via MSSVs	Restore AC power (After 11 hr)	HPSIS injection
#1	Success	Success	Success	N/A	Success	Failure
#2	Success	Failure	Success	N/A	Failure	N/A
#3	Success	Failure	Failure	Success	Failure	N/A
#4	Success	Failure	Failure	Failure	Failure	N/A
#5	Failure	Failure	Failure	Failure	Failure	N/A

Table VI. Explanation of selected scenarios for SBO

Scenario	Deliver Aux. feed-water using TDPs	Restore AC power (After 1 hr)	Steam removal via ADVs	Steam removal via MSSVs	Restore AC power (After 11 hr)	HPSIS injection
#1	Success	Success	Success	N/A	Success	Failure
#2	Success	Failure	Success	N/A	Failure	N/A
#3	Success	Failure	Failure	Success	Failure	N/A
#4	Success	Failure	Failure	Failure	Failure	N/A
#5	Failure	Failure	Failure	Failure	Failure	N/A

3.3 Analysis Results of Severe Accident DB

The developed severe accident DB was analyzed to compare the required action time between SAMG entrance and SI operation as well as available time for operator action between SAMG entrance and RV failure. Table VII shows time of significant events and comparison of required action time and available operator action time for SBLOCA #1. In sequence SBLOCA #1, the available is enough by comparison with minimum required action time. However, the available operator action time is not enough by comparison with maximum required action time except for break size of within 0.005 ft^2 as given in Table VII. And Table VIII shows time of significant events and comparison of required action time and available operator action time for MBLOCA #1. As shown in Table VIII, if the SAMG enter the CET at 650℃, available operator action time is less than minimum required action time. In other words, operator action time is insufficient. The other scenarios showed similar trends.

Table VII. Available operator action time to RV failure during SI operation mode (SBLOCA #1)

Significant events	Break size (ft^2)				
	0.001	0.005	0.01	0.015	0.02
Reaching time to CET 650℃(sec)	225,197	102,207	60,843	42,281	32,998
Time of H2 generation in core (sec)	220,152	98,555	59,752	41,637	32,446
Molten fuel relocation time (sec)	239,444	117,811	68,593	48,557	38,948
RV failure time (sec)	253,905	124,713	76,094	55,241	45,567
Required action time to SI (sec)	Max: 16,840 sec, Min: 8,810 sec				
Available time for operator action from SAMG entrance to RV failure (sec)	28,708	22,506	15,251	12,960	12,569

Table VIII. Available operator action time to RV failure during SI operation mode (MBLOCA #5)

Significant events	Break size (ft^2)				
	0.021	0.05	0.1	0.15	0.2
Reaching time to CET 650℃(sec)	8,697	6,876	6,913	6,858	6,931
Time of H2 generation in core (sec)	8,276	6,575	6,657	6,632	6,695
Molten fuel relocation time (sec)	12,988	11,085	11,308	11,253	11,251
RV failure time (sec)	18,431	16,619	16,949	16,717	16,784
Required action time to SI (sec)	Max: 16,840 sec, Min: 8,810 sec				
Available time for operator action from SAMG entrance to RV failure (sec)	9,734	9,743	10,036	9,859	9,853

3.4 Suggestion of Proper SAMG Entry Condition

In order to suggest a new SAMG entry condition, the measured variables which are closely related to core damage were acquired. The major measured variables are as follows: H2 generation amount in core, mass of water and temperature in core, pressure, temperature, and water level in PRZ, temperature and pressure in RCS, temperature and pressure in containment, and SG water level and pressure. Based on the comparison between measured variables and core damage, mass of water in core was selected as variables which indicate core damage precisely.

With the simulation results, the proper SAMG entry condition for SBLOCA #1 are as follows: failure of all system which are to mitigate core damage, CET over 430℃, and decrement of water level in core below the initial value. Figure 1 shows the mass of water in core and CET calculation for SBLOCA #1. When the SAMG entry condition is changed from 650℃ to suggested condition the available action time is increased about 800 sec as given in Figure 1. Also, the proper SAMG entry condition for MBLOCA #1 are as follows: Failure of all systems which are to mitigate core damage, CET over 420℃, and decrement of water level in core below the initial value. Figure 2 shows the mass of water in core and CET calculation for MBLOCA #1. When the SAMG entry condition is changed from current condition to suggested condition the available action time is increased about 350 sec. And the proper SAMG entry condition for SBO #3 are as follows: Failure of AC power restoration, CET over 420℃, and decrement of water level in core below the initial value. Figure 3 shows the mass of water in core and CET calculation for SBO #3. As a result, when the SAMG entry condition is changed from CET 650℃ to suggested variable, the available action time is increased about 4,300 sec. The other scenarios showed similar trends.

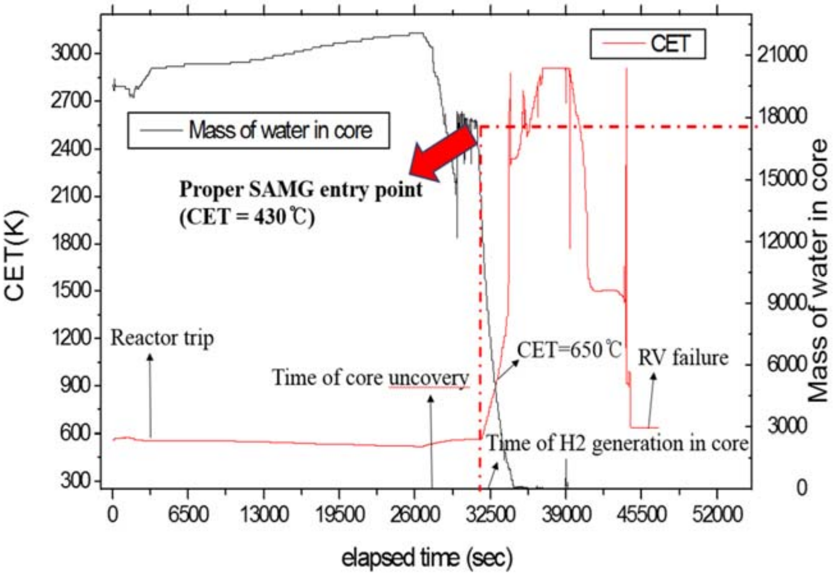

Figure 1. Mass of water in core and CET calculation for SBLOCA #1

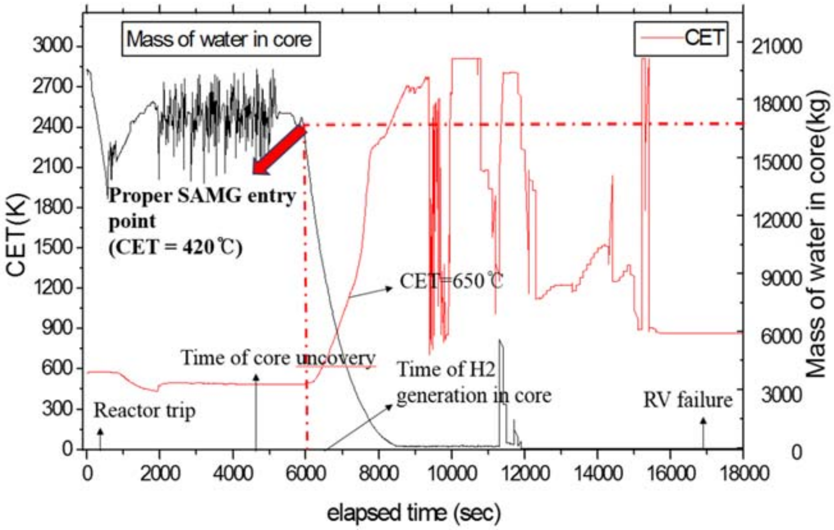

Figure 2. Mass of water in core and CET calculation for MBLOCA #1

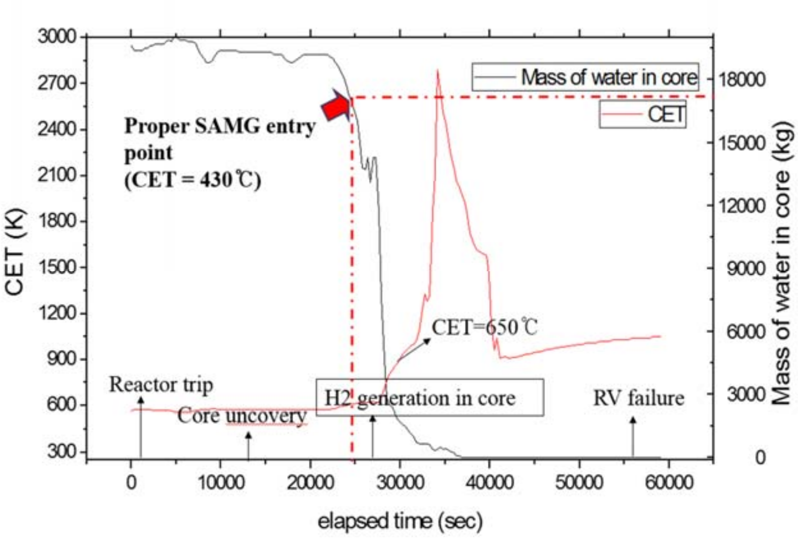

Figure 3. Mass of water in core and CET calculation for SBO #3

3.5 Verification of Suggested SAMG Entry Condition

To verity the suggested SAMG entry condition, considered severe accident sequences were simulated considering operator action time and reflecting the suggested SAMG entry condition. Figure 4 shows the simulation result for SBLOCA # 1. As a result, if the SI recirculation operation succeed, RV failure can be prevented. Table IX and X show time of significant events related to success and failure in SI recirculation operation for SBLOCA # 1. Although failure of the recirculation operation may cause RV failure, it can be confirmed that the operator action time is increased. Figure 5 the simulation result for LBLOCA # 1. Although the SI recirculation operation is fail, it can be confirmed that the operator action time is increased more than when the SAMG enter current entry condition. The other scenarios showed similar trends.

Table IX. Success of recirculation operation for SBLOCA #1

Significant events	**Break size (ft^2)**				
	0.001	**0.005**	**0.01**	**0.015**	**0.02**
Core uncover time (sec)	213,879	99,768	57,740	40,758	31,670
Time of H2 generation in core (sec)	217,417	101,856	60,145	41,784	35,451
Molten fuel relocation time (sec)	N/A	N/A	N/A	N/A	N/A
RV failure time (sec)	N/A	N/A	N/A	N/A	N/A

Table X. Failure of recirculation operation for SBLOCA #1

Significant events	**Break size (ft^2)**				
	0.001	**0.005**	**0.01**	**0.015**	**0.02**
Core uncover time (sec)	213,879	99,768	57,740	40,758	31,670
Time of H2 generation in core (sec)	217,417	101,856	60,145	41,784	35,451
Molten fuel relocation time (sec)	245,517	167,489	100,412	98,738	96,568
RV failure time (sec)	259,200	184,365	110,741	100,415	99,671

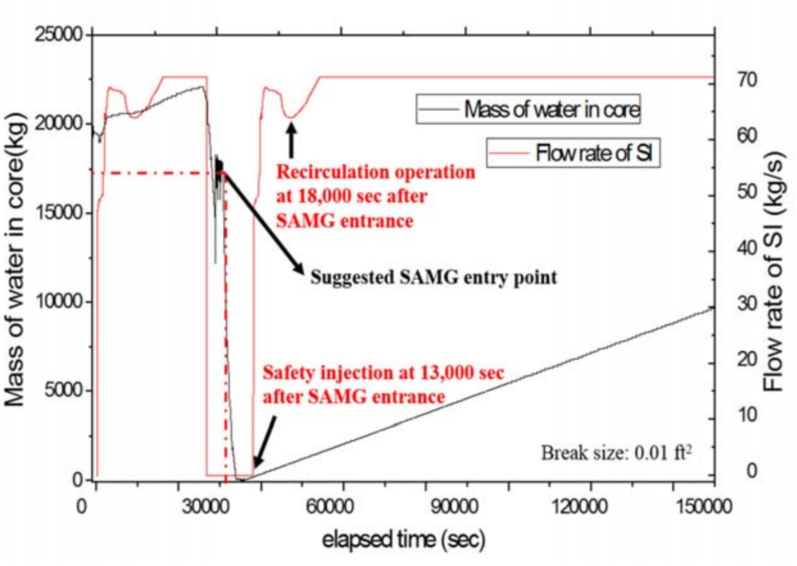

Figure 4. In case of success of SI recirculation operation for SBLOCA #1

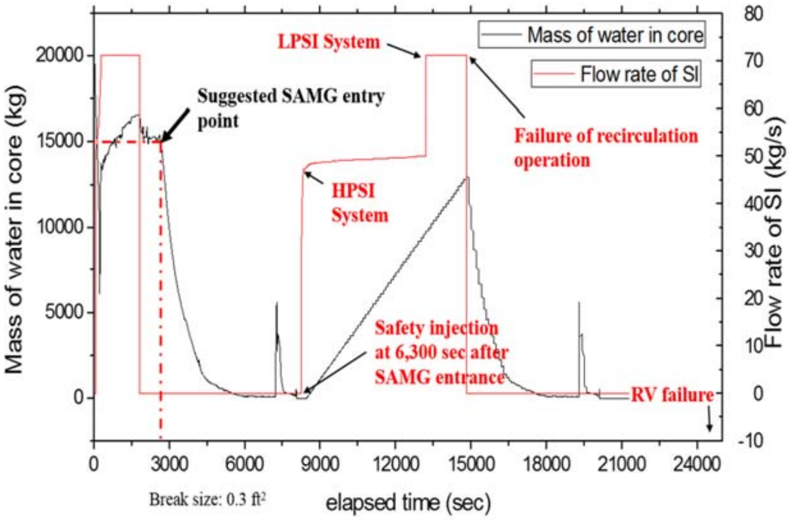

Figure 5. In case of success of SI recirculation operation for LBLOCA #1

4 CONCLUSIONS

Severe accident mitigation strategies are widely divided into EOPs and SAMGs in OPR 1000. The objectives of these mitigation strategies are different. EOPs are critical for ensuring reactor safety and preventing core damage. The main objective of the SAMG is to prevent a release of radioactive material into the environment during severe accident. However, current SAMG entry conditions have some problems. Since SAMG entry condition is only depending on CET 650℃, SAMG are not reliable. Additionally, available operator action time from the time of entrance to the time of RV failure is insufficient, and operator's performance is not considered. Therefore, current SAMG entry condition should be improve.

In this paper, to verify the entry condition, the SAMG entry condition analysis methodology is developed considering operator action time. Based on simulation results, the available action time from the time of SAMG entrance to the time of RV failure is not enough. Therefore, a new entry condition are suggested to consider the operator action time. When the SAMG entry condition is changed from CET 650℃ to the suggested variables, the available action time is increased from about 350 to 4300 seconds. Also, the developed methodology was verified through the simulation which is considering operation action time and reflecting the suggested entry condition. Through the simulation result, the suggested variables are a suitably effective transition point for revision of the current SAMG entry conditions.

5 ACKNOWLEDGMENTS

This research was supported by the Nuclear Research & Development Program of the National Research Foundation (NRF) grant funded by the South Korean government, Ministry of Science, ICT & Future Planning (Grant code: 2012M2B2B1055615).

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