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Safety Analysis of Loss of RHR Event During Mid-Loop Operation for Younggwang Units 1&2

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Abstract

The thermal hydraulic analysis of the loss of RHR event during mid-loop operation for Younggwang Units 1&2 nuclear power plant was performed using the RELAP5/MOD3.2.2beta code. The six cases of loss of RHR events that could occur during mid-loop operation were classified according to the opening configurations in the RCS. The time to boiling in the core, the core uncovery time, the maximum pressure in the RCS, the behavior of liquid level in the reactor vessel, and the fuel heatup time were obtained based on the analysis results for event. The boiling time for the events that occurred during mid-loop operation was about 800 seconds. Also, the event with the pressurizer manway opening under installation of nozzle dam during mid-loop operation and the event with the SG inlet plenum manway opening during mid-loop operation showed the earliest core uncovery time and core heat-up time than the other events. According to the results, it was found that the time to boiling in core was dependent on the initial conditions such the amount of reactor coolant in and above core. Also the time to core uncovery and the time core heatup ware strongly dependent on the RCS opening size and location.

I. Introduction

In order to perform certain specific inspection or maintenance of the components in a pressurized water reactor (PWR) after reactor shutdown, such as the steam generator (SG) U-tubes and reactor coolant pump seals, the primary coolant system is drained to the hot leg centerline. During reactor shutdown operation, the residual heat removal (RHR) system is used to remove the core decay heat. This operational mode is usually called mid-loop operation, which is defined as operation when RCS water level is below the top of hot leg. 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 loss of RHR resulting in the core uncovery and severe core damage [1]. Based on probabilistic evaluation on reactor safety, the risk of core damage from accidents during shutdown could be equivalent to the risk from accidents at full power operations [2]. Therefore, in order to enhance safety under the reduced inventory operation, US Nuclear Regulatory Commission (NRC) requested all licensees to respond to generic letter (GL) 88-17 [3]. It is recommendation that with regard to the improvement in the equipment for the mid-loop operation and the comprehensive for systems behavior during loss of RHR as well as under normal shutdown operation.

In a present study, the thermal-hydraulic behaviors after the loss of RHR event were analyzed to perform safety analysis related items of GL 88-17 recommendations and to prepare the normal and abnormal operational guidelines during mid-loop operation. The object of event analysis was the Younggwang Units 1&2 nuclear power plant (YGN 1&2), and detailed thermal hydraulic analysis code was used to the RELAP5/MOD3.2.2Beta code. The analysis cases were selected a number of events which could occur during mid-loop operation at the plant and classified according to the opening configuration in the RCS.

II. Analysis of Loss of RHR Events

II.1 RELAP5/MOD3 Input Model and Initial Conditions

The analysis of the loss of RHR event during mid-loop operation for YGN 1&2 was modeled with the RELAP5/MOD3.2.2beta code [4]. The RELAP5 Input model consists of 265 hydrodynamic volumes, 276 junctions, 311 heat structures as shown in Fig.1. Three loops, which have three hot legs and cold legs including steam generator, were separately modeled. Also, the pressurizer water attached to loop 1. The openings such as the pressurizer manway, SG manways, and cold leg break were modeled using the time dependent volumes and trip valves. Also, the boundary conditions were modeled using the time dependent volumes. The RHR system modeled by time dependent volumes and time dependent junctions was used to simulate steady state conditions before loss of RHR.

In order to model the loss of RHR event accurately, it is necessary to calculate the steady state conditions. Such a steady state condition was obtained using the initial and boundary conditions given in Table 1. The initial RCS water level was the centerline of the hot leg and the water temperature of hot and cold legs were also 330.37K and 304.36K, respectively. Space above the froth levels of the RCS and the SGs was filled with the air. The initial RCS pressure and SG secondary pressure are assumed to be atmospheric. The condition of steam generator secondary side is assumed that the SG of loop 1 and loop 2 are filled with water at 322K and the other SG is filled with air. At this time, the secondary water level is 14.6553 m, which covers the U-tube top elevation (water level > 17% of narrow range). During the loss of RHR event, there is no additional cooling source into steam generators to remove the decay heat.

The core power level chosen in this analysis is 10.1482MWt decay power that corresponds to 0.3657% of full power at 96 hours after reactor shutdown. The RHR coolant inlet temperature is the same as cold leg temperature, 304.36K. Normal RHR flow rate was estimated to be 93.3154kg/s.

II.2 Analysis Cases

Based on the typical plant configuration, the six cases of loss of RHR events that could occur during mid-loop operation are analyzed by using the RELAP5/MOD3.2.2beta code. These analyses are performed to understand major thermal hydraulic phenomena following the loss of RHR event. The events are classified according to the opening configuration in the RCS as shown in Table 2. In the present investigation, base case (Case 1) is the loss of RHR event when the pressurizer manway located at the pressurizer top is open. The pressurizer manway was always open all the cases, because it was found that pressurizer manway must be opened at least during mid-loop to avoid failure of the nozzle dams, in a previous study [5]. That is, the required minimum venting flow area to avoid failure of the nozzle dams was the flow area about 16" inside diameter when pressurizer manway is open. In Case 2, an additional opening at the cold leg top was analyzed to simulate the loss of RHR event occurring during maintenance of a RCP. The flow area of the additional opening was conservatively assumed as 1% of a cold leg cross sectional area. Case 3 and Case 4 assumed the SG manway was open, prior to the installation of nozzle dam. In these cases, the center of SG manway was assumed to be located at the inlet or outlet plenum centerline. Case 5 was selected to investigate the effect of nozzle dams installed at the inlet and outlet nozzles of both SGs. In this case, the pressurizer manway was open, too. In Case 6, the plant condition is the same as the Case 5, except that initial water level is lower than three feet below the reactor vessel flange.

For all the cases, two of three SGs are filled with water and the other SG is filled with air. Also, to maintain the secondary pressure near the atmospheric pressure, the steam relief valves in the main steam lines are opened.

II.3 Transient Calculations

The loss of RHR event is initiated at that time by isolating the RHR flow, and these steady state conditions immediately after the loss of RHR transient are obtained from new transient run up to 1,000 seconds. During the transient, the maximum time step of 0.l second was used in all transient calculation to minimize cumulative mass error. This transient calculation is terminated at the simulation time for about 15,000 seconds, because it is the sufficient time to observe important phenomena such as core uncovery and core damage after loss of RHR event.

Based on the analysis results of each case, major thermal hydraulic phenomena, for instance the boiling time, core uncovery time, the behavior of the system pressure, the change of liquid level in the pressurizer, the discharged mass through the RCS openings, and the fuel heatup time were compared. In this study, the time to boiling in the core was defined by when the void fraction if the highest core volume increased abruptly and the core uncovery time was defined by when the lowest upper plenum volume was completely voided [6].

III. Results and Discussions

Based on the RELAP5/MOD3 code, the YGN1&2 plant responses to the loss of RHR event during mid-loop operation were evaluated. The typical results were summarized for the six cases as shown in Table 3. Figures corresponding to major plant behavior after loss of RHR event were plotted in Fig.2 to Fig.8.

Figure 2 shows the liquid temperature and the saturation temperature at the core top after loss of RHR event. The fluid temperature smoothly increased for all Cases until it nearly reached saturation temperature. The core was be boiled off from that time. That is, the time to boiling in the core for Case 1 ~ Case 4 was about 800sec and for Case 5 was 750sec. Also, for event during the reduced inventory operation (Case 6), the core boiling occurred at about 1000 seconds.

Figure 3 shows the pressure of upper plenum after loss of RHR event. The pressure behavior shows the considerably different trends as the venting path. For the loss of RHR event when the pressurizer manway was open (Case 1, Case 5 and Case 6), after the boiling, the upper plenum pressure increased continuously. During the event, eventually the pressure for Case 1, Case 5 and Case 6 reached to 0.1781MPa, 0.1671MPa and 0.1967MPa, respectively. Also, the time that reached to maximum pressure was 8400sec, 4110sec and 4220sec, respectively. For Case 1, the time that reached to maximum pressure delayed because a part of decay heat removed through the SG U-tubes. After the maximum pressure reached, the pressure decreased because a large amount of decay heat was used for the fuel cladding heatup, reducing the steam generation. It indicates that the RCS maximum pressure and time that reached to maximum pressure differ as the RCS inventory and capability to remove the decay heat through SGs. For the loss of RHR event when the additional opening was open (Case 2, Case 3 and Case 4), the pressure was not increase largely as comparison with events when the pressurizer manway was open. Since the additional opening was located at lower elevation than the pressurizer manway, the additional opening was more important on the system behavior. After the boiling, the pressure increased slightly eventually the pressures for Case 2, Case 3 and Case 4 reached to 0.146MPa, 0.1113MPa and 0.1396MPa, respectively. The pressure decreased to the atmospheric pressure after flow paths were formed.

Figure 4 shows the behavior of pressurizer collapsed liquid level after loss of RHR event. From the figure, it was found that the liquid level in the pressurizer increased as the RCS pressure increased. For the loss of RHR events when the pressurizer manway was open (Case 1, Case 5 and Case 6), water in the hot leg entrained into the pressurizer and began to accumulate in the early phase. The maximum liquid level for three cases was 7.64m, 6.05m and 9.83m, respectively. For Case 6, a lot of liquid accumulated at the pressurizer due to having a large of quantity of water in the system, as comparison with events during the mid-loop operation. Also, the time that reached to the maximum liquid level for Case 1 delayed because the steam was condensed on the SG U-tube wall, as compared to the Case 5 and Case 6. After the maximum level reached, liquid level dropped due to decrease of RCS pressure. Thereafter, the liquid level of the pressurizer was maintained at quasi-steady level until the event was terminated. For the loss of RHR event when the additional opening was open (Case 2, Case 3 and Case 4), the behavior of pressurizer collapsed liquid level was similar to the RCS pressure as shown in Fig.3. For Case 2, the liquid level increased as the RCS pressure increased and it maintained at about 3.8 m until the event is terminated. For Case 3, the water was not accumulate in the pressurizer, so a large of water and steam was discharged through the SG inlet plenum manway opening as shown in the Fig.5-b. For Case 4, liquid collapsed level fluctuated according to the formation and destruction of liquid column at the U-tubes. After RCS pressure decreased to the atmospheric pressure in Fig.3, the water disappeared in the pressurizer.

Figure 5 indicates the integrated mass discharged through the pressurizer manway and the other opening after the loss of RHR events. Such the continuous discharge through the venting path caused the RCS inventory decreased as shown in the Fig.6. For the loss of RHR events when the pressurizer manway was open (Case 1, Case 5 and Case 6) in the Fig.5-a, a great quantity of water was accumulated in the pressurizer and these water and steam was discharged through the pressurizer manway. In Fig.5-a, for Case 3 and Case 4, the flow rate through the SG inlet/outlet plenum manway was larger than that through the pressurizer manway because the SG plenum manway was open at lower location and lower flow resistance from the core. For Case 3, Case 5 and Case 6, the Fig.6 shows that the reactor vessel collapsed water level rapidly decreased below the core top region in the early phase after the loss of RHR event. Especially, Case 3 showed a faster decreasing rate than the other two cases. It was that because a great quantity of water and steam was discharged through the RCS openings as shown in Fig.5-b. Also, the collapsed level for Case 4 was higher than the other cases, although water and steam were discharged too much through the SG outlet manway. Because a lot of steam was condensed on the SG U-tube, liquid level of reactor vessel was not reduced rapidly.

Figure 7 shows the behavior of the liquid fraction at the lowest upper plenum. From the figure, the earliest time to core uncovery was 6380s for the event that the SG inlet plenum manway was open (Case 3). Also, the last time to core uncovery was 12170s for the event that the SG outlet plenum manway was open (Case 4) as summarized in Table 3.

Figure 8 shows the behavior of the fuel cladding temperatures. The figure shows that the core heatup was initiated at about 11590s for Case 1, about 8320s for Case 5 and about 8600s for Case 6. For Case 2, Case 3 and Case 4, core heatup time was 11710s, 7710s and 13740s, respectively.

IV. Conclusions

The analysis of a loss of RHR event during mid-loop operation was performed for YGN units 1&2 under various plant conditions. To investigate the plant thermal hydraulic behavior following the event, the RELAP5/MOD3.2.2beta code was used. Also, the loss of RHR event initiated to occur at 96 hours after reactor shutdown.

In the transient analysis, the six cases for the loss of RHR event with different plant configurations were evaluated. The five cases for the loss of RHR event during mid-loop operation are the event with the pressurizer manway opening, the cold leg opening, the SG inlet plenum manway opening, the SG outlet plenum manway opening, the pressurizer manway opening under installation of nozzle dam. The other case of the loss of RHR event is the pressurizer manway opening under installation of nozzle dam during reduced inventory operation. For all the cases, in order to ensure minimum venting flow area to avoid failure of the nozzle dams, pressurizer manway was always open during the event. The results that were obtained from this analysis are summarized as follows.

(1) The earliest core boiling time was 750sec, as the event with the pressurizer manway opening under installation of nozzle dams during mid-loop operation.

(2) The earliest core uncovery time was 6380sec, as the event with the SG inlet plenum manway opening during mid-loop operation.

(3) The latest core uncovery time was 12170sec, as the event with the SG outlet plenum manway opening during mid-loop operation

(4) For the nozzle dam was not installed, a part of decay heat removed through the SGs.

As a result, it was found that the time to boiling in core was dependent on the initial condition such the amount of reactor coolant in and above core, also the time to core uncovery and the time core heatup ware strongly dependent on the RCS opening size and location.

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Table 1. Initial conditions of YGN units1&2 loss of RHR event

Parameter	Value
PZR manway diameter	0.4064 m
PORV diameter	0.05842 m
PSV line diameter	0.1318 m
RV upper head air vent diameter	0.0207 m
PZR top air vent diameter	0.0110236 m
SG manway diameter	0.4064 m
Cold leg break area	1% of cold leg area
Decay heat	10.1482 MWt (0.3657% of the nominal core power, 2775 MWt)
RCS pressure	0.101325 MPa
RCS hot leg temperature	330.37 K (= 135 ^{o}F)
RCS cold leg temperature	304.36 K (= 88.2 ^{o}F)
RCS liquid level	Centerline of the hot leg, Or 0.9m below reactor vessel flange
Secondary pressure	0.101325 MPa
Secondary temperature	322.04 K (= 120 ^{o}F)
Containment pressure	0.101325 MPa
RHR pump flow rate	93.3154 kg/s
RWST temperature	322.04 K (= 120 ^{o}F)
Nozzle dam design pressure	0.258525 MPa (22.8 psig)

Table 2. RELAP5 analysis cases of YGN units 1&2 loss of RHR event

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
PZR Manway	Open	Open	Open	Open	Open	Open
Cold leg break	Close	Open	Close	Close	Close	Close
SG inlet plenum manway	Close	Close	Open	Close	Close	Close
SG outlet plenum manway	Close	Close	Close	Open	Close	Close
Nozzle dams	No	No	No	No	Installed	Installed
Number of active SGs	2	2	2	2	0	0

Table 3. RELAP5 analysis result summary of YGN units 1&2 loss of RHR event

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Boiling Time (sec)	830	820	800	800	750	970
Maximum RCS Pressure (MPa)	0.1781	0.1460	0.1113	0.1396	0.1671	0.1967
Maximum PZR Liquid Level (m)	7.64	3.87	0.55	3.06	6.05	9.83
Core Uncovery Time (sec)	10270	10350	6380	12170	6790	7200
Core Heatup Time (sec)	11590	11710	7710	13740	8320	8600

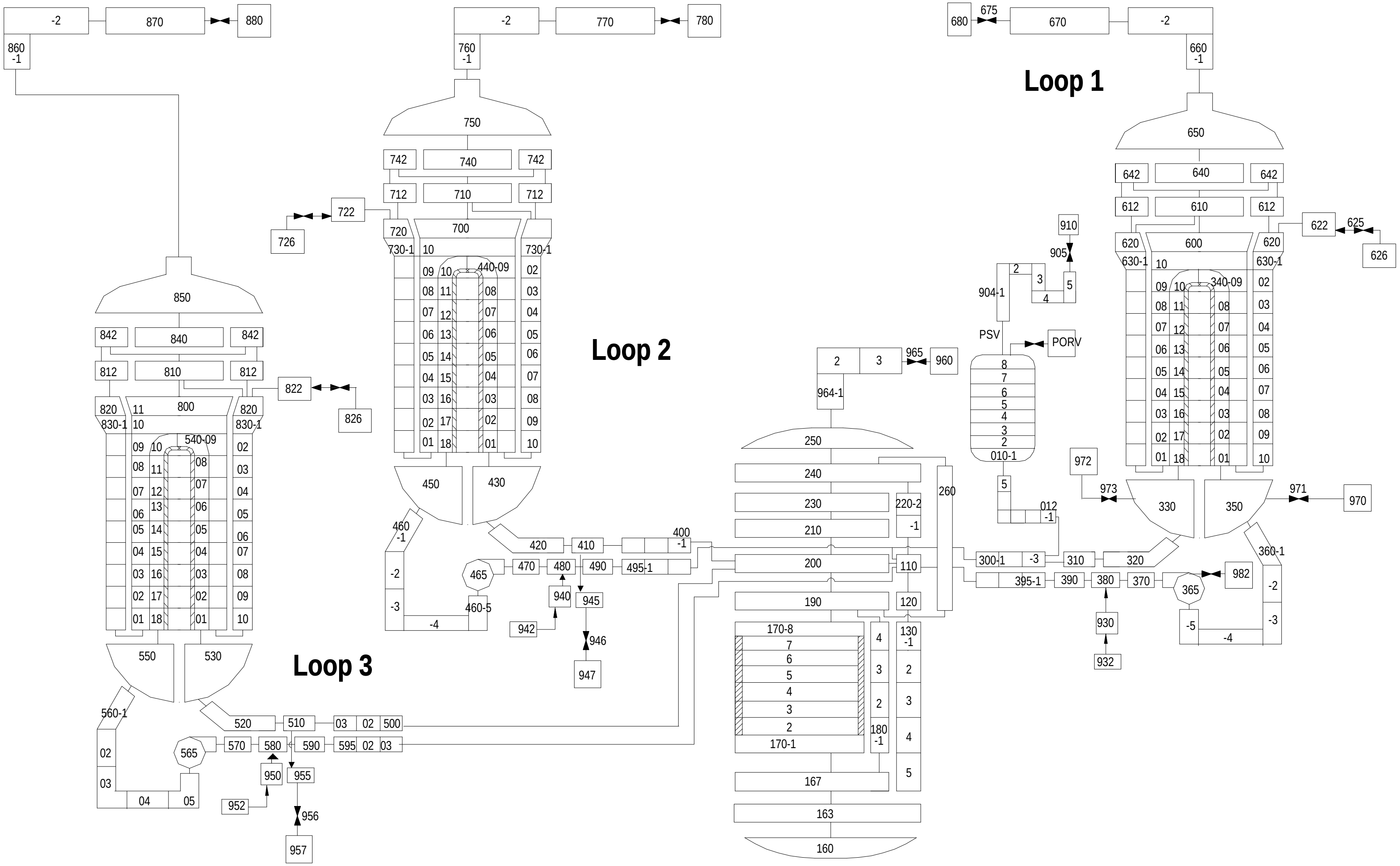

Fig.1 RELAP5/MOD3 nodalization for YGN 1&2 mid-loop operation

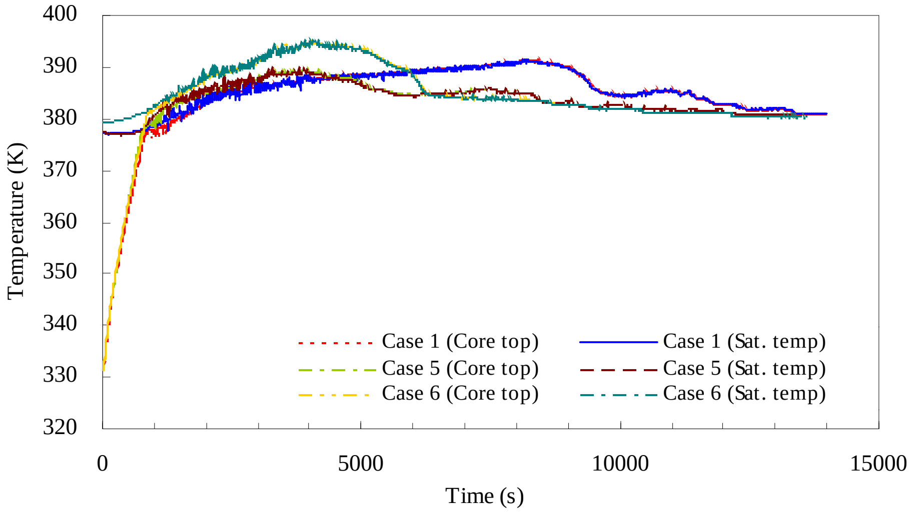

Fig. 2-a Liquid temperature at core top

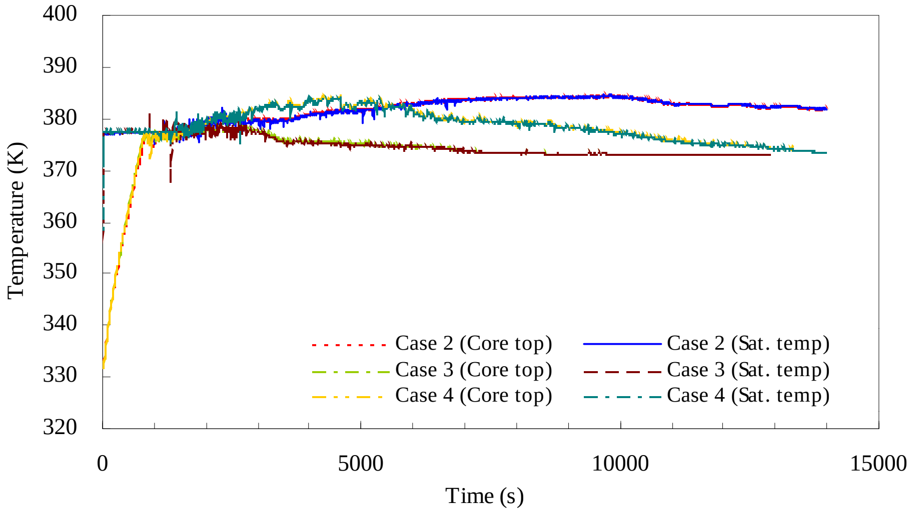

Fig. 2-b Liquid temperature at core top

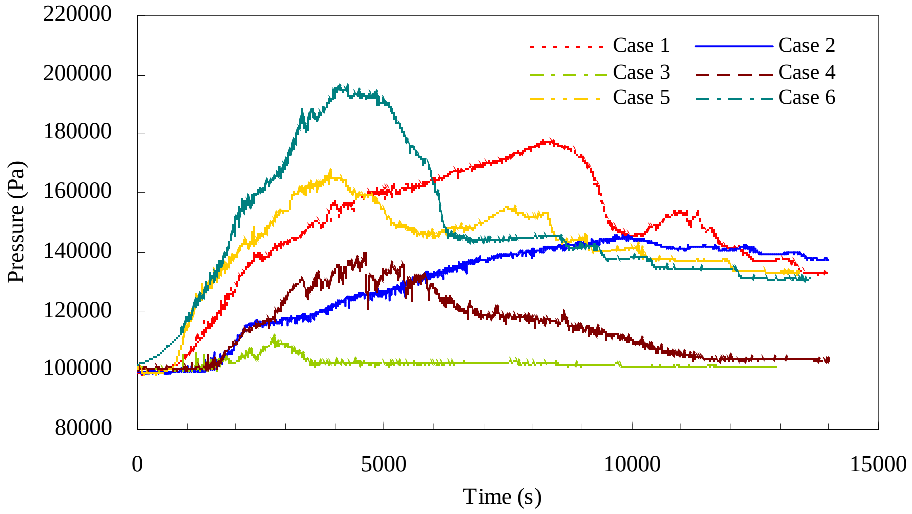

Fig. 3 Pressure at upper plenum

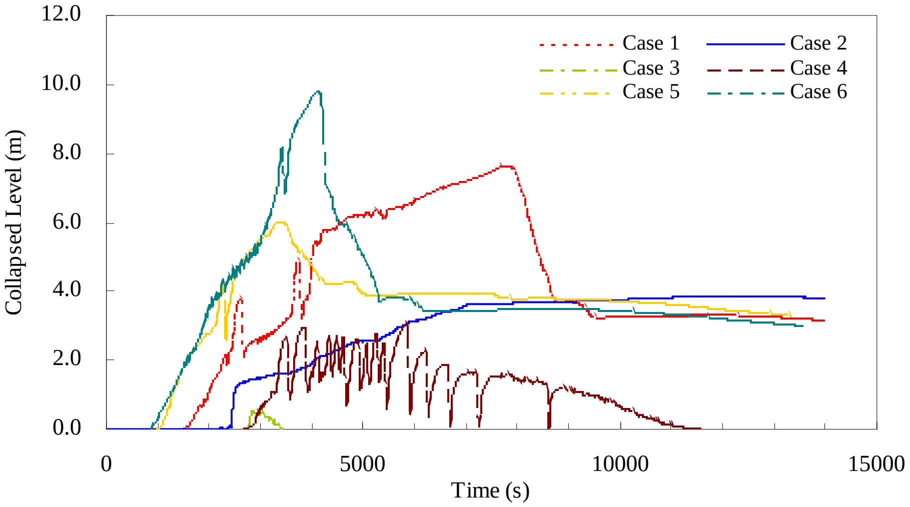

Fig. 4 Collapsed liquid level of PZR

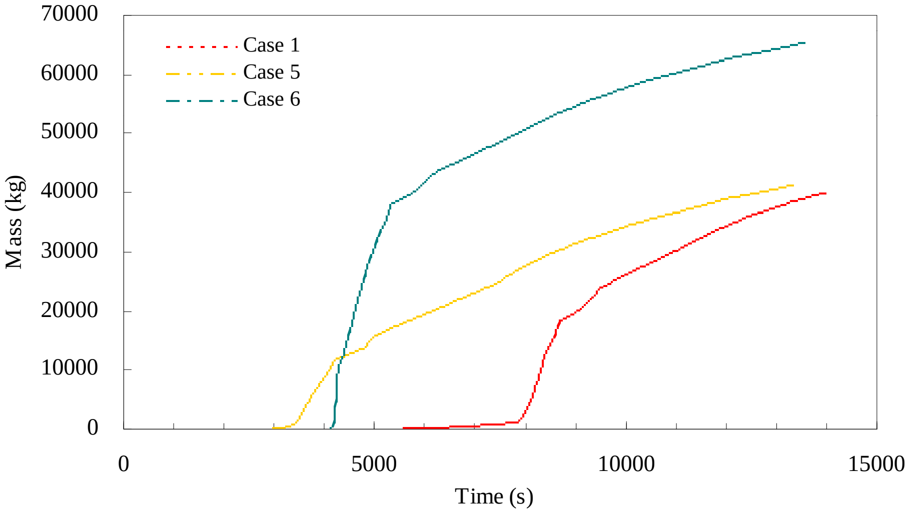

Fig. 5-a Integrated mass discharged through the PZR manway

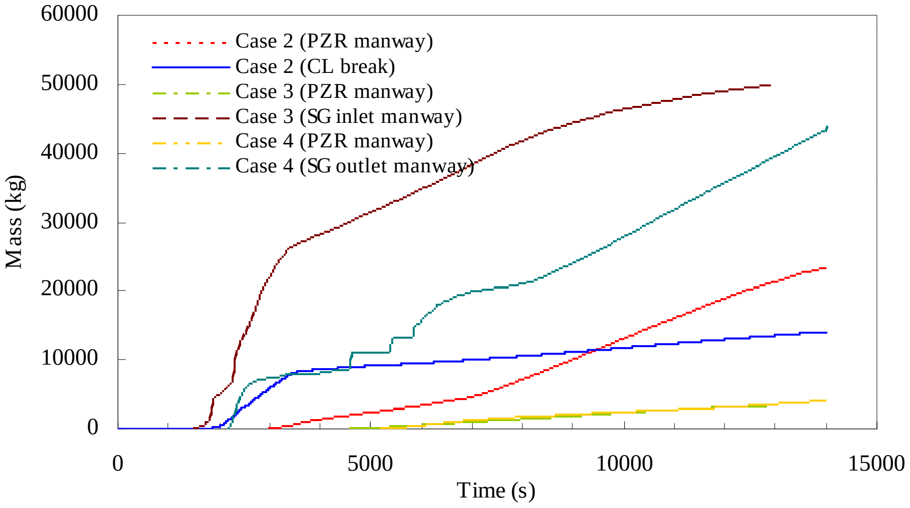

Fig. 5-b Integrated mass discharged through the opening

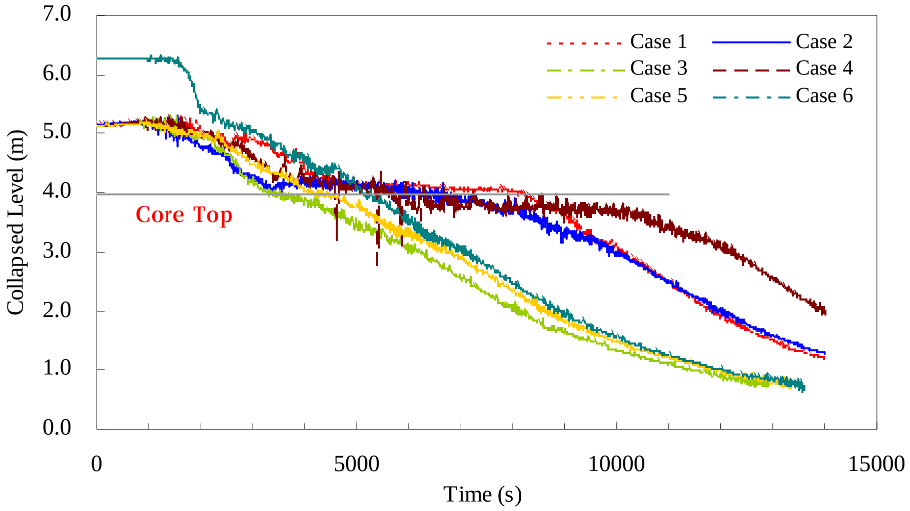

Fig. 6 Collapsed liquid level of reactor vessel

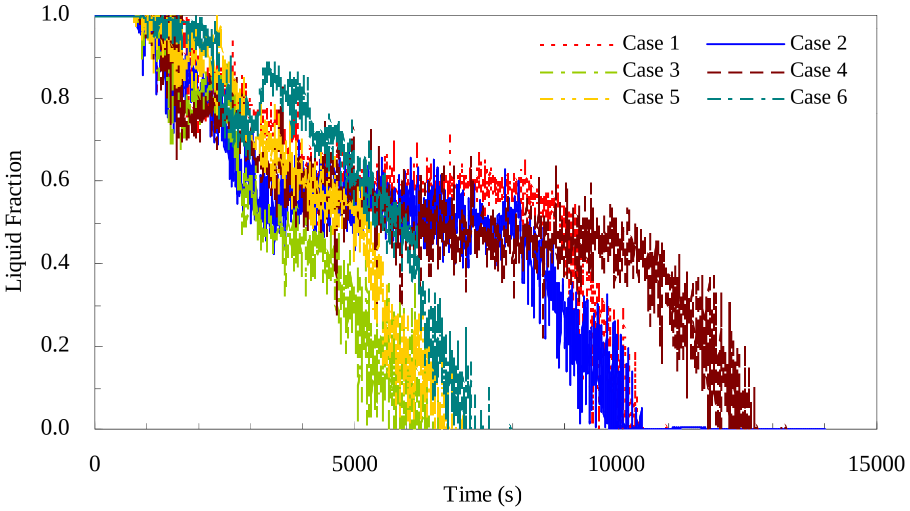

Fig.7 Liquid fraction at the upper plenum

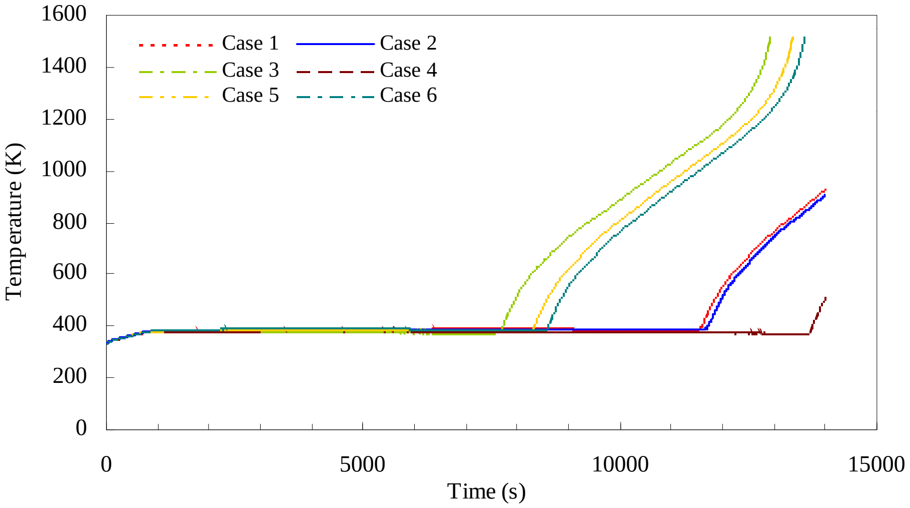

Fig.8 Fuel cladding temperature