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Analysis of Loss of Residual Heat Removal(RHR) during Mid-loop Operation of Kori 3&4 Nuclear Power Plants

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Abstract

This study aims to understand the thermal-hydraulic behavior, to predict allowable time until core uncovery and core damage, and to evaluate the appropriateness of the abnormal operation procedures during loss of RHR at mid-loop operation for Kori 3&4. RELAP5/mod3.2.2beta thermal-hydraulic transient code was used to analyze the thermal-hydraulic behavior for the following cases identified according to the combination of RCS configurations, venting path and steam generation status: 1) Case 1 : normal venting path (pressurizer and reactor vessel venting path are 3/4 inch and 1 inch venting valves, respectively) with water-filled steam generators (SG). 2), Case 2 : normal venting path with emptied SG, 3) Case 3 : the pressurizer manway opening (the size of manway is 16 inches) with emptied SG, 4) Case 4 : the SG manway opening (the size of manway is 16 inches) located in hot leg with emptied SGs. As a result, the RELAP5 code appropriately predicted the RCS boil-off in core region and the system pressurization during the transient period. In the Case 1, it was takeen long time to reach the core uncovery and heatup because the decay heat was enough transferred from RCS to secondary side. For all cases, the core boil-off was reached about 10~12.4 minutes after the event. Also, it was estimated that the core uncovery time was strongly dependent on the conditions of RCS venting path and the status of secondary side. This result indicated that the Case 3 is the worst one among the sequences investigated. In addition, the Case 3 was estimated that the containment isolation should be achieved within 133 minutes to prevent fission products from releasing to the environment.

I. Introduction

The residual heat removal (RHR) system or shutdown cooling system is used to remove the core decay heat during reactor shutdown operation of a pressurized water reactor (PWR). The system can be operated at the reduced reactor coolant system (RCS) inventory condition, which is usually called mid-loop operation, for inspection or maintenance of certain components such as steam generator U-tubes and reactor coolant pump. The mid-loop operation is defined as operation when the RCS water level is below the top of hot leg flow area at the injection with the reactor vessel. During mid-loop operation, vortexing at the junction of the RHR system suction line and the hot leg can occur and the air entrained into the RHR pump suction line can degrade or interrupt pump performance. Consequently, it may cause an event of the loss of RHR resulting in the core uncovery and severe core damage [1]. As the loss of RHR event has been occurring repeatedly, US NRC requested all licensees to respond to GL87-12 and GL 88-17 regarding the improvement in the equipment for the mid-loop operation and the comprehensive analysis for systems behavior during loss of RHR as well as under normal shutdown operation [2,3]. Several researchers analyzed a loss-of RHR event initiated from a RCS reduced inventory condition for various plant types and compared the calculation results with test facility experimental data [4-6].

In Korea, Kori Units 2 and 3 have been experienced the loss of RHR system during mid-loop operation in June 1984 and in September 1987, respectively [7]. The event of the Kori Unit 3, Westinghouse 3-loop PWR with 2775 MWth, in September 1987 [8], was caused by the inadvertent indication of RCS water level difference between the RCS water level and the Tygon gauge water level and resulted in the loss of RHR for 38 minutes. After the events induced that the RCS temperature reached about 95 ^{o}C. Although those two events were terminated without any severe damage, the analysis of the plant behavior following the event was requested to understand the thermal-hydraulic process of the event.

The objective of present analysis is to understand the thermal-hydraulic behavior after the loss of RHR event occurred at Kori Unit 3. And through the detailed transient analysis, the prediction of the allowable time until core uncovery and core damage will be discussed. Based on those predictions, and the appropriateness of the abnormal operation procedures to cope with the event will be evaluated.

II. Description of Present Analysis

RELAP5 Input Model

The analysis of the loss of RHR event during the midloop operation for Kori unit 3&4 nuclear power plant was modeled with the RELAP5/Mod3.2.2beta thermal hydraulic code[9]. The plants are the PWR-typed with three hot legs and cold legs. The RELAP5 input model for Kori unit 3 consists of 214 hydrodynamic volumes, 233 junctions, 284 heat structures and 11 time-dependent volumes as shown in Fig. 1. The time-dependent volumes were modeled to simulate the boundary conditions. The core region is simulated as a pipe element of 12 volumes.

Steady State Initialization

In order to model the loss of RHR event accurately, it is necessary to appropriately calculate the steady state conditions. The steady state was obtained using the boundary and initial conditions given in Table 1. The RCS water level was set to be at the center of the hot leg, and the water temperatures of hot and cold legs were also 140^{o}F and 122^{o}F, respectively. The rest of the RCS was initialized as air at the same temperature to the cold leg water. The RCS pressure is assumed to be atmospheric. The core power level was set 11.46 MWth decay power that corresponds to 0.48% of full power at 48 hours after reactor shutdown. The RHR coolant inlet temperature is the same as cold leg temperature, 122^{o}F. Normal RHR flow rate was estimated to be 627 lb/sec from energy balance. The RHR flow rate is discharged from one hot leg and equally injected into three cold legs during the steady-state run

Two conditions of the steam generators secondary side are considered: First case is that the SG is filled with air at 212^{o}F, and the other case is that the SG is filled with water at 212^{o}F. The SG secondary side is kept open to allow air and steam to escape from secondary side to containment.

Transient Simulation

The transient calculation was run for four different cases as shown in Table 2. The first case was for an intact S/Gs with normal vents in the RCS, which are consists of 3/4-inch valve on the pressurizer and 1-inch valve on the reactor vessel upper head. The second case is to model the normal vents with emptied SGs. The third case was for the emptied SGs with the opening of pressurizer manway (PMO) which of the size is 16 inches. The last case simulated for the emptied SG with the opening of a SG manway located in hot leg which of the size is also 16 inches. After simulating with normal RHR flow rate for 1000 seconds, the transient was initiated by closing the RHR flow. The RHR flow rate is stepped down to zero at 1000 s after initiation of the transient. The important parameters in the transient analysis are the time to boiling in the core, the time to core uncovery, the time the core heatup. To obtain those parameters, the transient was claculated for about 20,000 seconds using the RELAP5/Mod3.2.2beta code

III. Results and Discussion

Thermal-hydraulic analysis for the Kori unit 3 has been performed for several cases as the combination of RCS configurations, venting path and steam generation status during loss of RHR at mid-loop operation. The analysis has been performed for the four cases as follows;

Case 1 : normal venting path (pressurizer and reactor vessel venting path are 3/4 inch valve and 1 inch venting valves, respectively) with water-filled steam generators (SGs). 2) Case 2 : normal venting path case with emptied SGs. 3) Case 3 : the pressurizer manway opening (PMO; the size of manway is 16 inches) case with emptied SGs. 4) Case 4 : a SG manway opening (SMO; the size of manway is 16 inches) located in hot leg case with emptied SGs.

Results obtained from the four simulations are described in this section. Figure 2 shows the liquid temperature at the top of core for the four cases. From the figures, the fluid temperature smoothly increased for four cases until about 1600 ~ 1800 s, after which it assumes a nearly saturated value. The saturated temperature after the time is due to heating of saturated in the core, i.e., incipient boiling in the core. For the case 1, the fluid temperature at the top of core was kept on the saturated temperature more longer than other cases 3 and 4 because primary decay heat was continuously transferred to the secondary side by the natural convection. The fluid temperature was monotonously increased to about 450 °F for the case 2, which of the venting path is not enough to prevent RCS from pressuring without secondary heat sink as shown in Fig. 3. The fluid saturation temperature increases as the RCS pressure increases.

Boiling in the core pressurizes the reactor coolant system when the system is not sufficiently vented or cooled. Figure 3 displays the pressure trend at the top of core region for the four cases. As above described, it is difficult to remove the decay heat of the RCS for case 2 due to be emptied S/Gs with same venting path. So, the fluid pressure is much higher than case 1. The cases 3 and 4 show a lower pressure of 25 Psia owing to the opening in the pressurizer manway and S/G manway. The pressure may be far below the limit of the gravity injection from refueling water storage tank to RCS during the loss of RHR event at the midloop operation.

The time to core uncovery can be determined by the trend of the collapsed liquid level at the core given in Fig. 4. The collapsed levels in the core show that for the four cases, core uncovery begin 56,685 sec for case 1, 15,982 sec for case 2, 2,457 sec for case 3 and 5,928 sec for case 4 after loss of RHR as described in Table 3.

The continuous discharge through the venting path caused the RCS inventory decreased as shown in Fig. 4. The inventory decrease results in that the temperature of the fuel clad increase and the fuel damage can be induced without preventive actions. Figure 5 shows the behavior of the fuel clad temperatures for the four cases. The figure show that the core heatup was initiated at ~ 69,540 s for case 1, ~ 16,836 s for case 2, ~ 8,017 s for case 3 and ~ 9,528 for case 4 as summarize in Table 3.

As the above results, the RELAP5/Mod3.2.2beta appropriately predicted the RCS boil-off in core and the system pressurization. In the Case 1, because the heat is enough transferred from RCS to secondary side, it takes long time to reach the core uncovery and heatup. In all the cases, the core boil-off is reached to about 10~12.4 minutes after the loss of RHR function. Also, it was estimated that the core uncovery time is considerably different as the RCS configuration and status of secondary side. This result indicated that the third case is the worst one from the sequence investigated. From the present results of the third case analysis, it was estimated that the containment isolation should be achieved within about 133 minutes to prevent the release of fission products from the environment.

IV. Conclusions

The simulation for the loss of RHR event was performed for Kori Unit 3. The loss of RHR event was assumed to be initiated 48 hours after reactor shutdown. In the transient analysis, the four cases were considered in the combination of RCS venting path and SG status. As a result, the RELAP5/Mod3.2.2beta code appropriately predicted the RCS boil-off in the core region and the system pressurization after the event. In the Case 1, because the heat is enough transferred from RCS to secondary side, it was taken long time to reach the core uncovery and heatup. In all the cases, the core boil-off was reached about 10~12.4 minutes after the event. Also, it was estimated that the core uncovery time is strongly dependent on the RCS configuration and status of SG secondary side. This result indicated that the Case 3 is the worst one among the sequence investigated. In addition, the Case 3 was estimated that the containment isolation should be achieved within about 133 minutes to prevent the release of fission products from the environment.

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Table 1. Initial conditions of a loss of RHR event

Major Parameters	**Plant conditions**
Core power (kWth)	11.461(0.48% of full power)
Hot-leg temperature (°F/°C)	140/60
Cold-leg temperature (°F/°C)	122/50
Primary pressure (Psia)	14.7(Atmospheric)
Water level at loops	Center of Hot-leg
Secondary pressure (Psia)	14.7(Atmospheric)
Secondary fluid temperature (°F/°C)	122/50
Water status in SG	Water filled/Emptied
Non-condensable gas	Air
RHR flow rate (lb/sec)	627 (3 loops x 209/loop)
Venting path	Pressurizer 3/4-inch valve
	Reactor vessel head 1-inch valve
	Pressurizer manway open(PMO) 16 inches
	S/G manway open(SGO) 16 inches

Table 2. RELAP5 analysis cases of Kori unit-3 loss of RHR event

	RCS venting path	**S/G status**
Case 1	Normal venting path(NVP) - Pressurizer 3/4-inch valve - Reactor vessel head 1-inch valve	Water-filled S/Gs
Case 2	Normal venting path - Pressurizer 3/4-inch valve - Reactor vessel head 1-inch valve	Emptied S/Gs
Case 3	NVP with PMO	Emptied S/Gs
Case 4	NVP with SMO	Emptied S/Gs

Table 3. Summary of RELAP5 analysis results for Kori unit-3 loss of RHR event

	Case 1	**Case 2**	**Case 3**	**Case 4**
Boil-off time (s)	761 (12.7min.)	774 (12.9min.)	742 (12.4min.)	633 (10.6min.)
Core uncovery time (s)	56,685 (944.7min.)	15,982 (266.4min.)	2,457 (40.9min.)	5,928 (98.8min.)
Core heatup time (s)	69,540 (1,159min.)	16,836 (280.6min.)	8,017 (133.6min.)	9,528 (158.8min.)

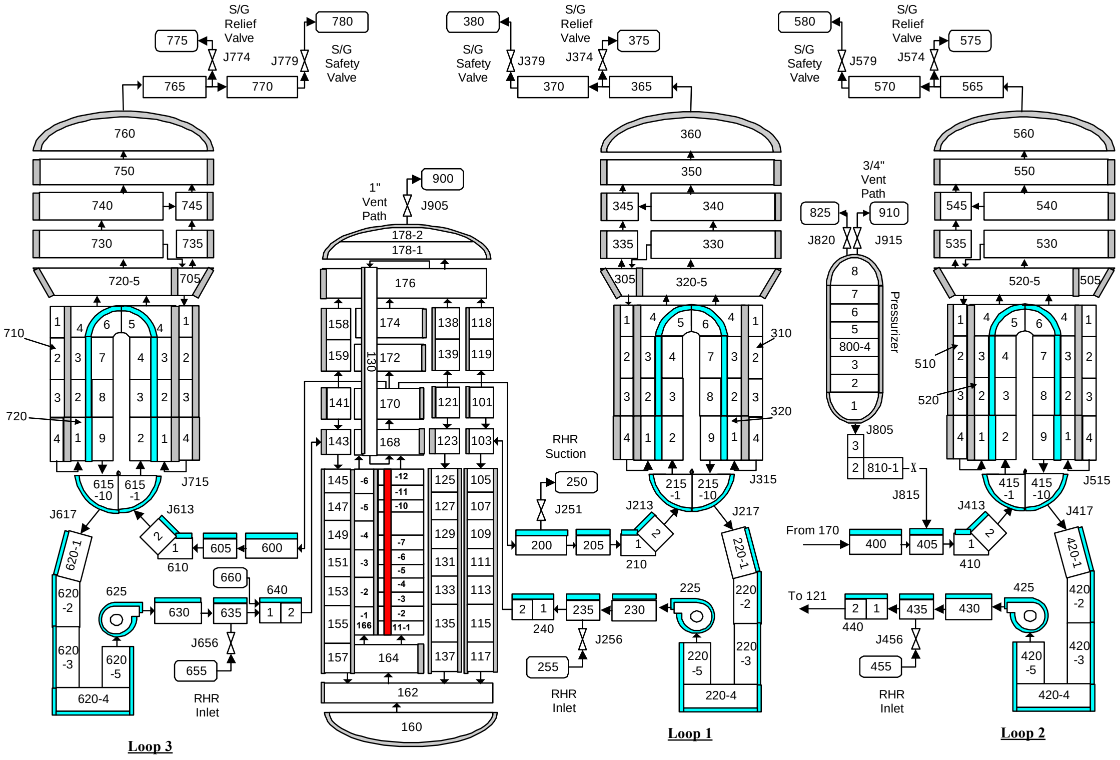
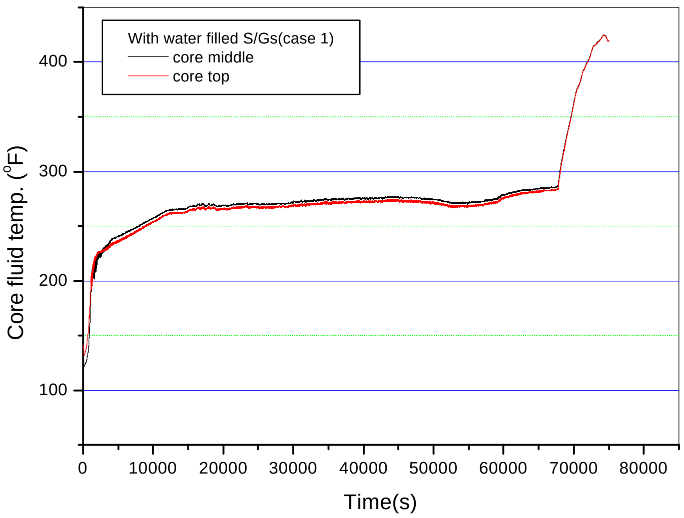
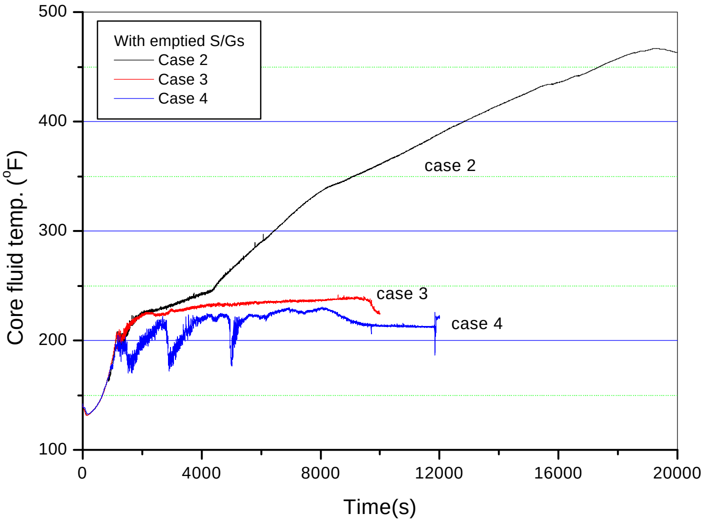


Fig. 1 RELAP5 nodalization for loss of RHR during midloop operation of Kori unit-3

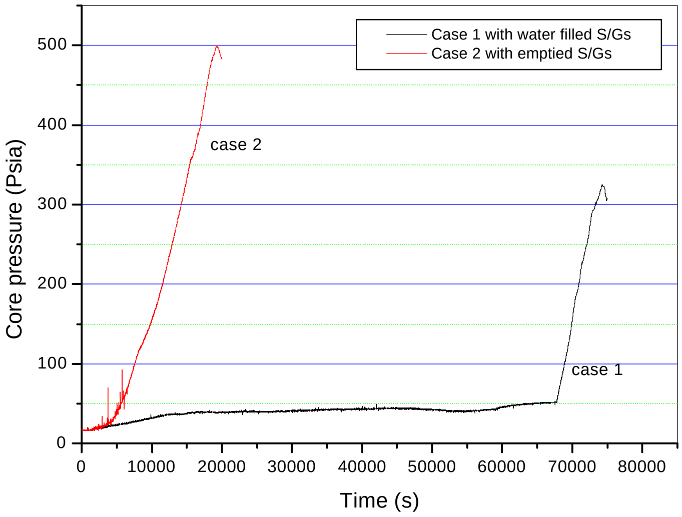


(a) For case 1

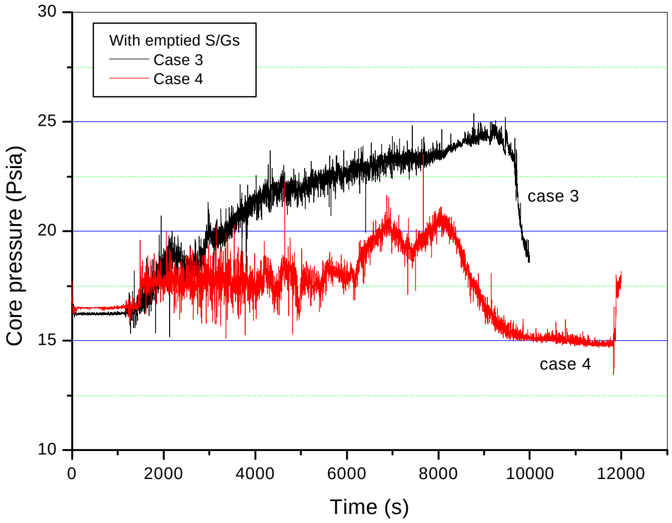


(b) For cases 2, 3 and 4

Fig. 2 Fluid temperature at the core for the four cases

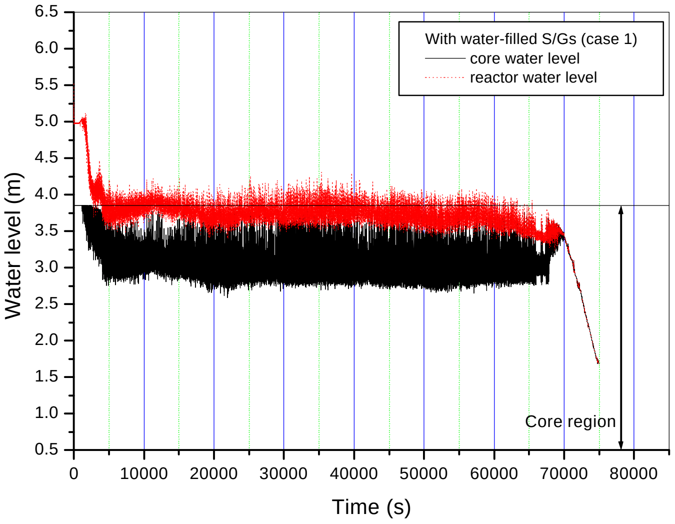


(a) For cases 1 and 2

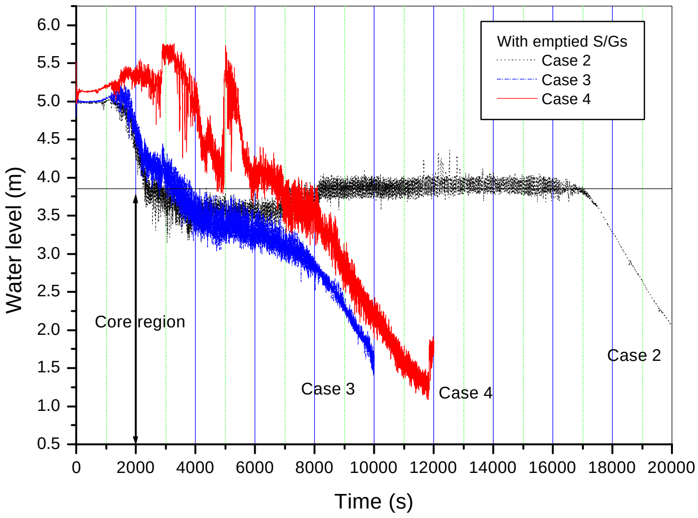


(b) For cases 3 and 4

Fig. 3 The trend of pressure at the core region

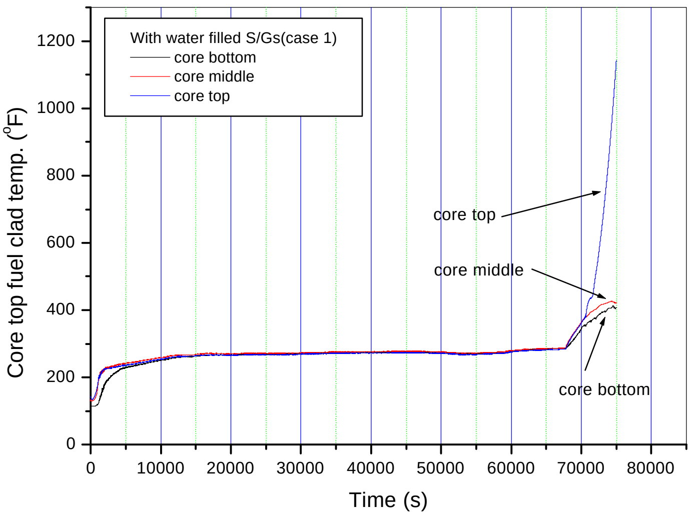


(a) For case 1

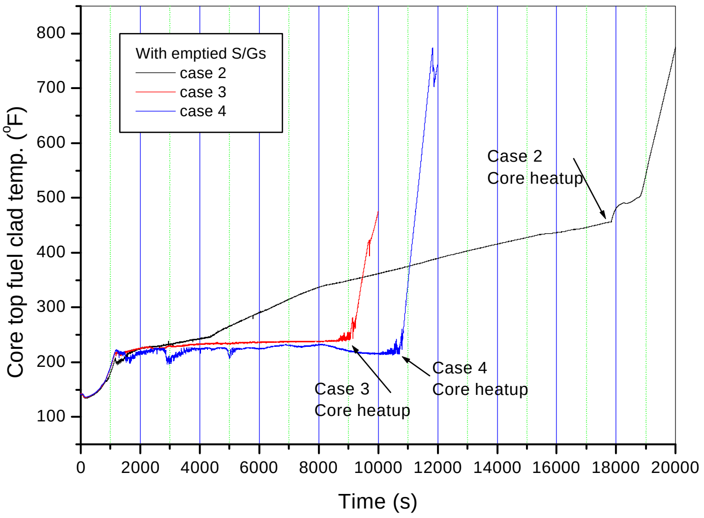


(b) For cases 2, 3 and 4

Fig. 4 Trend of the collapsed liquid level in the core



(a) For case 1



(b) For case 2, 3 and 4

Fig. 5 The behavior of the fuel clad temperatures