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Evaluation of Coolant Injection Procedure in the Severe Accident Management Strategy of APR1400

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1. Introduction

A coolant injection strategy in the severe accident management guideline (SAMG)[1] of APR1400[2][3] relates to immediate coolant injection into RCS (Reactor Coolant System) or injection following the recovery of secondary coolant inventory. This strategy could play important role in accident mitigation and radiological consequences.

In this study, appropriateness of the strategy was evaluated using MELCOR1.8.6[4] and several sensitivity studies of the key parameters were performed.

2. Technical Background

SAMG strategies of APR1400 were examined and the MELCOR modeling of APR1400 was investigated.

2.1 SAMG

APR1400 SAMG adopted the several high level actions which could be available for the operators and plant staffs. In general, high level actions in the PWR can be performed by the injection of the reactor pressure vessel/reactor coolant system (RPV/RCS), to depressurize the RPV/RCS, to restart reactor coolant pumps (RCPs), to depressurize steam generators and to inject into the steam generators. In APR1400 SAMG, the following procedure was adopted.

a. Depressurize the RPV/RCS
b. Depressurize steam generators and inject into the steam generators
c. Inject into the RPV/RCS

The coolant injection into RPV/RCS would be delayed due to the time for filling steam generators. Moreover, current procedure to depressurize the RPV/RCS does not specify any corrective actions after checking RCS coolant injection. In this paper, mobile pumps were considered as coolant injection devices which are installed in SKN 3&4.

2.2 MELCOR code Description

MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactor nuclear power plants. MELCOR is being developed at Sandia National Laboratories (SNL) for the U.S. Nuclear Regulatory Commission (USNRC) as the successor to the Source Term Code Package.

3. Methods and Results

MELCOR modeling and initial conditions and boundary conditions of the accident are described.

3.1 System Modeling

The RCS model includes the core, primary, and secondary coolant systems. The core is modeled as 5 radial rings and 16 axial levels including top- and bottom-end fittings. It also includes 2 steam generators, 4 reactor coolant pumps, and direct vessel injection from the Safety Injection System to the RCS (see Figure 1). The 51-cell containment model consists of 32 subcompartments, 1 environment, and the 18-cell IRWST with 3 axial levels in which 6 cells are azimuthally separated (see Figures 1).

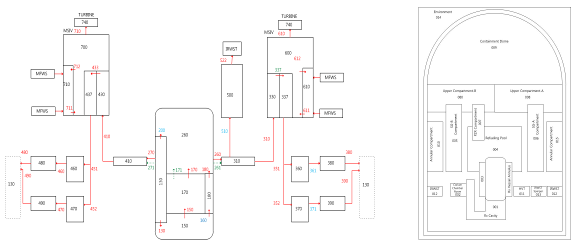

Figure 1. APR1400 MELCOR1.8.6 Nodalization

3.2 Accident Sequences and Boundary Conditions

The station blackout accident was selected in this study, which is one of representative high pressure accident scenarios. As summarized in Table 1, the accident assumes that the reactor trip, feedwater pump trip, and reactor coolant pump trip was assumed at time 0. Due to loss of all electrical power except DC, all active systems and components such as safety injection system, containment spray system are not available. As passive system, four safety injection tank (SIT), safety valves and several essential valves such as POSRVs, main steam atmospheric dump valves (MSADV) are available.

The boundary conditions are summarized in Table 1 and MELCOR1.8.6 achieved steady state conditions are listed in Table 2.

Table 1. RPS setpoints and boundary conditions

Setpoints and Characteristics	Setpoints	Simulated	Rmk
High Pressurizer Pressure, MPa	16.71	16.71	RPS
Low SG Level, (%)	45%, WR	45%, WR	RPS
Low Pressurizer Pressure, MPa	12.726	12.726	SIAS
Pressurizer POSRV - Open pressure, MPa - minimum req., ton/hr	 17.37 244.9	 17.37 244.9	
Steam Generator SRV, MPa	82.54	82.54	
RCP Trip (time after Rx. Trip)	Operator Action	10min.	
TBN Trip (time after Rx. Trip)	2 sec.	2 sec.	

Table 2. MELCOR 1.8.6 Steady State Condition

	Parameters	Desired	Simulated	Errors
RCS	Core Thermal Output, 100% (MW_{th})	3,983	3,983	0.00%
	Pressurizer Pressure (MPa)	15.5	15.7	1.29%
	RPV Outlet Temperature (℃)	323.9	336.3	3.83%
	RPV Inlet Temperature (℃)	290.6	299.9	3.20%
	RCS Flow (Mlb/hr)	166.6	140.8	15.5%
SG	Steam Pressure (MPa)	6.89	7.22	4.79%
	Steam Temperature (℃)	285.0	288.0	1.06%
	Feedwater Temperature (℃)	232.2	232.2	0.00%
	Total Steam Flow (kg/s)	2277.8	2265.9	0.52%

4. Results and Discussions

The Station Blackout sequence was analyzed and several sensitivity studies of the key parameters were performed.

4.1 Base Case

At time 0, the loss of offsite power is occurred with a concurrent demand failure of both the emergency diesel generators and the alternate AC generator. Therefore, the reactor, steam turbine and RCP trip occur at time 0 and MSIVs are closed at the same time. All active systems in RCS are stopped and the forced circulation heat transfer is changed to natural circulation. At 3582 seconds, steam generators are dried out and primary pressure increase upto the set points of pressurizer safety valves(PSV), 17.37MPa(2500psia). Pressurizer PSVs, which are called POSRVs (Pilot Operated Safety Relief Valves) in APR1400, start to open at 4650 and uncover of the core occurred at 5697seconds.

Core exit thermocouple (CET) temperature exceeds 1200°F at 8200 seconds, operator can start to use the SAMG. In this study, considering time margins, first operation to open POSRV is performed at 9600seconds. As RCS pressure decrease, SITs start to inject and all coolant is injected during several hundreds seconds. After second core uncovery, core melting restarts and finally, reactor pressure vessel lower head penetration has failed at 12740seconds.

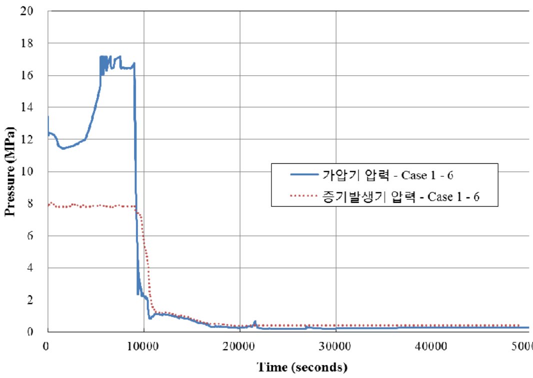

Figure 2. Pressurizer Pressure

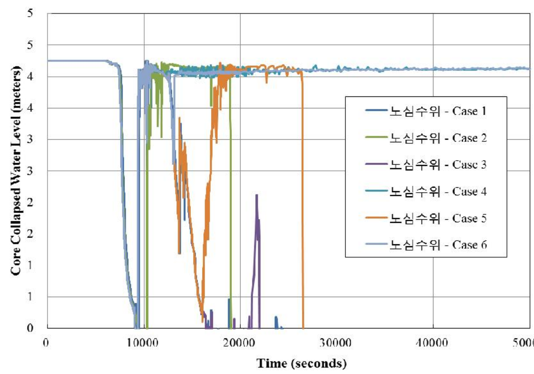

Figure 3. Core Collapsed Water Level

4.2 Sensitivity Cases

In order to evaluate the effectiveness of accident management strategies related to the inventory recovery by the operator action, the timing of the operator actions are selected as sensitivity parameter.

Table 3. Effectiveness of the Operator Action

Events	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Accident Initiation	0.s	0.s	0.s	0.s	0.s	0.s
CET > 1200°F	8200.s	8200.s	8200.s	8200.s	8200.s	8200.s
RCS Depressurization*	9000.s	9000.s	9000.s	9000.s	9000.s	9000.s
SITs Injection Start/End	9355. / 14231.s	10315. / 14231.s	9355. / 14231.s	9355. / 14231.s	9355. / 14231.s	9355. / 14231.s
2ndary Inventory Recovery** Start/End	9600. / 20400.s	N/A	9600. / 20400.s	9600. / 20400.s	9600. / 20400.s	9600. / 20400.s
RCS Inventory Recovery* Start/End	N/A	11800.s ~	21000.s ~	11000.s ~	16000.s ~	13000.s ~
Clad T > 1407K	15810.s	9120.	15981	-***	15981.s	-***
Vessel Failure	21536.s	18900.s	21929.s	-	26371.s	-

* Operator Action by mobile pump
** Operator Action for inventory recovery by mobile pump and depressurization
*** Peak Cladding Temperature : 1369K (at 9000.s)

As shown in table 3, the case 1 shows the RCS behavior only with secondary depressurization and coolant injection. In this case, reactor pressure vessel fails at 21536 seconds , 9000 seconds later than base case. On the other hand, the case 2 shows the RCS behavior only with RCS depressurization and coolant injection. In this case, reactor pressure vessel fails at 18900 seconds which is 6000 seconds later than base case. Comparing two cases, secondary depressurization and coolant injection are more effective than the RCS.

From case 3 to case 6, several cases for the timing of the RCS injection is used. In case 3, sequential operation is applied, but reactor pressure vessel is failed at 21929 seconds slightly later than case 1. It is considered that sequential operation of secondary and RCS injection does not provide any benefit to mitigate core damage.

In case 4 to 6, RCS coolant injection starts at 11000, 16000, and 13000 seconds to find the optimum time for RCS coolant injection. As a result, it was identified that 13000 seconds is the optimum time for injection.

5. Conclusions

Analysis for APR1400 using MELCOR 1.8.6 was performed to evaluate the effectiveness of accident management strategies and the following conclusions were identified.

a. Sequential operation of secondary and RCS injection may not be the best strategy and the simultaneous injection of secondary and RCS injection could be more preferable.
b. At least, the RCS injection should start before complete drainage of water in the safety injection tank using mobile pumps.

In this study, the effectiveness of timing of operator action has been examined and the amount of injection flowrate needs to be studied in the future.

REFERENCES

[1] Korea Electric Power Corporation, ShinKori Nuclear Unit 3,4 Severe Accident Management Guidelines (2012).
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[3] Korea Electric Power Corporation, ShinKori Nuclear Unit 3,4 Final Safety Analysis Report , (2011).
[4] R. O. Gauntt, et al., MELCOR Computer Code Manuals, Version 1.8.6 (2002).