Effectiveness of Modified Jakob Number as a SAMG Entry Condition of OPR1000

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1. Introduction

To mitigate the consequences of transients and accidents that have caused plant parameters to exceed reactor protection system set points or engineered safety feature set point, or other established limits, operators' action is guided by plant procedures of emergency operating procedures (EOPs). If the operators' action with EOP fails in bringing the plant to a safe state, significant core degradation may result in and the nuclear power plant system may experience the severe accident condition [1]. Once severe accident starts EOP action is terminated and accident management is handed into the technical support center (TSC). Since the severe accident, a new level of accident mitigation is invoked based on severe accident management guidance (SAMG).

For a reasonable SAMG entry condition, core exit temperature (CET) has been accepted as the most realistic and practical parameter because of its reliability of detecting and diagnosing the severe accident condition. For the OPR1000, CET=923 K was set as the SAMG entry condition. In fact, monitoring and diagnosing the cladding temperature under severe accident condition is of importance. However, it is impossible to read the cladding temperature and as an alternative CET could be the best measurement in inferring the cladding temperature. Because of its importance in mitigating the severe accidents, the effect of CET has been studied by many researchers [2,3]. Among many, recently Seo et al. [4] investigated effect of the four SAMG entry conditions using MELCOR code. Their results showed that applying different CETs as a SAMG entry condition would result in different mitigation result in terms of delayed failure time of the reactor pressure vessel (RPV). However, no direct evidence was drawn for the optimized CET value to define the best SAMG entry conditions. On the other hand, Lee et al. [5] suggested a new parameter for SAMG entry condition. Their results showed that modified Jakob number can be used to predict onset of oxidation and further can be applicable as an alternative SAMG entry condition in replacement of CET.

Therefore, in this study, in extension of Lee et al.'s study, various modified Jakob numbers were used for SAMG entry condition in the severe accident simulation using MELCOR 1.8.6. The objective of this study is to investigate the effect of accident mitigation in view of delaying RPV failure.

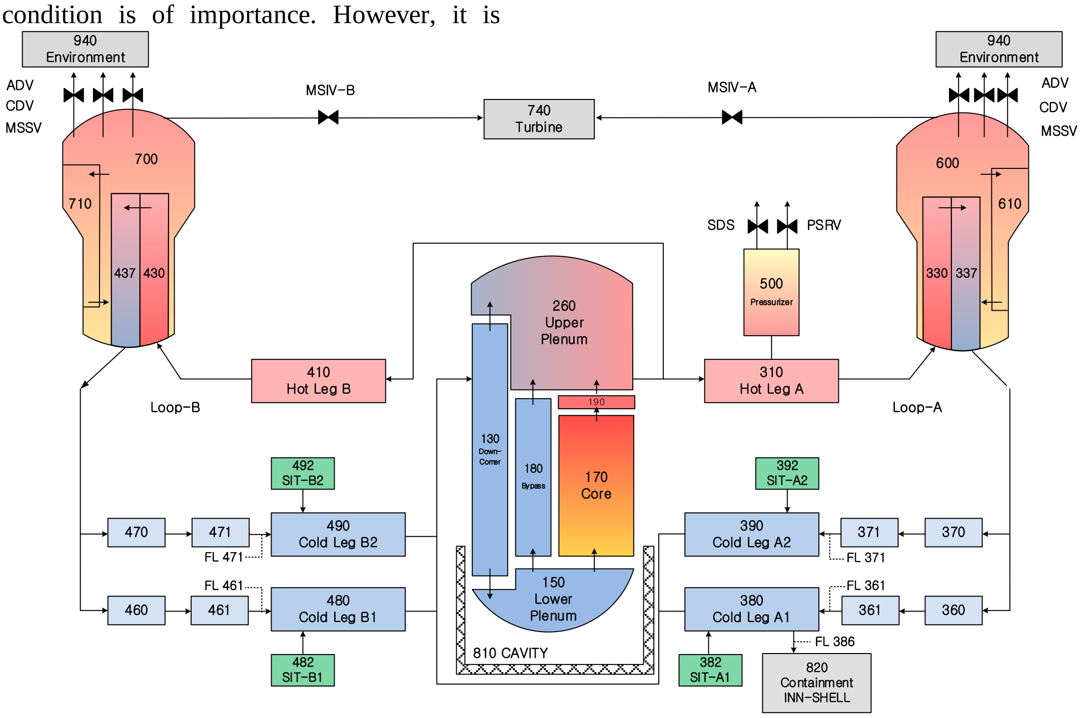

Fig. 1. Nodalization of MELCOR input model for OPR1000

2. Numerical Methods

2.1 MELOCR Description and input model of OPR1000

Korea Optimized Power Reactor (OPR) 1000 was selected for MELCOR simulation. Figure 1 shows a nodalization of the OPR1000 used as a MELCOR input. The input model includes two steam generators (SGs), two hot legs, four cold legs, RPV and pressurizer. Figure 2 shows the core nodalization of OPR1000 for MELCOR. The core consists of seven radial rings and fourteen axial levels. First axial level to third axial level are dedicated to lower plenum (CV 150) and fourth axial level to fourteenth axial level are dedicated to core region (CV170).

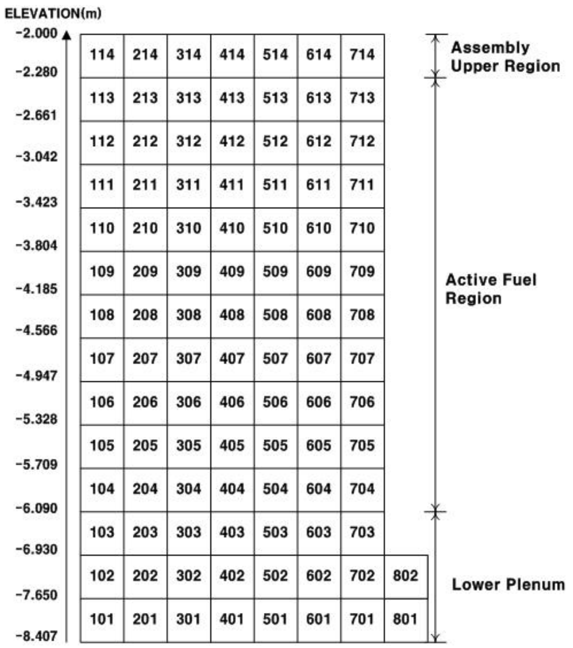

Fig. 2. The core nodalization of OPR1000 for MELCOR

2.2 Description of Modified Jakob Number

Jakob number (Ja) is the dimensionless number developed by Bosnjakovic [6] and is given in Eq. (1). Conventionally Ja indicates ratio of sensible heat of liquid to latent heat of vaporization. In this study, however, two-phase of coolant is overheated by decay heat and oxidation heat and thereby vapor superheating starts to appear during the accident condition. Thus, conventional Ja was modified to consider such transition from two-phase of water to superheat retained by vapor. As a result, the modified Jakob number (Ja') is manipulated using Eq. (1) and is given in Eq. (2), which represents the ratio of vapor superheat to latent heat of vaporization. Most attractive benefit of using Ja' is that it can incorporate the CET information as well as the thermo-physical properties of core coolant subject to the system pressure. Thus, rather than relying on CET only, implementing more comprehensive information of system pressure as well as CET is possible with Ja'..

$$Ja = \frac{C_{p,f}\rho_f (T_0 - T_{Sat})}{h_{fg}\rho_g} \quad (1)$$

$$Ja' = \frac{C_{p,g}\rho_g (T_0 - T_{Sat})}{h_{fg}\rho_g} \quad (2)$$

2.3 Test matrix

To investigate effect of various SAMG entry conditions, three severe accident scenarios of high probability of a transition to severe accident were selected according to on the recent probabilistic safety analysis (PSA) Level 1 of OPR1000 [7]. The scenarios chosen are small break loss of coolant accident without safety injection (SBLOCA without SI), station black out (SBO) and total loss of feed water (TLOFW). For SBLOCA without SI, an 1.35 inches break on a cold leg is assumed. For SBO, all off-site power is assumed unavailable and stopping all secondary feed water is assumed for TLOFW. Table I summarizes the initiating events which have high probability of a transition to severe accident.

Table I: Initiating events which have high probability of a transition to severe accident

Initiating Events	Probability (%)
Small Break Loss of Coolant Accident without Safety Injection	22.4
Station Black Out	14.4
Steam Generator Tube Rupture	13.8
Total Loss of Feed Water	13.8
Large Break Loss of Coolant Accident without Safety Injection	12.7
Medium Break Loss of Coolant Accident without Safety Injection	7.7

Table II: Summary of simulation cases

Accident	SBLOCA without SI	TLOFW	SBO
Depressurization component	ADV	SDS	SDS
SAMG entry condition (Ja')	1.0-2.0	1.0-2.0	1.0-2.0
ECCS	N/A	N/A	N/A

To investigate the effect of SAMG entry condition on delaying the RPV failure time, mitigation action of 'Depressurize reactor coolant system (RCS)' (Mitigation-02) guided by SAMG was selected. For the SBO and TLOFW, opening one safety depressurization system (SDS) is applied for the possible depressurization. In case of the SBLOCA without SI, depressurization is done naturally through the break. Thus, opening one atmosphere dump valve (ADV) as Mitigation-02 and 'injection into SG' (Mitigation-01) were selected for operators' actions. For all cases, high pressure safety injection (HPSI) and low pressure safety injection (LPSI) were assumed unavailable and only safety injection tanks (SITs) are available for RCS makeup. Table II shows summary of all cases.

3. Result and discussion

3.1 Steady State

Comparison of steady state parameters between final safety analysis report (FSAR) and MELCOR calculation was performed to verify reliability of the OPR1000 input model of MELCOR. Table III shows steady state parameters of FSAR and MELCOR calculation. The result shows that the MELCOR steady-state calculation is in good agreement with the FSAR.

Table III: Steady state parameter comparison between OPR1000 FSAR and MELCOR calculation

Parameter	FSAR	MELCOR
Core Thermal Power (MWth)	2815	2815
Primary Coolant Flow Rate (kg/s)	15305.5	15498
Primary System Pressure (MPa)	15.5	15.5
Core Inlet Temperature (K)	568.8	573.2
Core Outlet Temperature (K)	600.3	603.4
Core Flow Rate (kg/s)	14850	15048
SG Pressure (MPa)	7.37	7.37
Total Steam Flow per SG (kg/s)	800.0	808.5

3.2 Base case

Table IV shows initiating time of several significant sequences for base case. Oxidation time of SBLOCA without SI, TLOFW and SBO was estimated as 2.35, 1.08, and 2.29 hours, respectively. When the cladding temperature reaches approximately 900 K, oxidation heat starts to add additional heat beside the decay heat. This oxidation heat contributes on the core dry-out and eventually melting. Upon melting of majority of the core, the molten core is relocated to the lower plenum. SI was initiated after relocation of the molten core in case of SBLOCA without SI due to the significant depressurization of the system. However SITs were not actuated in cases of TLOFW and SBO because pressure relief valve operation was not sufficient to lower the system pressure to initiate the SITs. RPV failure by lower head penetration occurs in case of SBLOCA without SI and SBO and RPV failure induced by creep rupture occurs in case of TLOFW. RPV failure times of each case are 5.82, 2.3 and 3.78 hours for SBLOCA without SI, TLOFW, and SBO, respectively. Ja'$_{CET}$ of each base case at oxidation time was 1.8, 1.55 and 1.76 for SBLOCA without SI, TLOFW, and SBO, respectively. Table V shows Ja'$_{CET,}$ pressure and CET at oxidation time and Figure 3 shows Ja'$_{CET}$ for the base case. CETs at onset of oxidation are different with each case due to the different pressure.

Table IV: Significant sequences initiating time of base cases

Accident Sequences	Time (hr) , Base case		
	SBLOCA without SI	TLOFW	SBO
Accident Start	0	0	0
Reactor Trip	0.04 (151 sec)	0.01 (28 sec)	0
Reactor Coolant Pump Trip	0.06 (222 sec)	0.37	0
Oxidation Start	2.35	1.08	2.29
Core Dry-out	2.72	1.40	2.62
Relocation to Lower Plenum	2.89	1.56	2.83
SITs Injection	3.64	-	-
SIT Exhaust	5.89	-	-
RPV Failure	5.82	2.30	3.78

Table V: Parameter at oxidation time

Parameter	Accident		
	SBLOCA without SI	TLOFW	SBO
Oxidation Start (hr)	2.35	1.08	2.29
Pressure (MPa)	10.27	16.23	14.49
CET (K)	900	919	942
Ja'$_{CET}$	1.80	1.55	1.76

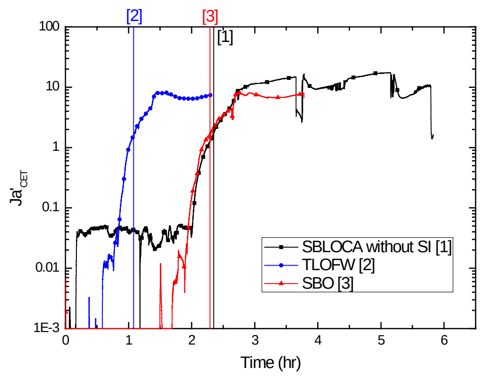

Fig. 3. Ja'$_{CET}$ for Base Cases and Oxidation time

3.3 Cases with mitigation

Using Ja'$_{CET,}$ various SAMG entry conditions were applied for each case. Opening one ADV for the SBLOCA and opening one SDS for the TLOFW and SBO were selected for mitigation. It was assumed that mitigation is performed immediately after SAMG entry conditions. Tables VI, VII and VIII show initiation time of significant sequences for each case. When mitigation action is performed before oxidation, oxidation initiating was delayed significantly for the SBLOCA without SI. However, delay of oxidation for TLOFW and SBO was insignificant. Opening the ADV helps recovering the coolability of the SG, which in turn, facilitates to decrease steam temperature in the core and delay the oxidation. In case of opening SDS, the coolability of SG was not recovered and SITs were actuated after core dry-out. Therefore mitigation effect of delaying oxidation was insignificant.

Table VI: Sequences initiating time of SBLOCA without SI

Accident Sequences	Time (hr) , SAMG entry condition changed to Ja'_{CET} =					
	1	1.2	1.4	1.6	1.8	2.0
SAMG entry condition (Ja_{CET}')	2.23	2.27	2.31	2.33	2.35	2.37
Oxidation Start	15.8	15.9	15.8	16.0	2.35	2.35
Core Dry-out	22.2	22.4	23.4	22.6	27.6	26.0
SITs Injection	2.40	2.43	2.47	2.48	2.51	2.51
SIT Exhaust	3.18	3.14	3.27	3.20	9.59	12.0
RPV Failure	24.9	24.8	25.0	25.1	30.4	29.1
Corresponding CET (K)	766	800	833	867	900	934

Table VII: Sequences initiating time of TLOFW

Accident Sequences	Time (hr) , SAMG entry condition changed to Ja'_{CET} =					
	1	1.2	1.4	1.6	1.8	2.0
SAMG entry condition (Ja_{CET}')	1.00	1.03	1.05	1.08	1.10	1.11
Oxidation Start	1.10	1.11	1.11	1.08	1.08	1.08
Core Dry-out	1.11	1.12	1.15	1.16	1.17	1.18
SITs Injection	1.15	1.18	1.21	1.23	1.24	1.25
SIT Exhaust	12.3	5.37	5.46	6.51	6.51	5.16
RPV Failure	16.9	6.67	7.62	8.25	8.25	7.04
Corresponding CET (K)	813	855	897	925	949	989

Table VIII: Sequences initiating time of SBO

Accident Sequences	Time (hr) , SAMG entry condition changed to Ja'_{CET} =					
	1	1.2	1.4	1.6	1.8	2.0
SAMG entry condition (Ja_{CET}')	2.17	2.20	2.23	2.27	2.29	2.33
Oxidation Start	2.30	2.32	2.33	2.34	2.29	2.29
Core Dry-out	2.27	2.29	2.32	2.34	2.36	2.39
SITs Injection	2.31	2.35	2.38	2.41	2.43	2.47
SIT Exhaust	2.91	2.96	2.98	5.78	5.17	5.85
RPV Failure	8.02	6.43	6.69	6.45	7.12	5.84
Corresponding CET (K)	812	854	897	925	947	1001

Figure 4 shows RPV failure delay time of case with mitigation action. For all cases of SBLOCA without SI, RPV failure was delayed at least 19 hours. With the adoption of Ja'_{CET}, RPV failure occurred 8 hours later in case of Ja'_{CET}=1.0 for the TLOFW case. For the SBO case, RPV failure was delayed up to 4.3 hours. Delay of SITs exhaust causes RPV failure to delay in case of SBLOCA without SI with Ja'_{CET}=1.8 and TLOFW with Ja'_{CET}=1.0. However, despite no difference with other cases, RPV failure of SBO with Ja'_{CET}=1.0 case was delayed 4.3 hours.

It is observed that corresponding CET at the best mitigation effect for the SBLOCA, SBO, and TLOFW are, 900K, 813K, and 812K, respectively. It should be noted that accident management can be performed by event-oriented action, if the event is well diagnosed and determined. In this case, if a single CET (viz. CET=923 K for OPR1000) is used for all types of severe accident events, undesirable mitigation may result in.

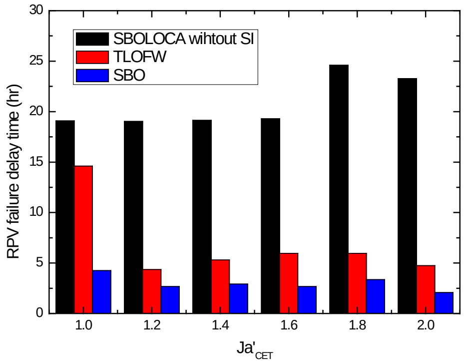

Fig. 4. RPV Failure Delay Time of Case with mitigation

4. Conclusions

Three accidents of the SBLOCA without SI, TLOFW, and SBO were simulated using MELCOR code 1.8.6. Using $Ja'_{CET,}$ various SAMG entry conditions for the OPR1000 were applied for each accident. Total 21 cases of accidents were performed. Three of them were base cases without mitigation and 18 cases were simulated accidents with mitigation action. It was found that Ja'_{CET} was useful to predict onset of oxidation. Thus, if mitigation action is performed before oxidation, delayed RPV failure can result in. Although delay of oxidation by mitigation action was significant in SBLOCA without SI and equivalent results was not achieved for the TLOFW and SBO. However, by adopting various Ja'_{CET} rather than a single CET=923 K, more comprehensive implementation of the core thermal-hydraulic state is expected for more effective accident management. Finally, use of Ja'_{CET} may bear in a more practical measure of the core thermal state and possible range of Ja'_{CET}=1-2 could be applied. With Ja'CET=1.8, the mitigation effect was the best for the SBLOCA. With Ja'CET=1.0, the mitigation effect was greatest for the SBO and TLOFW. To confirm the general relationship between the Ja'CET and mitigation effect, a more detailed study is needed. Adoption of Ja'CET lower than 1 may be investigated in the future. Also more detailed analysis is needed to confirm that

Ja'_{CET} indeed can be used for another standard of suitable SAMG entry condition.

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