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Application of RELAP5/MOD3.2 to the Loss-of-Residual-Heat-Removal Event Under Shutdown Condition

Prepared by

K.W. Seul, Y.S. Bang, H.J. Kim, KINS

Korea Institute of Nuclear Safety
P.O. Box 114
Yusung, Taejon
305–600, Korea

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Abstract

The long-term transient following a loss-of-residual-heat-removal (loss-of-RHR) event during reactor shutdown was analyzed to determine the containment closure time (CCT) to prevent the release of fission products to environment and the gravity-injection path and rate (GIPR) to effectively cool the core. The thermal-hydraulic analysis was carried out using the RELAP5/MOD3.2 code and relevant modeling scheme, which were assessed with the LSTF experiment in a previous study (NUREG/IA-0143). Based on the plant-specific geometry data including various operating conditions, the possible event sequences were identified for the Yonggwang Units 3&4 plant (YGN 3/4), which is CE-typed PWR of 2,815 MW thermal power in Korea. As a result, the real plant simulation gives the similar calculation characteristics to the previous LSTF simulation, and then it was found that the RELAP5/MOD3.2 code is capable of appropriately simulating the loss-of-RHR event of the real plant.

From the five cases of the CCT analyses, it was estimated that the containment closure should be achieved within about 40 minutes to prevent the release of fission products in the large cold-leg opening case under the worst event sequence. However, it was also found that the first core uncovery could occur in the early phase of the event by the loop seal clearing phenomenon in the crossover leg. From the six cases of the GIPR analyses, it was revealed that the system was well depressurized and the core boiling was successfully prevented by the gravity-injection in cases with the injection point and opening on the different leg side. However, it was also found that the gravity-injection process could be ineffective in the case of relatively high pressurizer-manway opening because of the water holdup phenomena in the pressurizer. Also, it was estimated that about 54 kg/s of minimum injection rate was required to maintain core cooling and the core cooling could be provided for about 10.6 hours with the nominal water capacity of refueling water storage tank (RWST).

These results will provide useful information to operators to cope with the event. And, to apply them to the emergency and recovery procedures against the event, additional case studies will be needed for wide range of operating conditions such as reactor coolant system inventory, RWST water temperature, and core decay heat rate.

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Executive Summary

To investigate the mitigation measures following a loss-of-RHR event during reactor shutdown, the plant operating conditions of the Yonggwang Units 3 and 4 (YGN 3/4), PWR type of 2,815 MW thermal power in Korea, were reviewed. The possible event sequences were identified and the long-term transient analyses were performed using RELAP5/MOD3.2 code. This analysis is finally to determine the containment closure time (CCT) to prevent the release of fission products to environment and the gravity-injection path and rate (GIPR) to effectively cool the core after event. To do this, based on the combination of the RCS opening and the SG secondary water level condition, the five cases of typical RCS configurations were identified for the CCT analysis as follows:

Case 1. a pressurizer-manway-opening (PMO) case with water-filled SG
Case 2. a pressurizer-manway-opening (PMO) case with emptied SG
Case 3. a SG-inlet-plenum-manway-opening (SMO) case with emptied SG
Case 4. a small cold-leg-opening (CLO) case with emptied SG
Case 5. a large cold-leg-opening (CLO) case with emptied SG

Also, based on two available gravity-injection lines from the cold water of refuel water storage tank (RWST) and three of large RCS openings as a RCS drain path, the six cases of the injection paths were identified for the GIPR analysis as follows:

Case A. a hot-leg injection and a PMO discharge
Case B. a hot-leg injection and a SMO discharge
Case C. a hot-leg injection and a small CLO discharge
Case D. a cold-leg injection and a PMO discharge
Case E. a cold-leg injection and a SMO discharge
Case F. a cold-leg injection and a large CLO discharge

The applicability of the code to the loss-of-RHR event under shutdown conditions was assessed in a previous study (NUREG/IA-0143), which was based on the comparison of the calculation with the experiment simulating the event during mid-loop operation in the Large Scale Test Facility (LSTF). The same code and consistent modeling scheme were used in this calculation. The major findings from the long-term transient analysis of the loss-of-RHR event for the real nuclear power plant were as follows:

(1) The real plant simulation of the YGN 3/4 plant gives the similar calculation characteristics to the LSTF simulation in the required CPU time, computational time step, and system mass error. Thus, it was found that the RELAP5/MOD3.2 code was capable of appropriately simulating the loss-of-RHR event of the real plant.

(2) From the CCT analysis for the five cases of typical RCS configurations with no RCS makeup and unavailable secondary cooling, the time to boil after event was estimated to be about 10 to 13 minutes regardless of the opening size and location. Also, the time to core uncovery was estimated to be about 40 to 183 minutes depending on the elevation and size of the opening and the SG secondary water level condition. Particularly, in case with the water-filled SG, it was delayed about 100 minutes by the reflux condensation on SG U-tubes, as compared to the emptied SG case. However, it indicated that the first core uncovery could occur in the early phase of the event by the loop seal clearing phenomenon in the crossover leg for the cold-leg opening case. As a result, it was found that the earliest CCT was 40 minutes after event for the SG-inlet-plenum-manway opening or the large cold-leg opening cases. Beside, the containment closure is needed to initiate before the boiling time because the discharge via the opening after boiling could threaten the workers in the containment.

(3) From the GIPR analysis for the six possible gravity-injection paths from the RWST, the following conclusions were obtained. In cases with the PMO, where was located at higher elevation than the RWST water level, the system pressure continued increasing due to the water holdup phenomenon in the pressurizer and then the core was uncovered at about 96.6 minutes despite of the gravity-injection process. In cases with the injection point and opening on the same leg side, the core cooling was dependent on the core flow. Particularly, in the cases with the injection point and opening on the different leg side, the RCS was well depressurized and the core boiling was successfully prevented for a long-term transient. As a result, those injection paths were estimated to be the most suitable paths in avoiding core boiling for a long-term period. In addition, about 54 kg/s of minimum injection rate was required to maintain core cooling. Such an injection rate was capable of providing the core cooling for about 10.6 hours if 70% of the RWST water was available.

(4) These results will provide useful information to operators to understand the plant behavior and to cope with the event in timely manners. And, to apply them to the emergency and recovery procedures against the loss-of-RHR event, additional case studies will be needed in the future for wide range of operating conditions such as RCS inventory, RWST water temperature, and core decay heat rate.

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Nomenclature

CCFL	Counter Current Flow Limitation
CCT	Containment Closure Time
CLO	Cold-leg Opening
ECCS	Emergency Core Cooling System
GIPR	Gravity-Injection Path and Rate
LSC	Loop Seal Clearing
LSTF	Large Scale Test Facility
NOO	Non-Opening
NPP	Nuclear Power Plant
PMO	Pressurizer Manway Opening
PWR	Pressurized Water Reactor
Pzr	Pressurizer
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System
RPV	Reactor Pressure Vessel
RWST	Refueling Water Storage Tank
SG	Steam Generator
SMO	SG-inlet-plenum Manway Opening
YGN 3/4	Yonggwang Units 3 and 4 Plants

I. INTRODUCTION

The residual heat removal (RHR) system is used to remove a core decay heat under shutdown condition or refueling stage in pressurized water reactor (PWR). It is operated, in some occasions, with the reactor inventory reduced to a mid-water level of the primary loop, which is called mid-loop operation, for a maintenance or inspection of components such as steam generator U-tubes and reactor coolant pumps during a plant outage. Recently, the loss-of-RHR event during the mid-loop operation was of great concern, since there have occurred many events associated with it and the potential for the significant risk has been identified.

During shutdown operation or refueling, three initiators are considered as major causes of the loss-of-RHR event: a loss of reactor coolant system (RCS) inventory, a loss of RHR flow, and a loss of support systems. The loss of RCS inventory could be caused by overdrain while going to reduce the RCS inventory or by failure to maintain a water level during reduced inventory such as mid-loop operation. It would eventually lead to a loss of RHR flow due to the reduction in RHR pump suction head. A loss of offsite power or a failure of RHR heat exchanger or pump would also cause a failure of the RHR system. Recently, the loss-of-RHR events have been experienced several times in PWR plant [1, 2]. The causes of the events were found mainly to be a failure of RHR pump or a loss of vital ac power [3]. Although the plant was recovered within a proper time after event, the continued recurrence of the events raised the issues on the reliability of the RHR system and the importance of the plant recovery measures.

In order to cope with the event in a timely manner, abnormal operating procedure should be prepared based on the plant responses to the event. Generally, it includes two types of actions to mitigate the event. One is to protect the personnel working in the containment and to prevent an uncontrolled release of fission products to atmosphere, which includes an evacuation of nonessential personnel from the containment and a closure of the containment openings. After the loss of the RHR function, the coolant heat-up would lead to core boil-off and core damage. In particular, for the case that the RCS is open, the RCS coolant could be discharged into containment and threaten the personnel working in the containment. In addition, if there is containment opening, such as personnel or equipment hatches, an uncontrolled release of fission products to environment would be possible in the early phase of the event. Thus, the timing to take actions for the containment closure is important in mitigating the event and it should be determined from the detailed transient analysis under various plant conditions and operating states.

The other is to restore the removal capability of the core decay heat, which includes a recovery of the RHR system and/or an alignment of the water-feed line for an alternate core cooling. Naff, et al. [4] investigated the important thermal-hydraulic processes following the event during reduced inventory operation and discussed the recovery measures. Particularly, they analyzed two types of alternate cooling methods for the decay heat removal in the absence of the RHR system. One is a reflux condensation cooling in a closed RCS using steam generators (SG) as a heat sink and the other is a gravity-injection cooling using water of the refueling water storage tank (RWST). They concluded that the condensation cooling was a viable strategy to maintain core cooling after event, however the integrity of temporary RCS closures such as nozzle dams could be threatened due to the high system pressure. Meanwhile, they reported that the gravity-injection cooling could be an effective measure to maintain core cooling under the open RCS conditions. In practice, the RCS has various openings for maintenance during plant outages. Also, the gravity-injection processes are very different from plant to plant. Thus, an appropriate injection path and rate to mitigate the event should be determined from the detailed transient analysis based on the plant-specific conditions and configurations.

Parrish and Till [5] analyzed the loss-of-RHR event for the Palo Verde Nuclear Generation Station to investigate the plant recovery measures. They used the RETRAN code and a very simple nodalization to simulate the event, and also used a hand calculation to reduce the computational time. The results of the simulation indicated that the power station could undergo the event without experiencing a rapid core uncovery due to water ejection through opening. However, due to the simple models and conservative assumptions, they could not simulate some dominant thermal-hydraulic phenomena, such as a loop seal clearing in the crossover leg, a liquid holdup in the pressurizer, and non-condensable gas effect. Also, the long-term behavior up to the core heat-up could not be simulated due to the calculation limitation. Hassan and Raja [6] also performed the transient analysis of typical four-loop PWR using the RELAP5/MOD3 code for two cases, non-opening and pressurizer-vent opening cases. They reported that the fuel cladding temperature was below the accepted safety limits throughout one hour of transient. However, depending on the plant configurations such as the size and location of the RCS opening and secondary water condition, the core could be damaged even in the early phase of transient. In addition, the core cooling capability will be significantly dependent on the RCS water makeup process.

The present report describes two long-term transient analyses after the loss-of-RHR event for the various real plant configurations, the containment closure time (CCT) analysis and the gravity-injection path and rate (GIPR) analysis. The CCT analysis is to determine the containment closure time to prevent an uncontrolled release of fission products to atmosphere under the situation that the recovery of the decay heat removal is delayed for a long-term period. The GIPR analysis is to determine the gravity-injection path for an effective core cooling and the injection rate needed to prevent core boiling under the situation that the RCS makeup is available in a proper time. In general, the plant responses to the event are strongly dependent on the operating states and the plant configurations. Thus, the real plant conditions of the Yonggwang Units 3 and 4 (YGN 3/4) are reviewed to identify the possible event sequences. The plant is CE-typed PWR plant of 2,815 MW thermal power begun commercial operation in 1995 in Korea. Particularly, the location of RCS openings and the water-injection paths are investigated. The transient analyses for the identified event sequences are carried out using the best-estimate system transient analysis code, the standard version of RELAP5/MOD3.2, with detailed simulation of the real plant. Based on the calculation results, the applicability of the code to the event of the real plant is also discussed.

II. DESCRIPTIONS OF PLANT CONFIGURATIONS

II.A. Possible Event Sequences

When the loss-of-RHR occurs as an initiating event during shutdown operation, various scenarios following the event are possible according to the operating states and plant geometry conditions. Particularly, during the plant outages, the RCS could be in different operating states from the full power operation, and the major safety systems could be in an inoperable state. Thus, the possible and prominent event sequences could be identified depending on the mitigation measures against the event [7]. Based on these event scenarios, nine possible event sequences could be derived in the YGN 3/4 plant as shown in Fig. 1.

If the RHR function is recovered quickly after the event, the core decay heat would be successfully removed, and the plant would reach a safe condition (sequence 1). But, if the recovery of the RHR system is delayed for a long time, the plant behavior is generally divided into two main paths, one with an open RCS and the other with a closed RCS. If the RCS is open, the secondary cooling cannot be provided, but a bleed path can be established. Thus, if the RCS inventory makeup is available for a long term, the core decay heat would be successfully removed (sequence 4) and, if not available, the core would be damaged (sequence 2). Also, if the long-term recirculation in the RCS is not available even with inventory makeup, the core could be challenged (sequence 3). In the case of the closed RCS, if the secondary cooling with available SGs (sequence 5) or the RCS inventory makeup and long-term recirculation (sequence 9) is available, then the core decay heat would be also removed. However, with the secondary cooling not available due to an installation of nozzle dams or a maintenance of auxiliary feedwater system, if either the water feeding into the RCS or the steam bleeding outside the RCS is inoperable, the core would be uncovered and damaged (sequences 6, 7, and 8). As a result, Fig. 1 shows that the core could be damaged for the five event sequences out of nine.

In general, the closed RCS provides an additional barrier of fission products and a longer time for the personnel to work in the containment after event. If the RCS is open, the fission products would be released into the containment through the opening and then jeopardize the personnel working in the containment. In addition, if the containment is open, the radiological materials would be released to atmosphere. Therefore, the event with the RCS openings may result in serious consequences. In the present study, the sequence 2 is selected as the worst event sequence for the CCT analysis because the core damage and the containment challenge are expected to take place in the earlier phase of the transient. There is no RCS inventory makeup and SG secondary cooling by natural circulation throughout the transient. Also, the sequences 3 and 4 are selected for the GIPR analysis to evaluate the core cooling capability after event. In these cases, the RCS inventory makeup can be provided with two types of water-feeding means, i.e., pump and gravity feeding from the water sources such as the RWST. In general, the forced-injection process using the active pump requires the off-site power supply, and if it is possible, it is expected to sufficiently make up the coolant inventory and maintain the core cooling after the event. Thus, the gravity-injection process, which possible without an off-site power, is evaluated in this study as an alternate core cooling measures.

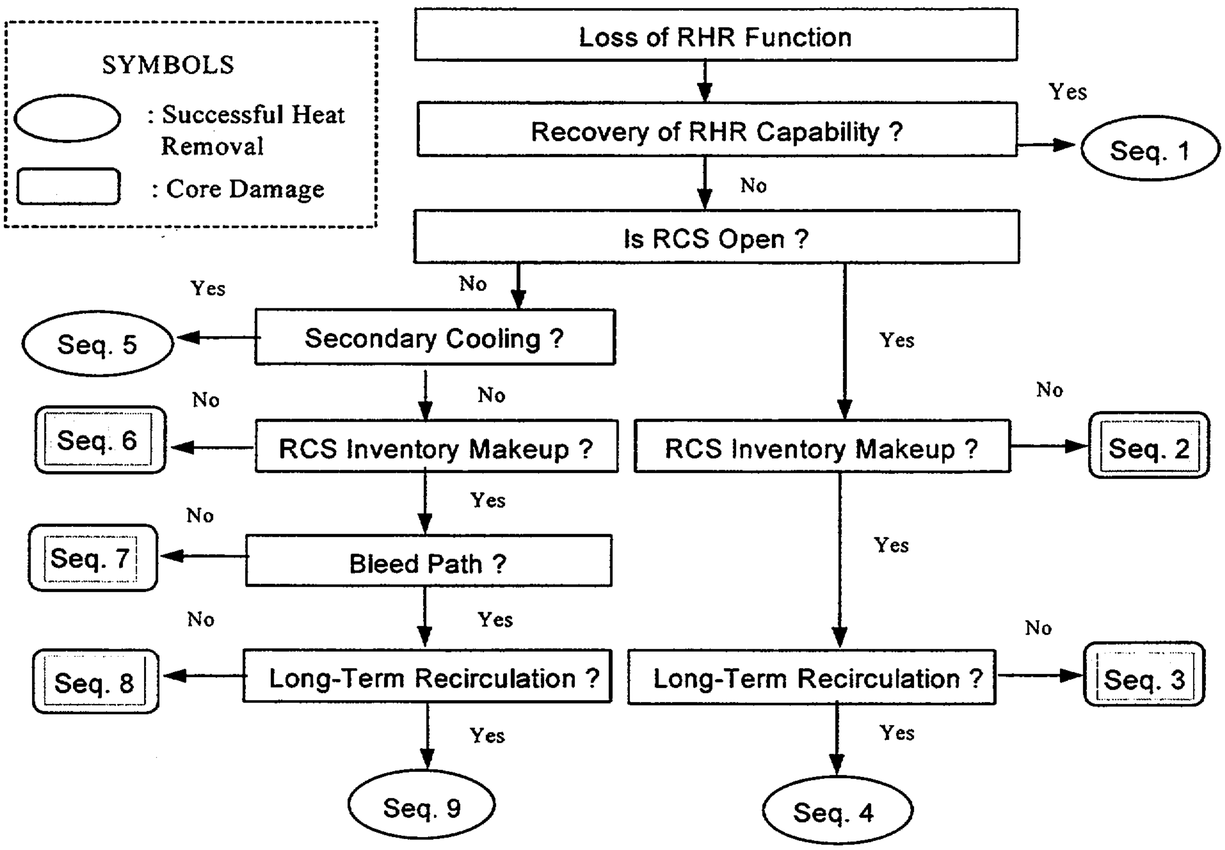

Fig. 1. Possible event sequences following a loss-of-RHR event

II.B. Plant Configurations

During plant outages, the RCS has various openings. For instance, a pressurizer manway is open for the RCS coolant drain, SG manways are open for the SG U-tube inspections after installing nozzle dams, and a reactor coolant pump (RCP) seal or impeller assembly can be removed for a repair. Also, the drain or vent paths out of the RCS, such as pressurizer safety valves or reactor vessel head vents, could be open during the water-feeding processes.

In general, the location and size of the RCS openings are known to significantly affect the plant behavior and the thermal-hydraulic processes after event [4]. Table 1 represents the potential RCS openings during shutdown operation and refueling of the YGN 3/4 plant. Table 2 shows the elevation of the openings and reference height of the major location. Among those RCS openings, the largest opening size is the manways in the SG plenum and the top of the pressurizer, that is 16 inches inner diameter, except the opening of the reactor vessel head-off. The cold-leg opening size is assumed 5 to 30% of the cold-leg cross sectional area while the RCP seal or impeller assembly is removed. The highest elevation of the opening is about 17.6 m of the pressurizer manway above the centerline of the hot leg, and the lowest opening is on the cold leg.

Table 1. Potential RCS openings during shutdown operation of YGN 3/4

RCS Openings	Diameter (in.)	Remarks
• Pressurizer manway	16	- for RCS coolant draining
• Primary SG inlet plenum manways	16	- for SG U-tube inspection
• Primary SG outlet plenum manways	16	- for SG U-tube inspection
• Pressurizer safety relief valves	6	- for maintenance
• Vessel upper head vent	3/4	- for venting
• Pressurizer vent line	1	- for venting
• Reactor vessel head off	-	- for refueling
• RCP seal or impeller	5%-30% of cold leg area	- while repaired

Table 2. Major elevation and reference point of YGN 3/4

Elevation	Reference Point	Remark
• 161 ft 3 in	- Top of the pressurizer	- Pressurizer manway
• 137 ft	- Top of the RWST	
• 129 ft	- 10 % of the pressurizer water level	
• 116 ft 3 in	- Flange of the reactor pressure vessel	
• 109 ft 3.5 in	- Inlet of SG U-tube	- SG inlet/outlet plenum manways
• 105 ft 1 in	- Top of the hot-leg	
• 103 ft 4 in	- Centerline of the hot and cold legs	- Cold-leg opening

Besides, two sources of cold water may be available for the RCS makeup during the plant outages; the accumulators and the RWST. The gravity-injection from the accumulators is not a practical method because it is difficult to manually control the injection flow, even they could be pressurized by the gas. Meanwhile, the gravity-injection from the RWST could be an effective measure if there is a net positive differential pressure between the RWST and the RCS. During mid-loop operation, the RWST water level is generally higher than the RCS water level, resulting in providing the net positive elevation head. However, because the injection paths are long and complex, and fitted with various components such as flow-orifices, valves, pumps, or heat exchangers, it is important to identify the possible and effective paths for the gravity injection. The YGN 3/4 plants have multiple injection paths from the RWST to the RCS as follows:

- The cold-leg injection path through a high pressure safety injection system
- The cold-leg injection path through a charging and letdown system
- The cold-leg injection path through a RHR system
- The hot-leg injection path through RHR suction lines, etc.

Among those flow paths, the hot-leg injection path via the RHR suction lines has relatively low hydraulic resistance because there are no pumps and a few numbers of valves on the flow path.

II.C. Analysis Cases

II.C.1. The Containment Closure Time (CCT) Analysis

For the CCT analysis, three locations of the RCS openings are selected based on the above typical plant configurations: pressurizer-manway opening (PMO), SG-inlet-plenum-manway opening (SMO), and cold-leg opening (CLO). When there are these openings during the event, it is expected that the reactor coolant would be discharged into the containment via the openings from the early phase of the event. In addition, the secondary water level condition will affect the thermal-hydraulic process in the RCS. Thus, based on the combination of the RCS openings and the SG secondary water level condition, the five cases of typical RCS configurations are identified to analyze in detail the plant behavior.

1. a pressurizer-manway-opening (PMO) case with water-filled SGs (Case 1)
2. a pressurizer-manway-opening (PMO) case with emptied SGs (Case 2)
3. a SG-inlet-plenum-manway-opening (SMO) case with emptied SGs (Case 3)
4. a small cold-leg-opening (CLO) case with emptied SGs (Case 4)
5. a large cold-leg-opening (CLO) case with emptied SGs (Case 5)

The CCT could be determined based on the time to boil, the time to core uncovery, and the time to core heatup after event obtained from the detailed transient analyses. The time to boil is defined as the time for the water in the reactor vessel upper head to reach a saturation temperature under atmospheric pressure. The time to core uncovery is defined as the time for the collapsed water level to be below the top of the core. The time to core heatup is defined as the time for the fuel surface temperature to begin to rapidly increase. Generally, to prevent the release of fission products to environment, the containment closure needs to be initiated before the time to boil and completed before the time to core uncovery.

II.C.2. The Gravity-Injection Path and Rate (GIPR) Analysis

For the GIPR analysis, the six cases of the gravity-injection paths are identified to evaluate the core cooling capability after event. It is based on two available gravity-injection lines, the cold-leg and the hot-leg injections, and three of large RCS openings as a RCS drain path, which are the same openings as the CCT analysis. The six cases of the identified injection paths are as follows;

1. a hot-leg injection and a PMO discharge (Case A)
2. a hot-leg injection and a SMO discharge (Case B)
3. a hot-leg injection and a small CLO discharge (Case C)
4. a cold-leg injection and a PMO discharge (Case D)
5. a cold-leg injection and a SMO discharge (Case E)
6. a cold-leg injection and a large CLO discharge (Case F)

Especially, in the YGN 3/4 plant design, the total water volume of the RWST as a water source for core cooling is 2978 m^3 [8]. When 70% of the RWST water is available during plant outages, the water level of the RWST is about 7.0 m above the hot-leg centerline. The pressure and the water temperature in the RWST are assumed to be atmospheric and 307 K, respectively.

The diameter of the pipe from the RWST to the RCS injection point is assumed 25.4 cm, based on the pipe diameter of safety injection system. In practice, the pipe size varies depending on the flow path, and also the injection flow is constrained by a hydraulic resistance on the flow path. Thus, the sensitivity on the gravity-injection flow rate is studied and discussed in Section IV.B.3. Figure 2 represents the possible gravity-injection paths and the locations of the RCS openings in the YGN 3/4 plant.

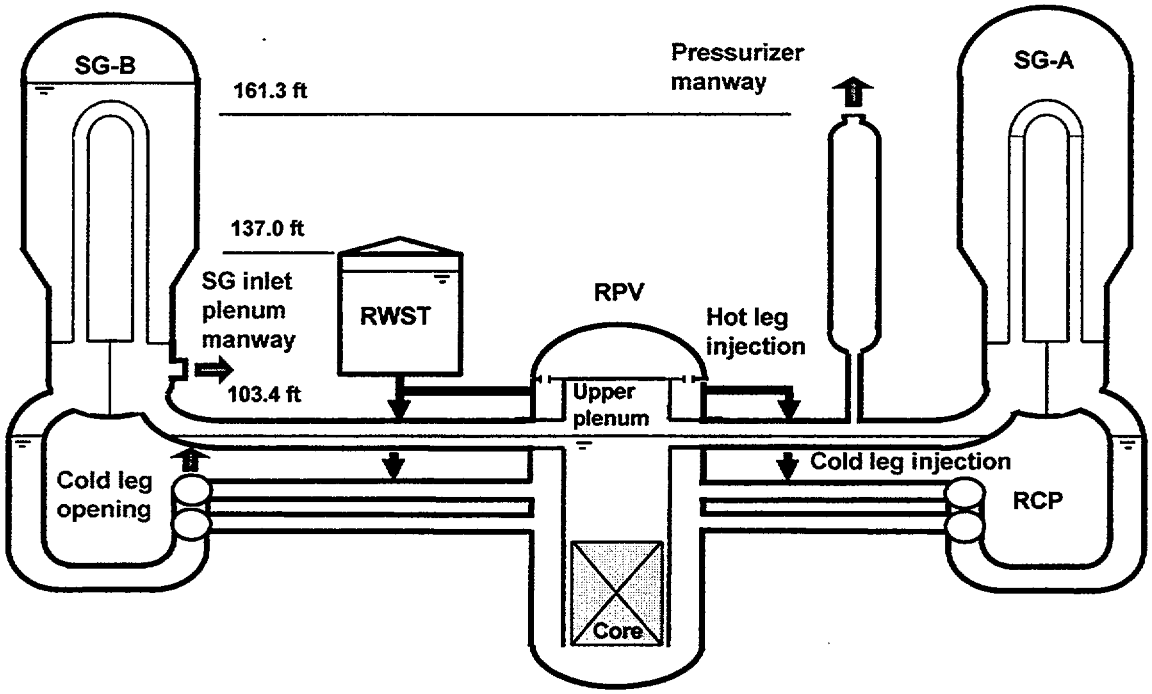

Fig. 2. RCS configurations and gravity-injection paths in the YGN 3/4

III. DESCRIPTIONS OF ANALYSIS MODEL

To analyze the thermal-hydraulic behavior following the event, the system transient analysis code, the standard version of RELAP5/MOD3.2 released by the U.S. Nuclear Regulatory Commission (NRC) [9], is used. The code is run on a DEC 5000/240 workstation. The applicability of the code to the loss-of-RHR event under shutdown conditions was assessed in a previous study [10, 11]. The assessment was based on the comparison of the calculation with a Rig of Safety Assessment-IV/Large Scale Test Facility (ROSA-IV/LSTF) experiment simulating the event during mid-loop operation [12]. It revealed that the code was capable of simulating appropriately the major thermal-hydraulic processes following the event, including the coolant boiling, the system pressurization, the steam condensation on SG U-tube wall, the loop seal clearing in the crossover leg, the water holdup in the pressurizer, and the non-condensable gas behavior. Also, Banerjee et al. [13] reported that the code gave a good qualitative agreement with the same experiment data. Recently, Ferng and Lee [14] also indicated that the code and models behaved well in capturing the overall system responses to the event through the assessment of the RELAP5 code with Taiwan's INER Integral System Test (IIST) data for the loss-of-RHR event.

However, there have been many difficulties in getting convergence of the transient calculation following the loss-of-RHR event during the mid-loop operation. Particularly, it was difficult to calculate the transport process of the mixture including non-condensable gas under the low flow and low pressure conditions. When the non-condensable gas enters a hydrodynamic volume filled with steam, an extremely small size of time step was required and a long CPU time was consumed. Recently, Seul. et al. [10] reported that the RELAP5/MOD3.2 version, which incoporated new models and improvements related to the analysis of the loss-of-RHR event, was capable of simulating the event with an appropriate time step and CPU time. They also indicated that the long-term behavior of the transient including the non-condensable gas behavior could be reasonably predicted.

In this calculation, the same code and consistent models as the previous study are used except the difference of the plant geometrical conditions. The nodalization for simulation of the plant is consisted of ~ 236 hydrodynamic volumes connected by ~ 263 junctions and ~ 228 heat structures, as shown in Fig. 3. The RPV elements (volumes 100 to 130) include the volumes corresponding to the downcomer, the lower plenum and upper plenum, the core, the upper head, and the guide thimble channel. The core is modeled as two-channel core with 12 volumes and heat structures per each channel connected by crossflow junctions. This arrangement is adopted to compensate the multi-dimensional effect such as an natural circulation flow in the core region. Also, to simulate the steam bypass flow from the upper plenum to the upper head, the guide thimble tube is modeled.

The two loops are consisted of an intact loop (volumes 200 to 299) and a broken loop (volumes 400 to 499) in a nearly symmetrical way. Each loop is composed of a hot leg, SG inlet and outlet plena, a SG U-tube, two crossover legs and RCPs, and two cold legs. Especially, the crossover legs are modeled as 9 nodes to accurately simulate the loop seal clearing phenomena. The pressurizer is connected to the hot leg in intact loop through the surge line elements. The secondary sides of two SGs (volumes 300 to 399 and 500 to 599) are simulated with a downcomer, boiling section, a steam separator and a steam dome. The RHR system is modeled by time dependent volumes and junctions connected to the hot leg and the cold leg in both loops. The RHR lines are needed to calculate the steady-state conditions during the mid-loop operation of the plant. Basically, in the current YGN 3/4 transient analysis, the same options related to the volume and junction and the same special models such as the CCFL model, the cross flow model and the control logic including the time step control are used as the previous LSTF assessment [10].

The initial conditions used in the calculation are represented in Table 3. They are nearly same for the CCT analysis and GIPR analysis. The decay heat rate depending on the time after reactor shutdown is conservatively assumed to remain 0.5% of full power throughout the transient. The RCS water level is assumed to be in mid-level of the hot leg. The pressure in the primary and secondary systems remains atmosphere, and the gas space is filled with non-condensable gas of air. The steady state conditions are obtained from new transient run up to 1000 s and the loss-of-RHR events are initiated by isolating the RHR flow and opening the PMO, the SMO, or the CLO. In the GIPR transient analysis, the gravity-injection from the RWST is assumed to begin at 20 minutes after event, based on the typical operator action time.

The input decks for the steady state and transient calculations of the event in the YGN 3/4 plants are attached to this report as an Appendix A and B. In the following section, the analysis results are discussed separately for the CCT and GIPR calculations. Table 4 indicates the list of major parameters represented in the figures of this report.

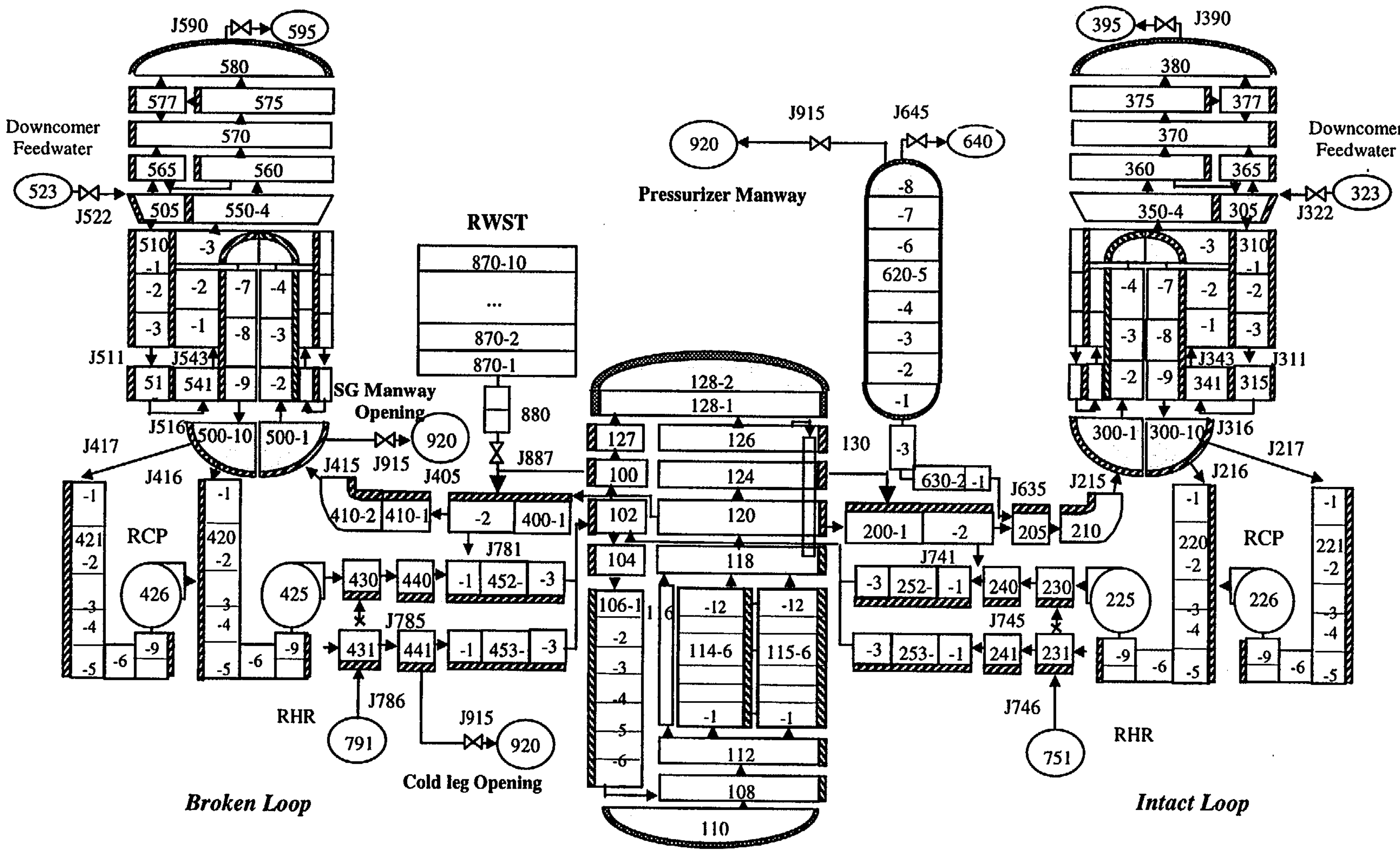

Fig. 3. RELAP5 nodalization for simulation of a Loss-of-RHR event in YGN 3/4 plants

Table 3. Initial conditions for transient analysis

Major Parameters	Simulation Conditions
• Core power (MW thermal) • Primary and secondary pressures • Hot leg and cold leg water temperature (K) • SG secondary water temperature (K) • Water level in primary side • Water level in SG secondary side (m) • Initial mass inventory (kg) • Non-condensable gas • RWST water level • RWST water temperature (K) • PMO and SMO area (m^2) • 5 % and 30 % of CLO area (m^2)	• 14.125 (0.5 % of full power) • Atmospheric • 327.6 and 313.1 • 313.1 • Mid-level of loop • empty or 11.0 • 104618 • Air • 70 % of full height • 307.0 • 0.13 • 0.0228 and 0.1368

Table 4. List of the major parameters represented in the figures

Major Parameters	Figures	Calculated Parameters
• Pressure at upper plenum	Fig.4, 12, 18, 25	p-120010000
• DP at crossover leg downside-BL	Fig.15	cntrlvar-755
• DP at crossover leg upside-BL	Fig.15	cntrlvar-753
• Water temperature at hot leg-IL	Fig.8	tempf-200010000
• Water temperature at cold leg-IL	Fig.8	tempf-253030000
• Water temperature at upper plenum	Fig.23, 26, 31	tempf-120010000
• Fuel cladding temperature at top	Fig.11, 17	httemp-001001201
• Collapsed water level in RPV	Fig.10, 13, 24, 28	cntrlvar 125
• Collapsed water level in pressurizer	Fig.7, 20	cntrlvar 126
• Flow rate through opening	Fig.6, 16, 21, 30	mflowj-915000000
• Flow rate from RWST	Fig.19, 27, 29	mflowj-887000000
• Void fraction at hot leg-IL	Fig.9, 14, 22	voidg-200010000
• Void fraction at cold leg-IL	Fig.9, 14, 22	voidg-253030000
• Total heat transfer-IL	Fig.5	cntrlvar 63
• CPU time	Fig.32	cputime-0
• Calculated time step	Fig.34	dt-0
• Courant time step	Fig.34	dtcrnt-0
• Estimated mass error of primary	Fig.33	sysmer-1

* DP: Differential pressure, BL: Broken loop, IL: Intact loop

IV. ANALYSIS RESULTS AND DISCUSSIONS

IV.A. The CCT Analysis Results

IV.A.1. Analysis Results for the Hot-Leg Side Opening (Cases 1, 2, and 3)

The plant response following the loss-of-RHR event is generally dependent on the location of the RCS opening, especially whether it is on the hot-leg side or on the cold-leg side. For the hot-leg side opening cases, as shown in Fig. 4, the pressure in the upper plenum rapidly increases in the early transient phase due to the coolant heat-up and boiling after the event. Particularly, the Case 2 with the PMO shows the rapid pressure increase, eventually reaching a maximum of 240 kPa. The Case 1 also shows the same rate of pressure increase in the early phase, and thereafter a moderately increasing rate throughout the transient. This difference is because the Case 1 with the water-filled SG transfers more decay heat into the secondary side by a reflux condensation on the SG U-tubes than the Case 2 with emptied SG. Figure 5 shows the total heat transfer through the SG for the Cases 1 and 2. More than 8 MW among the total core power of 14.125 MW is removed through the both SGs. Nearly same amount of heat removal by the SGs was also reported by Hassan and Raja [6]. Meanwhile, the Case 3 with the SMO, located at relatively low elevation, shows much less pressurization. It is because the coolant is discharged much earlier than that for the PMO cases.

Figure 6 shows the discharging flow and its initiating time through the opening into the containment. For the Cases 1 and 2, the discharging flow has a similar pattern with a time delay of ~ 7000 s due to the different pressurization rate. The Case 3 shows that the two-phase mixture is vigorously discharged in the earlier phase of the transient. It implies that the coolant discharge behavior is strongly dependent on the location of opening as well as the SG secondary water level condition.

In addition, in the PMO case, the reactor coolant is held up due to flooding in the bottom of the pressurizer. Figure 7 shows that the collapsed water level in the pressurizer increases and stabilizes depending on the pressure behavior for the Cases 1 and 2. Particularly, for the Case 2, Figures 8 and 9 show that the water in the hot leg reaches a saturated temperature and voided in a short time of transient. After the hot leg is emptied, the increase of the water level in the pressurizer stops, and thereafter the significant discharging flow via the PMO is established. It indicates that the water holdup phenomena in the pressurizer and the discharging flow significantly affects the behavior of the coolant inventory in the RPV. As shown in Fig. 10, for the Cases 1 and 2, the RPV water level slowly decreases before the significant discharging flow. However, it rapidly decreases after the coolant discharge. Especially, the Case 3 indicates the rapidly decreasing water level in the earlier phase of the transient because of the early discharge.

As the water level in the RPV is reduced to the top of the core, the core uncovery occurs, and eventually the core heat-up is initiated. From this water level behavior, the time to core uncovery is estimated to be ~ 12000 s for the Case 1, ~ 6000 s for the Case 2, and ~ 3600 s for the Case 3. And, Fig. 11 shows that the core heat-up is initiated at ~ 2000 s after the core uncovery. It implies that the core damage time is strongly affected by the location of opening and SG secondary water level.

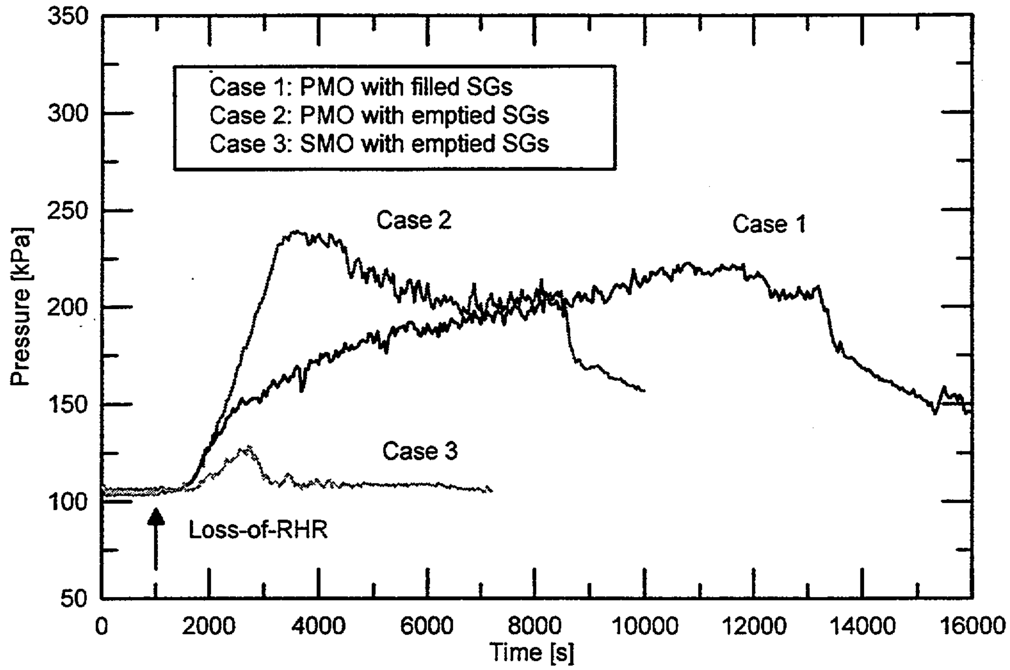

Fig. 4. Pressure behavior in the upper plenum (cases 1, 2, and 3)

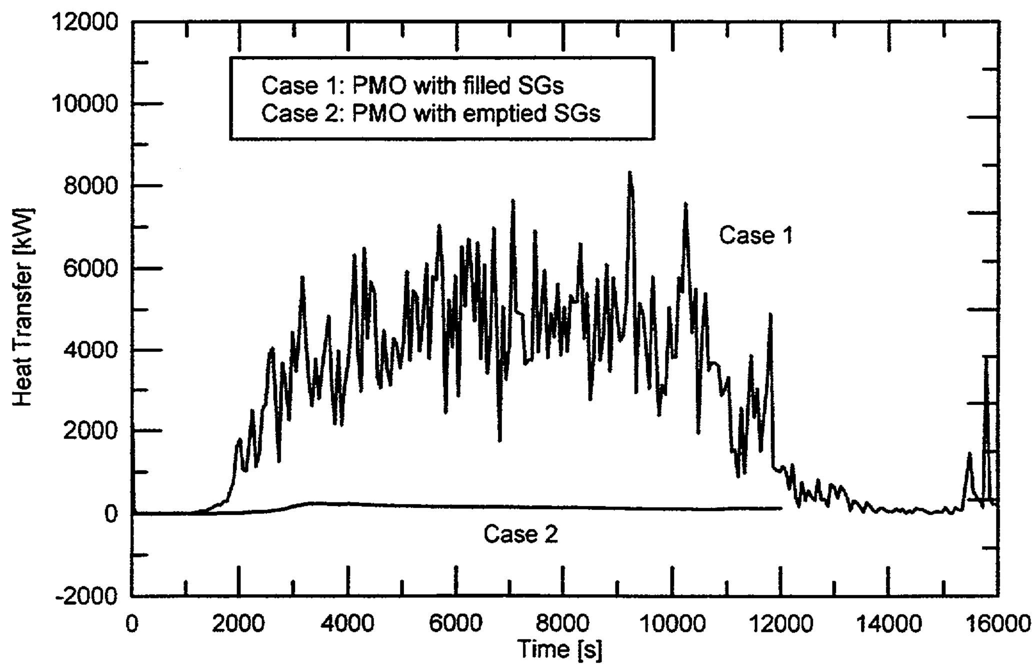

Fig. 5. Total heat transfer through the intact-loop SG (cases 1 and 2)

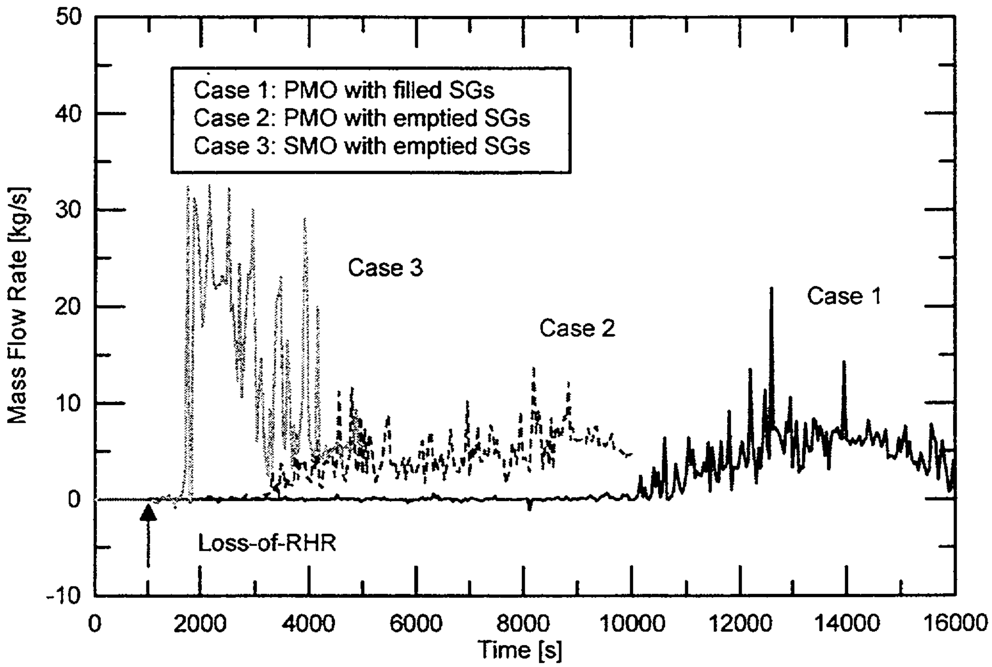

Fig. 6. Discharging flow through the opening (cases 1, 2, and 3)

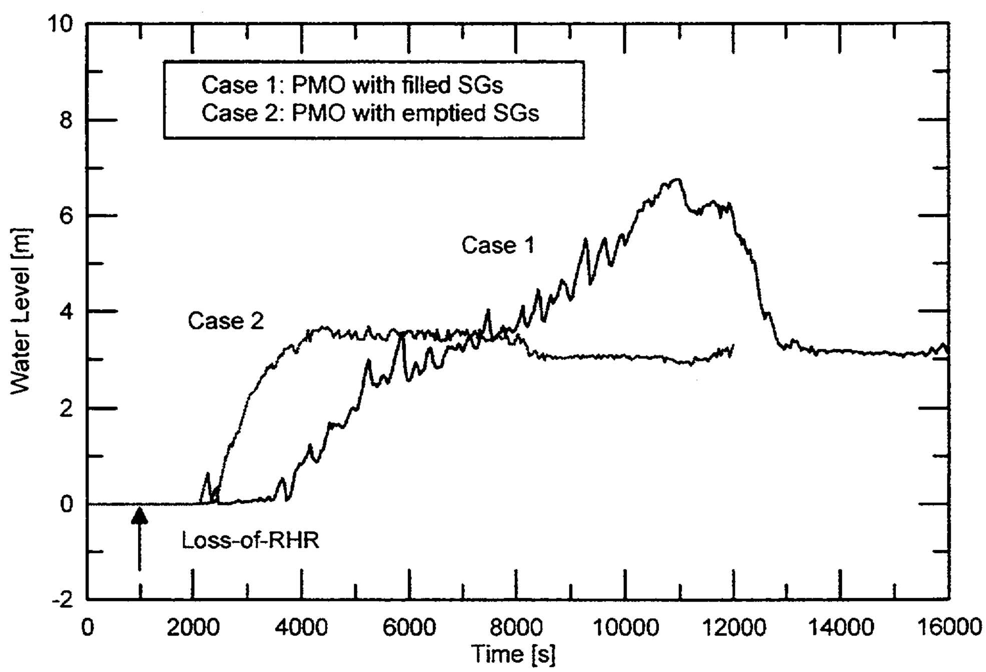

Fig. 7. Collapsed water level in the pressurizer (cases 1 and 2)

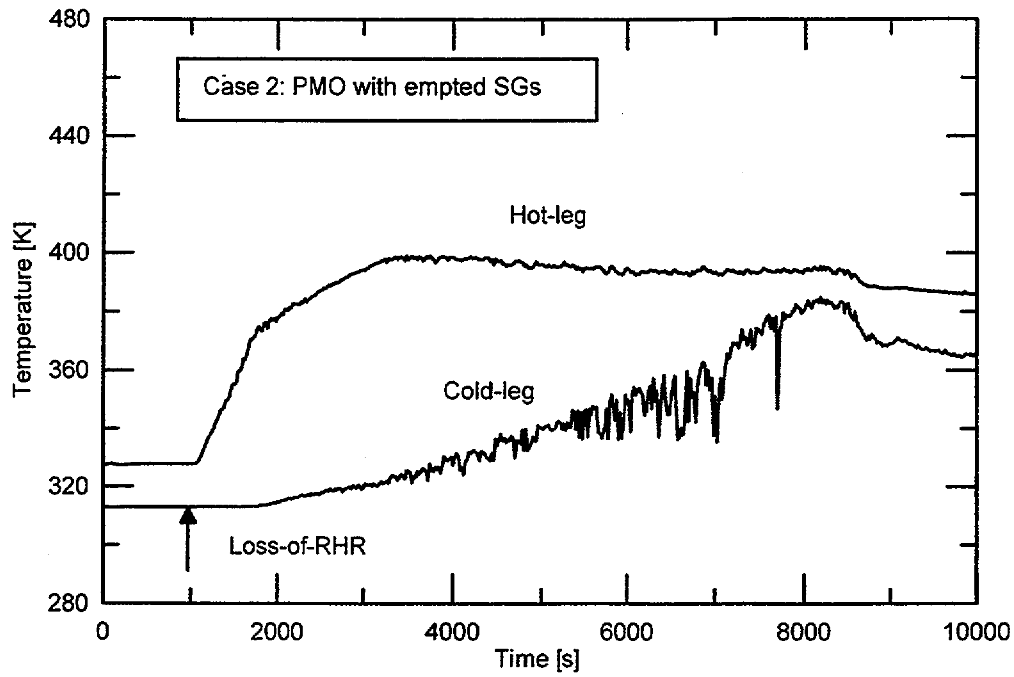

Fig. 8. Water temperature in the hot and cold legs (case 2)

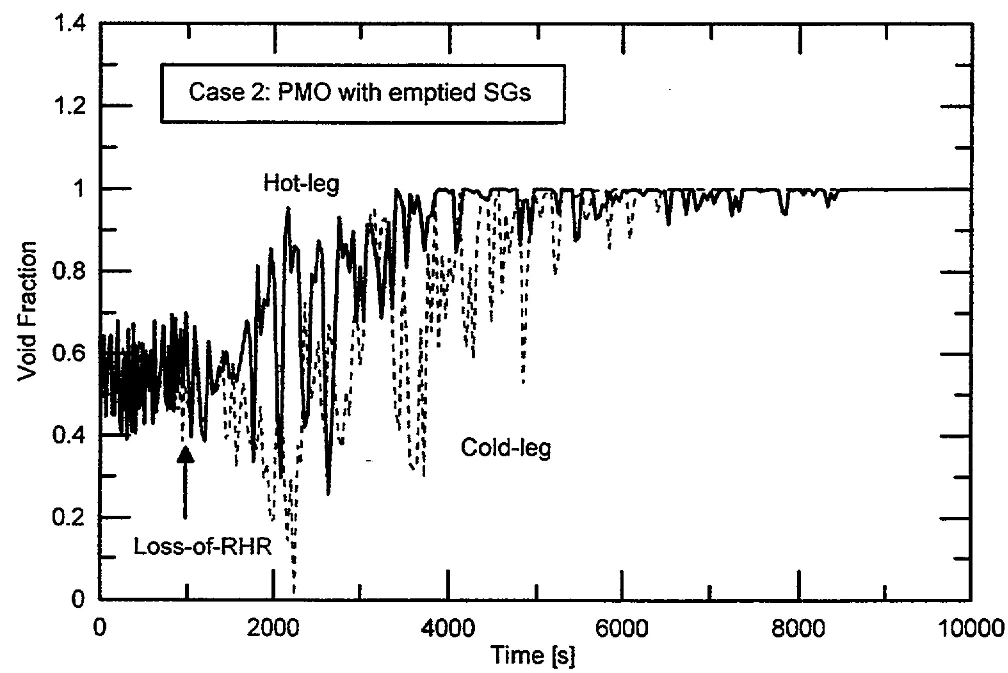

Fig. 9. Void fraction in the hot and cold legs (case 2)

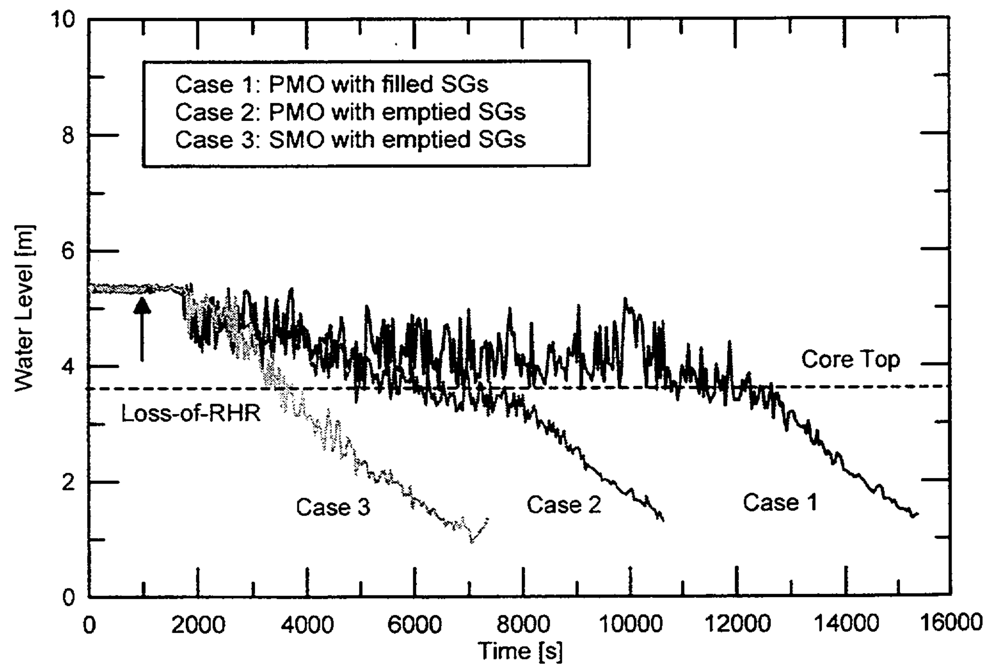

Fig. 10. Collapsed water level in the RPV (cases 1, 2, and 3)

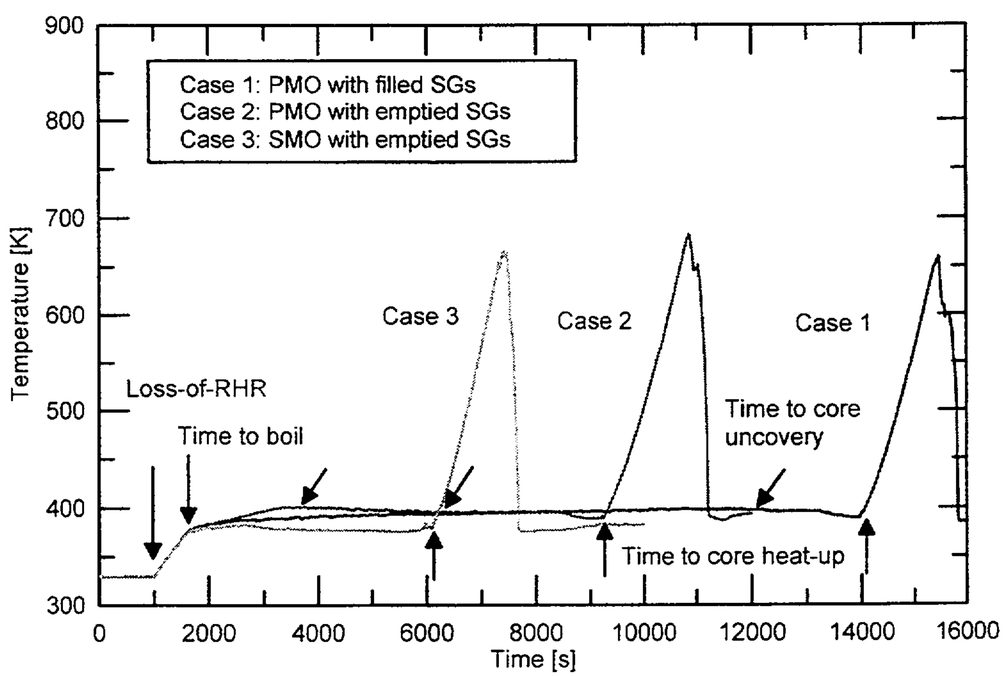

Fig. 11. Fuel cladding temperature (cases 1, 2, and 3)

IV.A.2. Analysis Results for the Cold-Leg Side Opening (Cases 4 and 5)

The cases with the cold-leg side opening show somewhat the different plant behavior from the hot-leg side opening cases. In particular, the reactor coolant in the cold leg begins to discharge to the containment in the earlier phase of the transient because the opening is located at relatively lower elevation. As shown in Fig. 12, the system pressure rapidly increases after boiling at ~ 1610 s, and then the pressure difference between the hot leg and the cold leg becomes increasing. The high differential pressure expels the water in the crossover leg and RPV toward the cold leg with the opening, and eventually the coolant is discharged via the opening to the containment. Then, the water level in the RPV decreases below the top of the core in the early phase of the boiling, resulting in the first core uncovery, as shown in Fig. 13. When the pressure reaches a maximum of 153 kPa for the Case 4 and 135 kPa for the Case 5, the water in the crossover leg is immediately cleared, which is called a loop seal clearing (LSC). Simultaneously, the pressure in the hot leg and upper plenum drops to the cold leg pressure and such a pressure drop quickly increases the water level in the RPV because the compression force of the steam space in the upper plenum is disappeared. Eventually, the core is covered again by the coolant.

Figures 14 and 15 show the voiding in the hot leg and the complete LSC in the crossover leg for the Case 4. Figure 16 also indicates that the coolant is significantly discharged via the opening before the LSC. After the LSC, because of the continuous steaming in the core region, the system pressure again increases. The Case 4 with the small opening shows a higher pressurization rate than the Case 5. As the RPV is pressurized, the steam is again discharged through the opening and then the water level in the RPV decreases moderately, as shown in Fig. 13. Eventually, the core is uncovered again at ~ 5500 s for the small CLO case and ~ 3400 s for the large CLO case. Thereafter, the water inventory further decreases and the core heat-up is initiated, as shown in Fig. 17. As a result, the calculation indicates that the first core uncovery is initiated from ~ 1600 s regardless of the opening size, whereas the second core uncovery time is dependent on the opening size.

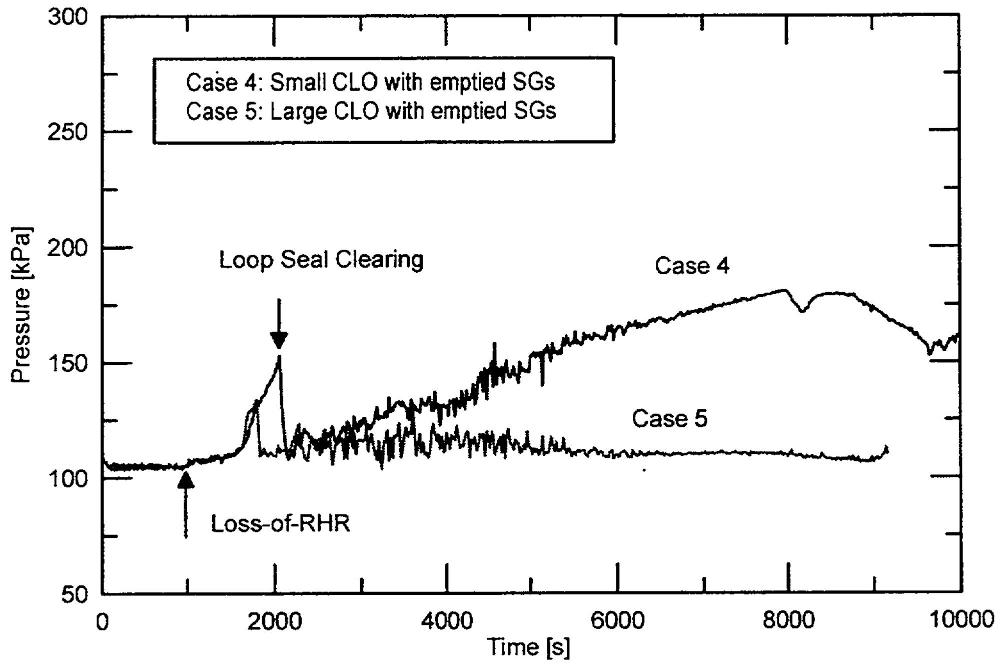

Fig. 12. Pressure behavior in the upper plenum (cases 4 and 5)

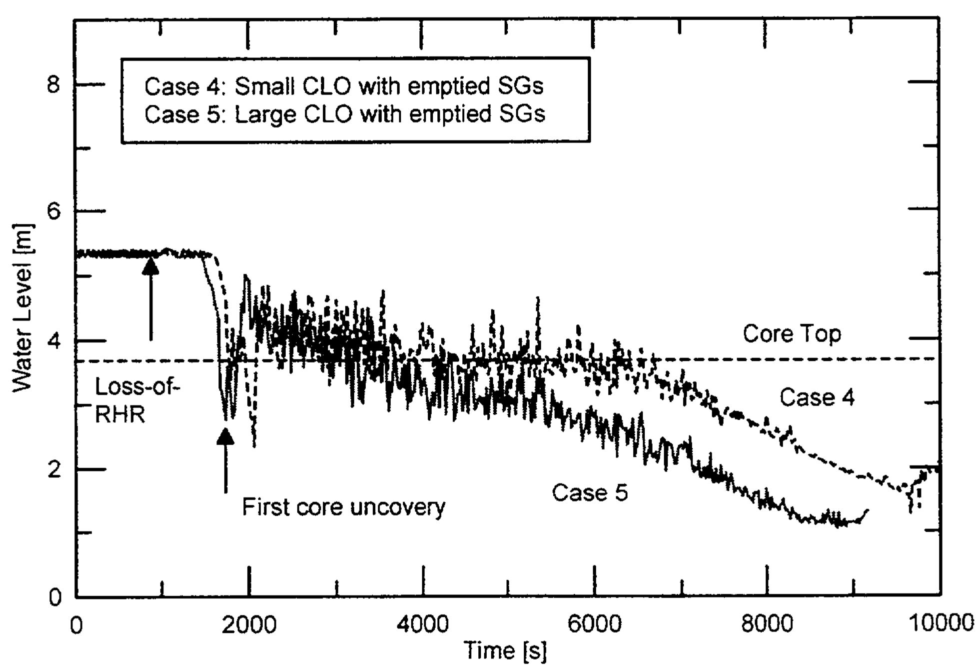

Fig. 13. Collapsed water level in the RPV (cases 4 and 5)

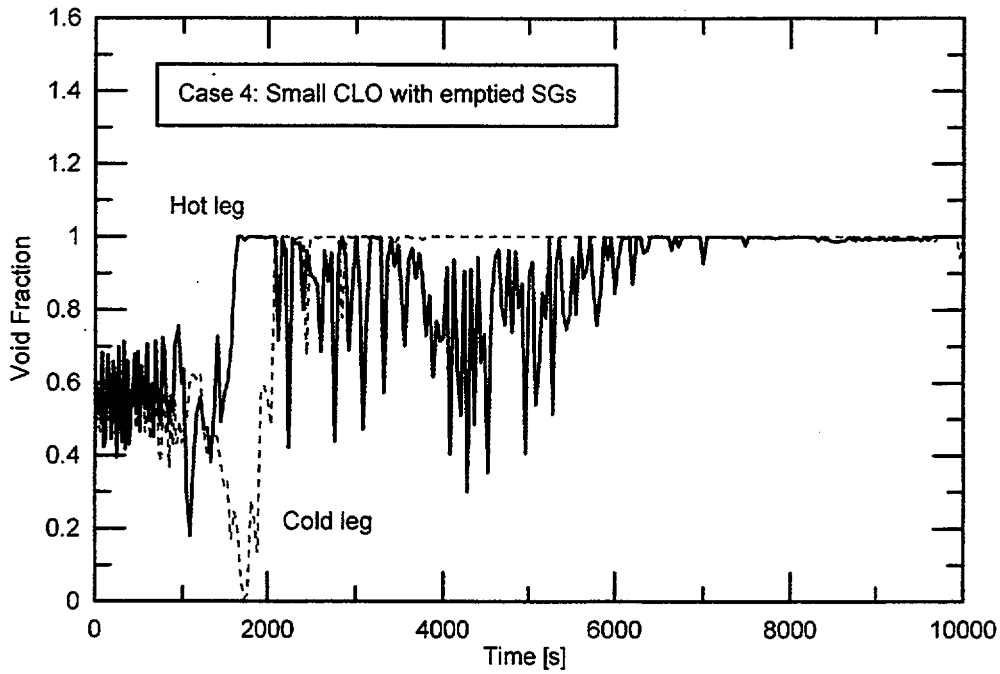

Fig. 14. Void fraction in the hot and cold legs (case 4)

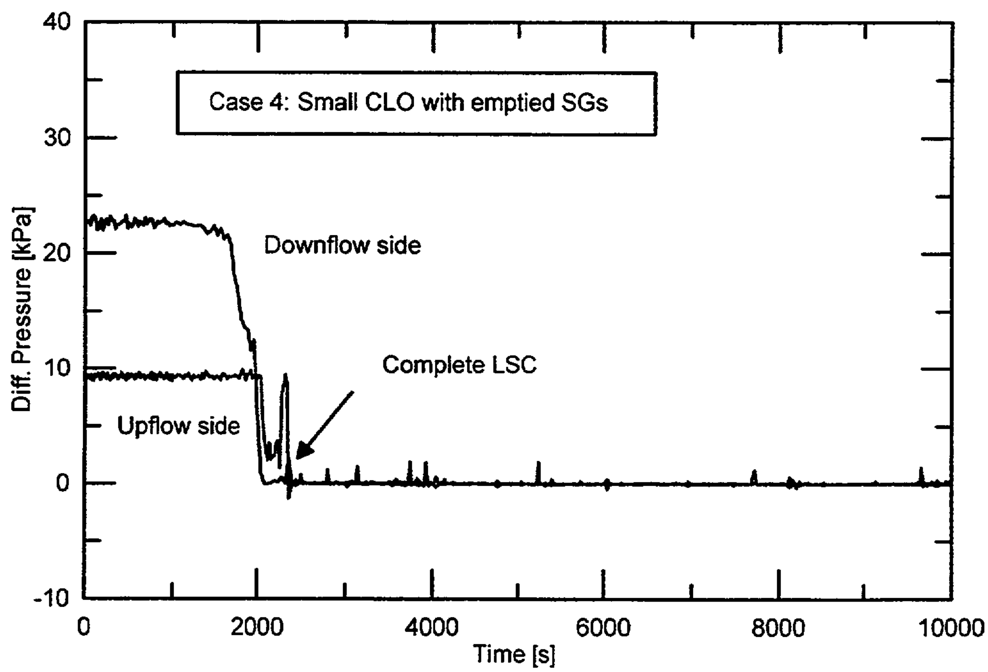

Fig. 15. Pressure difference in the crossover leg (case 4)

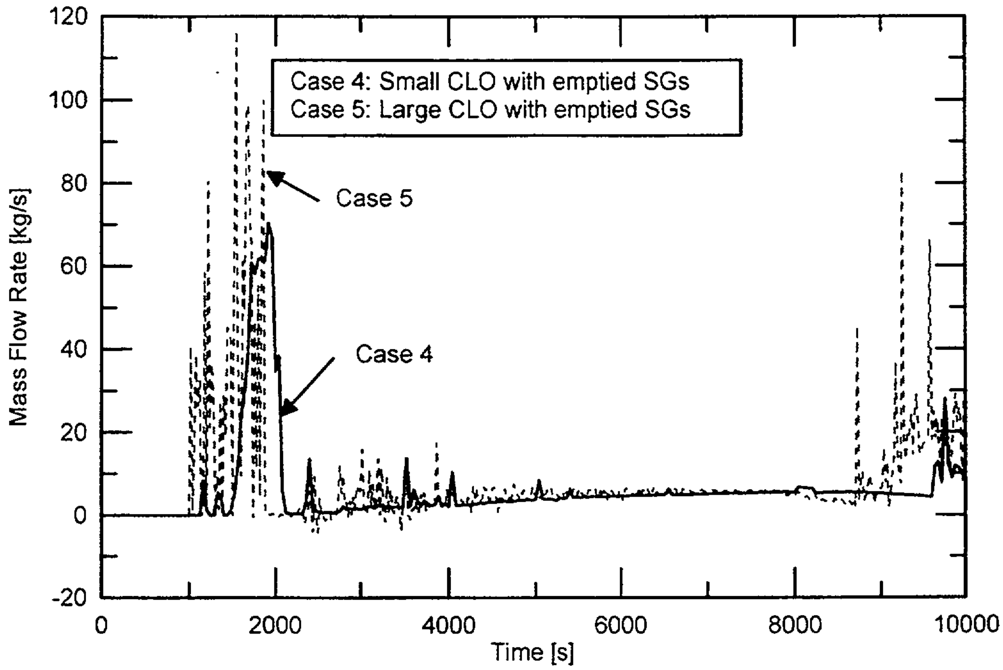

Fig. 16. Discharging flow through the opening (cases 4 and 5)

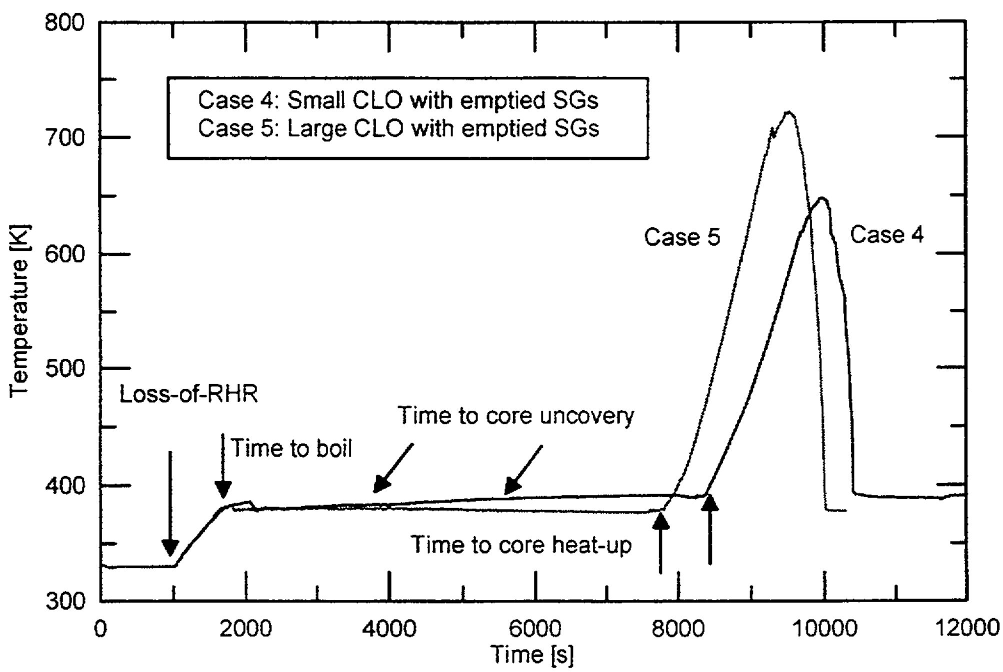

Fig. 17. Fuel cladding temperature (cases 4 and 5)

IV.A.3. Discussion on the Containment Closure Time (CCT)

The results of CCT analyses for the five cases of typical RCS configurations under the worst event sequence were summarized in Table 5 and compared with some available data of the CE-typed PWR [15]. It indicates that the time to boil-off and the time to core uncovery of the YGN 3/4 are estimated to be slightly earlier than that of the CE-typed PWR. It is due to the difference of the calculation models and plant geometry. In the YGN 3/4 simulation, the time to boil-off is estimated to be about 10 to 13 minutes regardless of the opening location and the SG secondary water level condition. It is because the time to boil-off is strongly dependent on the initial conditions such as the decay heat load and the amount of reactor coolant in and above the core. This result agrees well with 12 minutes of Parrish and Till's calculation [5].

On the contrary, the time to core uncovery and the time to core heat-up are strongly dependent on the size and location of the opening and the secondary water condition. The Case 5 with the large CLO and emptied SG indicates the earliest time to core uncovery of 40 minutes after event. The Case 3 with the SMO also indicates 42.5 minutes of the core uncovery time and 85.7 minutes of the core heat-up time, which is the earliest core heat-up in the five cases. Also, the Case 1 with the water-filled SG shows that the time to core uncovery is delayed up to 183.3 minutes due to the secondary side cooling.

Table 5. Results of transient analyses for the YGN 3/4

(unit: minutes)

RCS Openings	Time to Boil	Time to Core Uncovery	Time to Core Heat-up
• Case 1; PMO with water-filled SGs	12.3	183.3	218.0
• Case 2; PMO with emptied SGs	12.3	83.3	139.0
• Case 3; SMO with emptied SGs	13.0	42.5	85.7
• Case 4; Small CLO with emptied SGs	11.6 (13.6)	75.0 (91.5)	123.3
• Case 5; Large CLO with emptied SGs	10.6 (13.6)	40.0 (59.9)	111.7

* ( ) is CE-typed PWR data

In general, time is required to completely close the containment openings such as personnel or equipment hatches. Thus, an initiating time and completion time of the containment closure must be estimated to ensure the habitability of the personnel in the containment. From these transient analysis results, it is found that the containment openings are needed to start closing before coolant boiling because the high enthalpy of steam or two-phase mixture is discharged to the containment shortly after coolant boiling. It could result in jeopardizing the personnel working inside the containment. Particularly, the simulations for the CLO cases indicate that the core could be instantaneously uncovered and partially damaged in the early phase of the boiling. Thus, if the containment closure is initiated after coolant boiling, it is needed to evaluate the in-containment environment to ensure the survivability of the workers in the containment. Also, to prevent the uncontrolled release of fission products to atmosphere, the containment openings must be completely closed before time to core uncovery. If the containment closure is achieved after the core uncovery, the environmental impact is needed to analyze. Based on these evaluations, the CCT could be determined from the time to core uncovery. For example, if there is a large opening such as the SMO (Case 3) or the CLO (Case 5), the containment closure must be achieved within ~ 40 minutes after event. Also, if the pressurizer manway is open (Case 2), the containment closure must be completed within ~ 83 minutes. However, if the SGs are filled with water for the same opening (Case 1), it could be extended to ~ 183 minutes.

As a result, it was found that the earliest CCT was 40 minutes after event for the SG-inlet-plenum-manway opening or the large cold-leg opening cases with the emptied SGs. Also, the containment closure is needed to initiate before boiling time because the discharge via the opening after boiling could threaten the workers in the containment.

IV.B. The GIPR Analysis Results

IV.B.1. Analysis Results for the Hot-Leg Injection Cases (Cases A, B, and C)

In the GIPR analysis to investigate the core cooling capability by the RWST water, the plant behavior before the gravity-injection is similar to that of the CCT analysis. Following the loss of the residual heat removal function, the core coolant is heated up and boiled off at a saturation temperature, and the RPV is pressurized. Figure 18 shows the pressure behavior in the upper plenum for the Cases A, B, and C with the same hot-leg injection and the different RCS opening. After the gravity-injection, the Case A shows a continuous pressure increase, while the pressure in the Cases B and C remain nearly constant. Such a pressure difference results from the different injection rate depending on the location of the RCS opening.

As shown in Fig. 19, the gravity-injection flow for the Case A completely stops at ~ 550 s after gravity-injection, while the injection flow for the Cases B and C continues to remain high. This is because the pressure in the Case A continuously increases due to the water holdup in the bottom of the pressurizer and it makes the gravity flow stopped when it reaches about 172 kPa corresponding to the hydrostatic elevation head between the RWST and the RCS water levels. The water holdup phenomenon was already discussed in the CCT analysis. Figure 20 shows the collapsed water level in the pressurizer for the Case A. It indicates that a large amount of water is held in the pressurizer.

After the gravity-injection flow is lost, the pressure further increases because of the water boil-off in the core region. When the pressure reaches about 300 kPa at ~ 4700 s, the two-phase mixture begins to be discharged through the PMO, and thereafter, the pressure moderately decreases. As shown in Fig. 21, the discharging flow via opening immediately increases at the maximum pressure for the Case A. Also, Fig. 22 shows that the hot leg is voided after the significant discharging flow. Thereafter, the steam is steadily discharged and the water level in the pressurizer is stabilized.

Meanwhile, in the Cases B and C with the openings at lower elevation than the RWST water level, the RCS outflow through the opening is well established as well as the gravity-injection flow. Especially, Fig. 21 indicates that the discharging flow for the Case C is very stable and steady. The Case B also indicates the sufficient discharging flow even with some flow oscillations. Eventually, the system pressure remains atmospheric for a long-term transient after gravity-injection.

Figure 23 indicates that the water temperature above the core region immediately drops due to mixing between the RCS coolant and the injected water when the gravity injection starts. Depending on the mixing effect, the core coolant remains either a subcooled or a saturated condition. The Case A shows that the temperature again increases up to the saturation within a short time after the gravity injection. As discussed above, it is because the core decay heat could not be removed due to the stop of the gravity-injection flow. Meanwhile, the Cases B and C show that the temperature remains subcooled for a long-term transient. It is because the core flow is sufficiently established by the gravity injection and the core decay heat is fully removed. As a result, it indicates that the core boiling after event is prevented in the Cases B and C by the gravity-injection using the RWST water, whereas the gravity-injection process in the Case A could be ineffective.

Figure 24 shows that the collapsed water levels in the RPV rapidly increase for all the cases when the gravity injection starts. The Cases B and C, thereafter, show that the levels remain nearly constant due to the stable RCS inflow and outflow. However, the Case A shows the water level decreasing. The initially rapid decrease is due to the stopped RCS inflow and the movement of the RCS coolant toward the pressurizer, and the lately moderate decrease is due to the two-phase mixture discharging through the opening. The continuous discharging leads to reduce the water level below the top of the core, and then the core is uncovered at ~ 6800 s, that is 96.6 minutes after event.

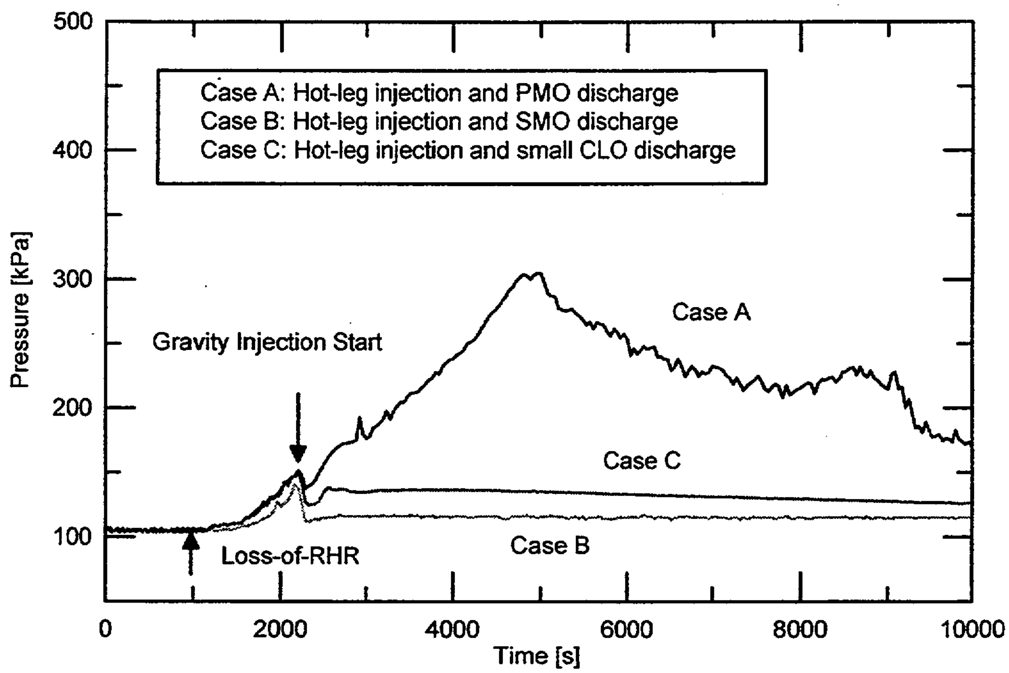

Fig. 18. Pressure behavior in the upper plenum (cases A, B and C)

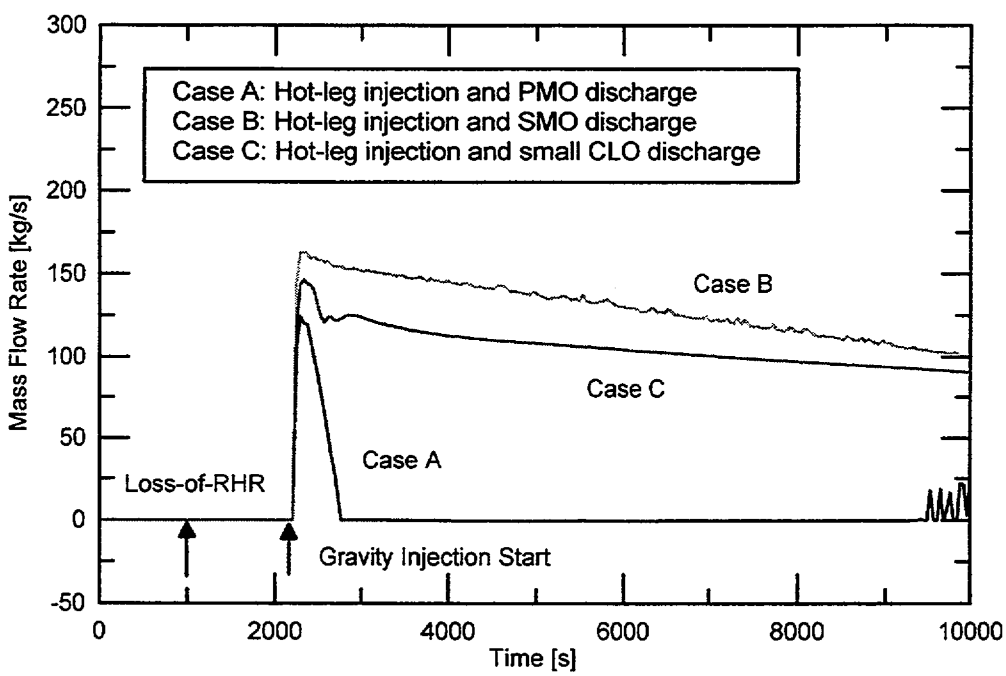

Fig. 19. Mass flow rate from the RWST (cases A, B and C)

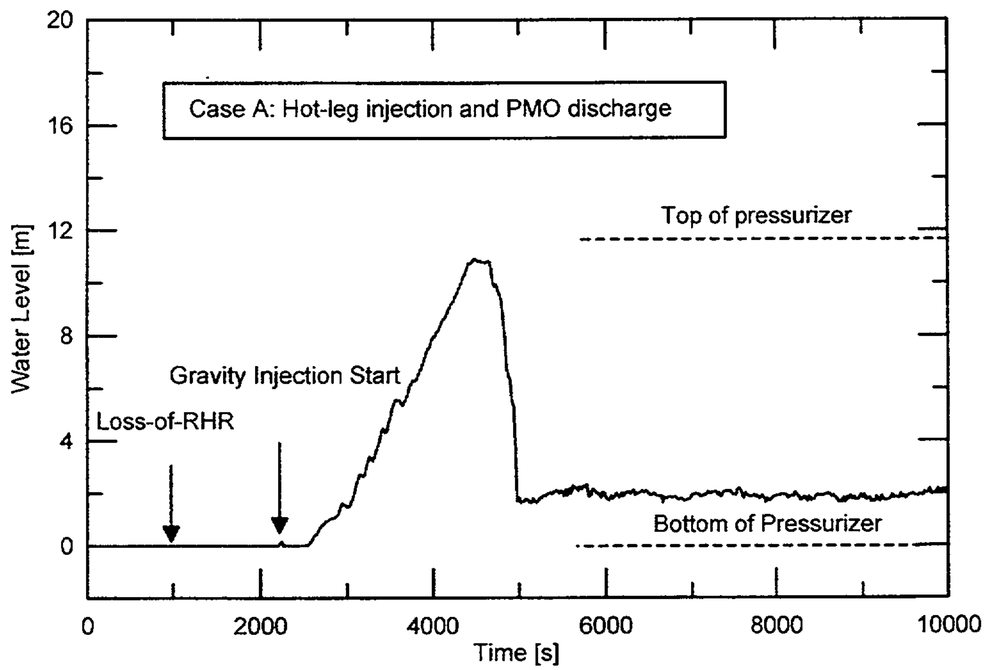

Fig. 20. Collapsed water level in the pressurizer (case A)

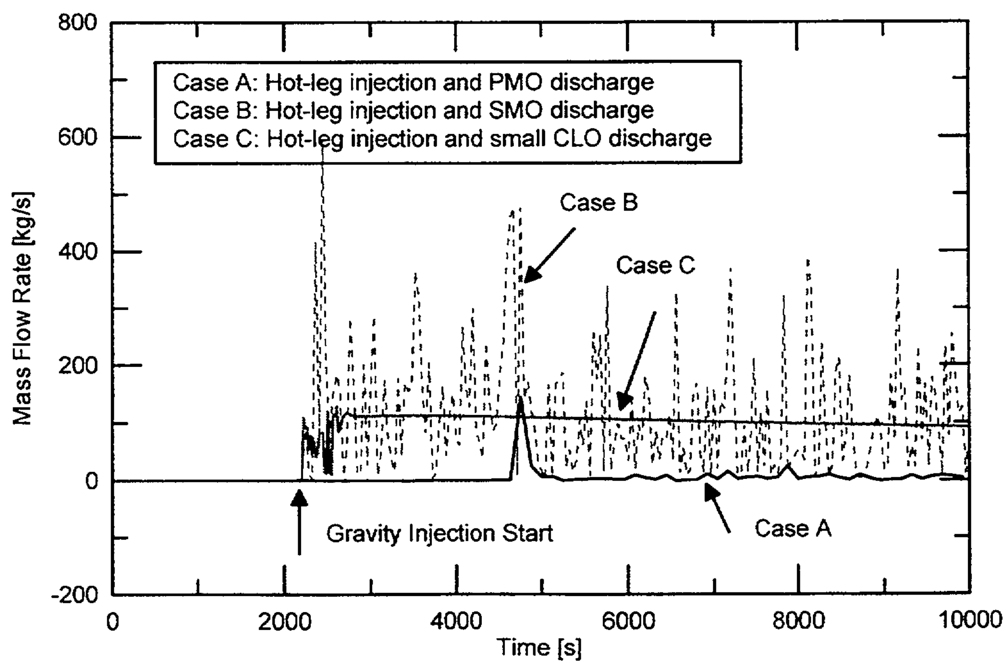

Fig. 21. Discharging flow rate through the opening (cases A, B, and C)

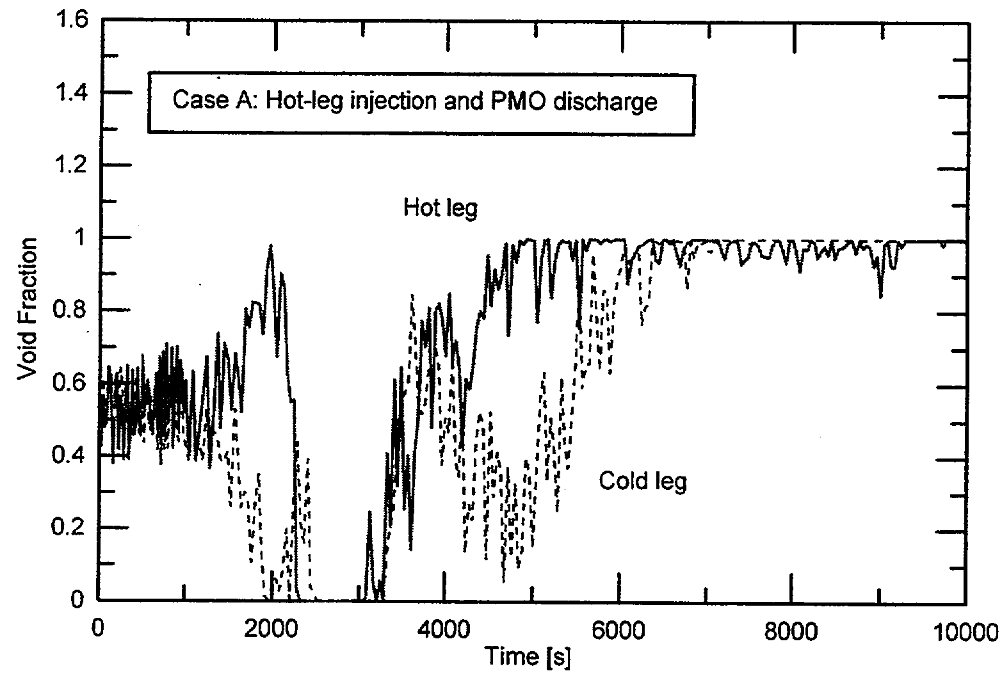

Fig. 22. Void fraction in the hot and cold legs (case A)

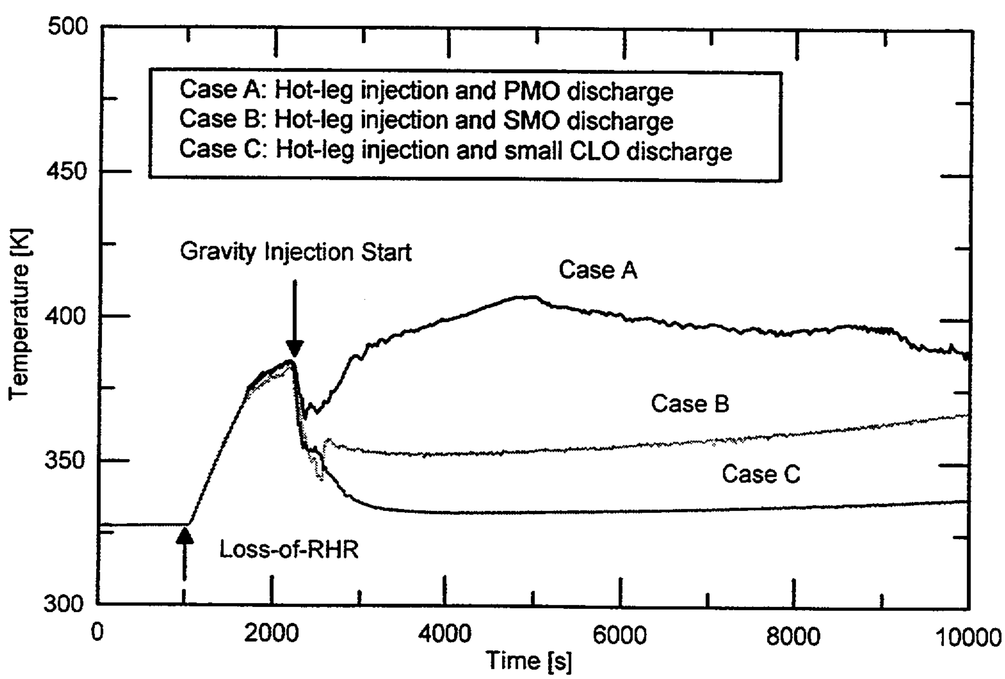

Fig. 23. Water temperature above the core region (cases A, B and C)

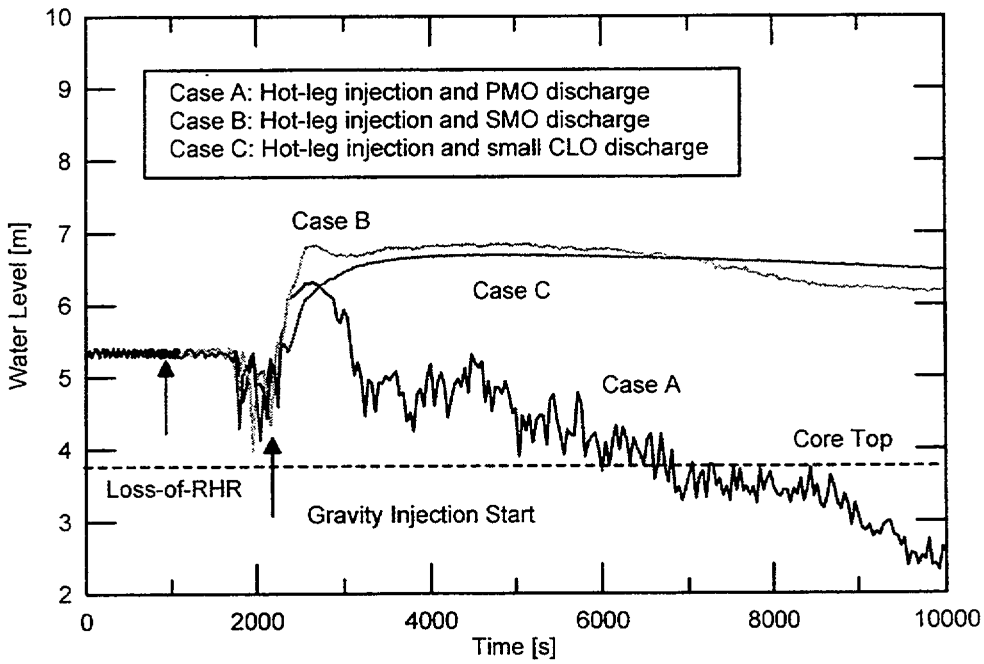

Fig. 24. Collapsed water level in the RPV (cases A, B and C)

IV.B.2. Analysis Results for the Cold-Leg Injection Cases (Cases D, E, and F)

The Cases D, E and F with the same cold-leg injection and the different RCS opening have the thermal-hydraulic behavior similar to the cases of the hot-leg injection. As shown in Figs. 25 and 26, the Case D with the PMO indicates that the system pressure continues increasing and the core is boiled off after gravity injection. As similar to the Case A, the gravity flow completely stops at ~ 500 s after gravity-injection, as shown in Fig. 27. Then, due to the continuous discharge via opening, the water level in the RPV decreases and the core uncovery occurs. As shown in Fig. 28, the core is uncovered at the nearly same time as the Case A. This result indicates that the core cooling for the PMO case could not be maintained by the gravity-injection process regardless of the injection paths.

The Case E with the SMO shows that the system pressure remains low enough to maintain the injection flow rate as the Case C after gravity-injection. The core is also successfully cooled for a long-term transient by the well-established RCS inflow and outflow. As a result, it indicates that the Cases C and E with the injection and opening on the different leg side, such as the hot-leg side injection and cold-leg side discharge, are the most suitable gravity-injection paths to avoid the core boiling after event.

The Case F with the CLO also indicates low pressure as the Case B, but the water in the core region is saturated and boiled off after gravity-injection as shown in Fig. 26. It is because most of the cold water injected through the cold leg is directly discharged through the CLO without passing the core region. Meanwhile, in the Case B with the hot-leg injection, part of the cold water injected passes the upper part of the core region and then the core boiling is prevented. As a result, it indicates that the Case B with the injection point and opening on the hot-leg side is a little more effective in core cooling after event than the Case F with the injection point and opening on the cold-leg side.

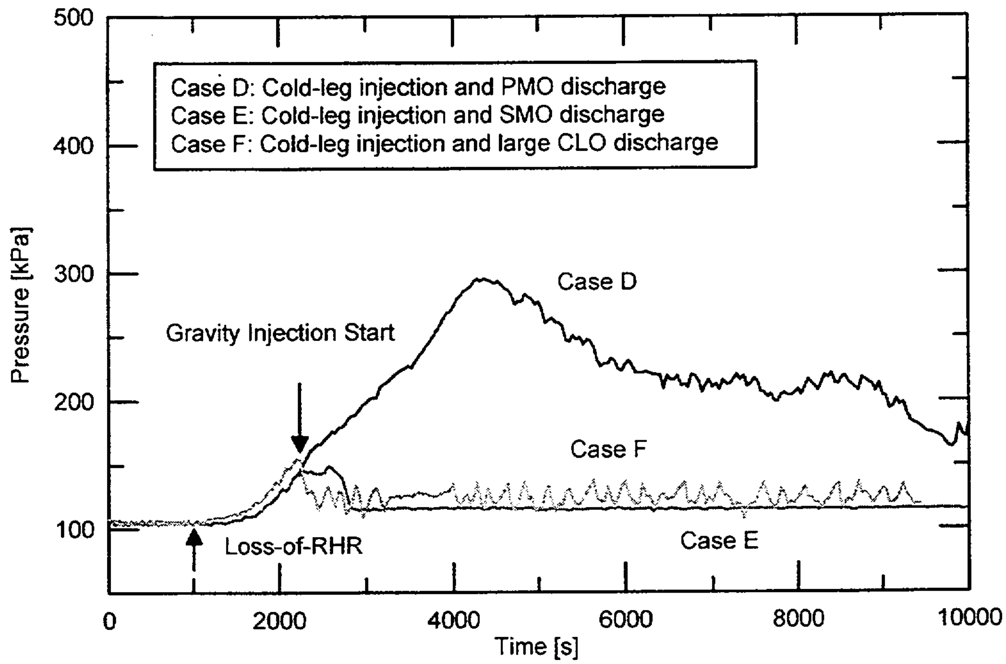

Fig. 25. Pressure behavior in the upper plenum (cases D, E and F)

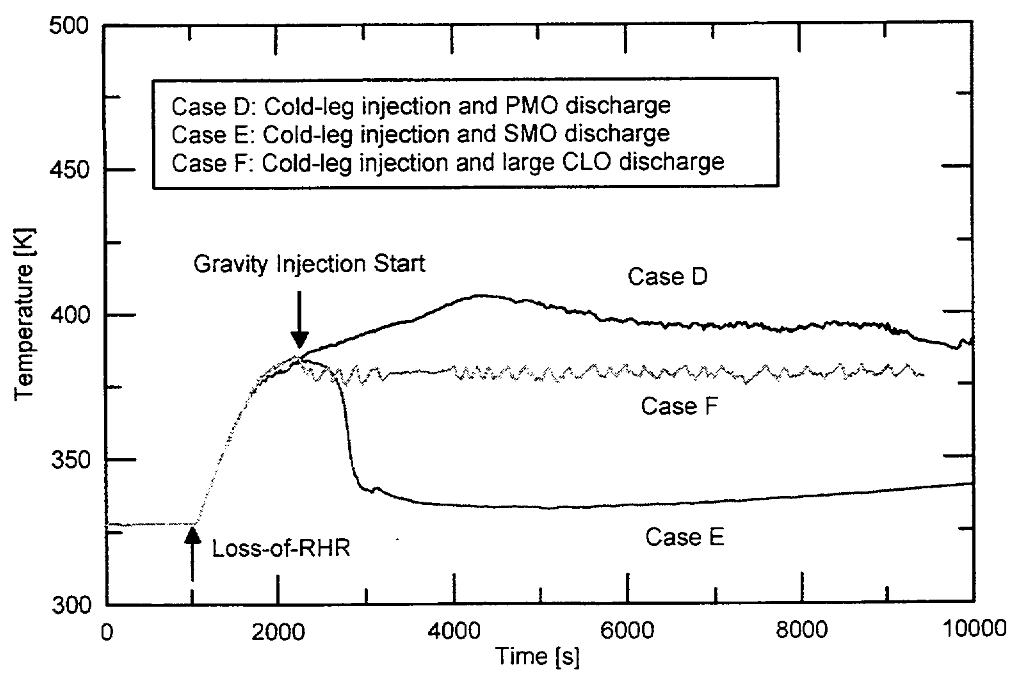

Fig. 26. Water temperaturesabove the core region (cases D, E and F)

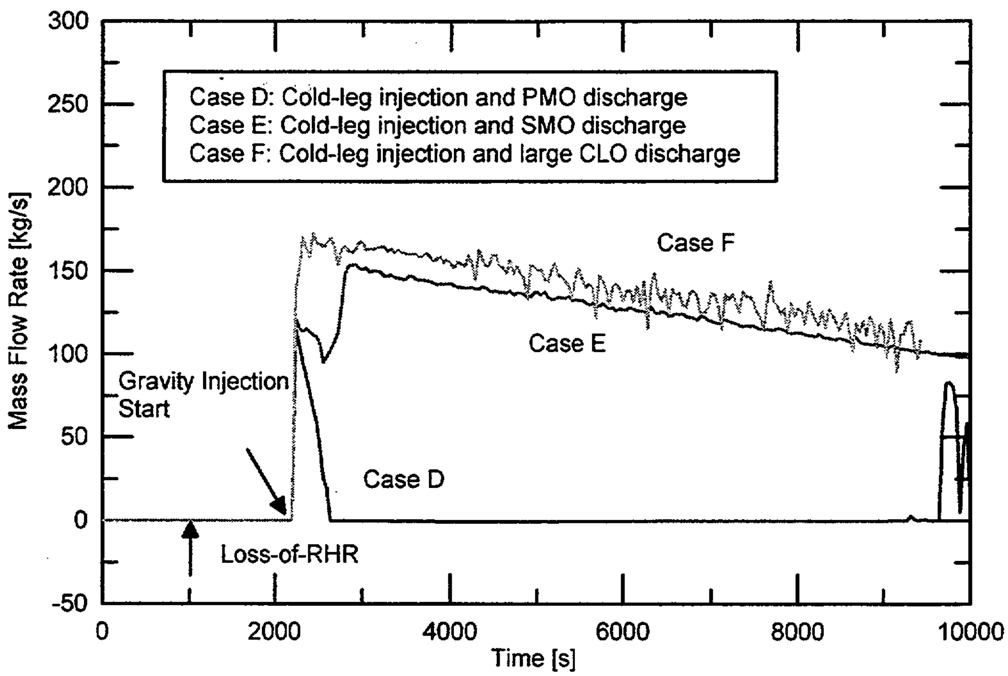

Fig. 27. Mass flow rate from the RWST (cases D, E and F)

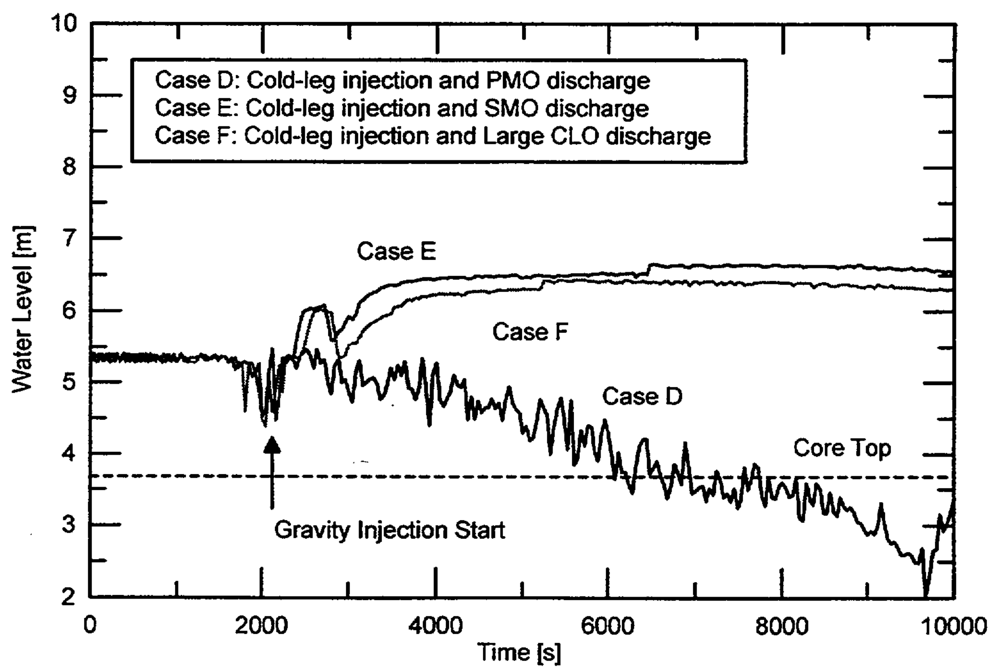

Fig. 28. Collapsed water level in the RPV (cases D, E and F)

IV.B.3. Discussion on the Gravity-Injection Path and Rate (GIPR)

From the above GIPR analysis, it is found that the gravity-injection flow rate is dependent on the differential elevation head between the RWST and the RCS water levels and the RCS opening size and location. However, in practice, the gravity flow can be constrained by the hydraulic resistance of the flow path, such as valves, flow orifices, or pumps. In addition, the injection flow rate can be throttled by operator for a proper cooling or RCS inventory control. In the present study, to determine the minimum flow rate needed to prevent core boiling after event, additional calculations are performed with varying the injection line size for the Case C with the hot-leg injection and CLO discharge. The range of injection line size is 5 up to 10 inches. The Case C was estimated to be the most suitable injection path to remove the decay heat after event in this transient analysis.

Figure 29 shows that the gravity-injection flow rate depends on the injection line sizes. As the line size reduces, the RWST injection rate decreases. In particular, more than 6 inches of the line size indicates a uniform injection flow for a long-term transient after gravity-injection. As above discussed, the reason is that the RCS inflow from the RWST is balanced with the RCS outflow through the opening. Figure 30 shows the stable discharging flow for more than 6 inches. However, for less than 5 inches diameter, the coolant in the core region continues boiling off because of the insufficient RCS inflow. Fig. 31 shows that the water temperature above the core region remains saturation condition despite of the gravity-injection. Eventually, it loses the gravity-injection flow at ~ 8000 s due to the system pressurization and the discharging flow is stopped after 9000 s.

As a result, it indicates that the injection line with more than 6 inches diameter is effective to keep the reactor coolant subcooled by the gravity injection. The injection rate corresponding to the 6 inches diameter averages about 54 kg/s. That is a minimum gravity-injection rate needed to prevent the core boiling after event. Based on the minimum injection rate and the nominal capacity of the RWST of the YGN 3/4, the injection duration, which could delay the core boiling, is estimated to be about 10.6 hours if 70% of the RWST water is available. It indicates that the gravity-injection using the RWST water is capable of providing the core cooling for a sufficient long-term transient for the Case C after the event. The results are similar to the Case E with the cold-leg injection and the SMO discharge, even not presented in this report.

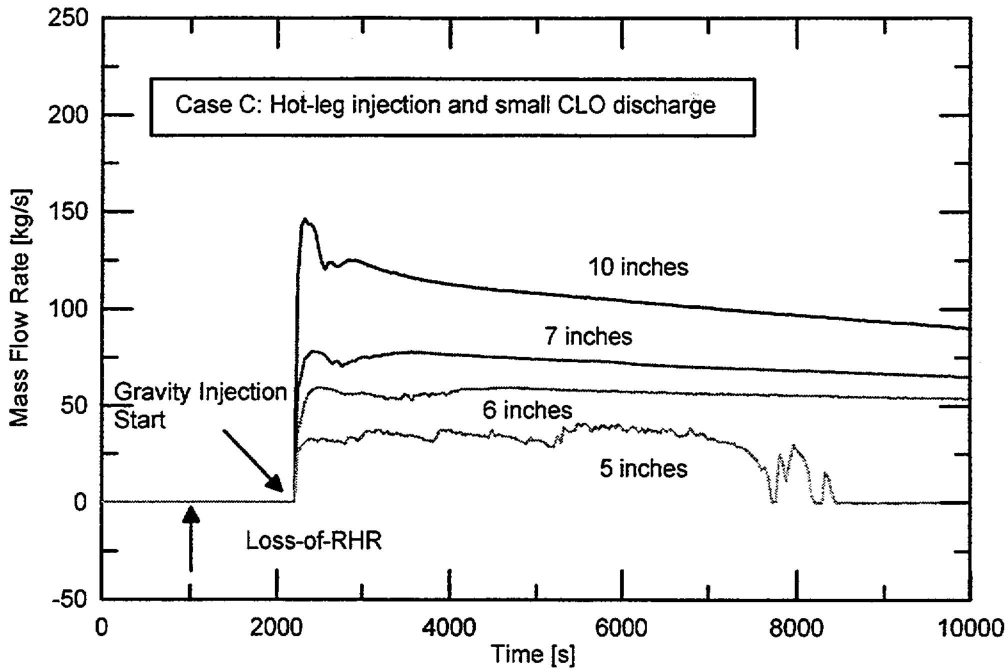

Fig. 29. Mass flow rate from the RWST (sensitivity)

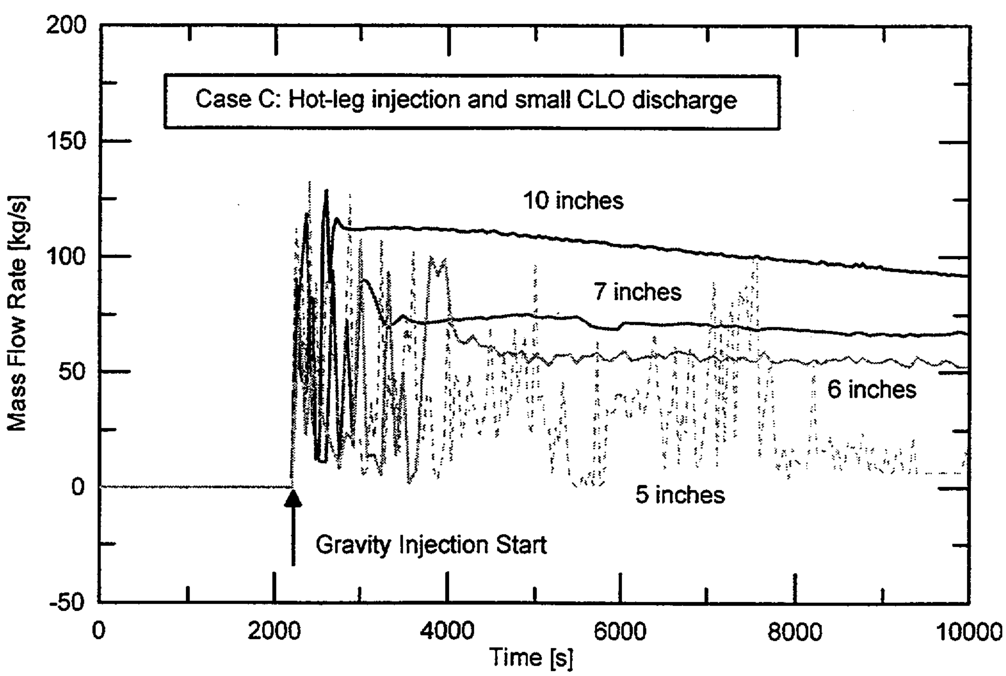

Fig. 30. Discharging flow rate through the opening (sensitivity)

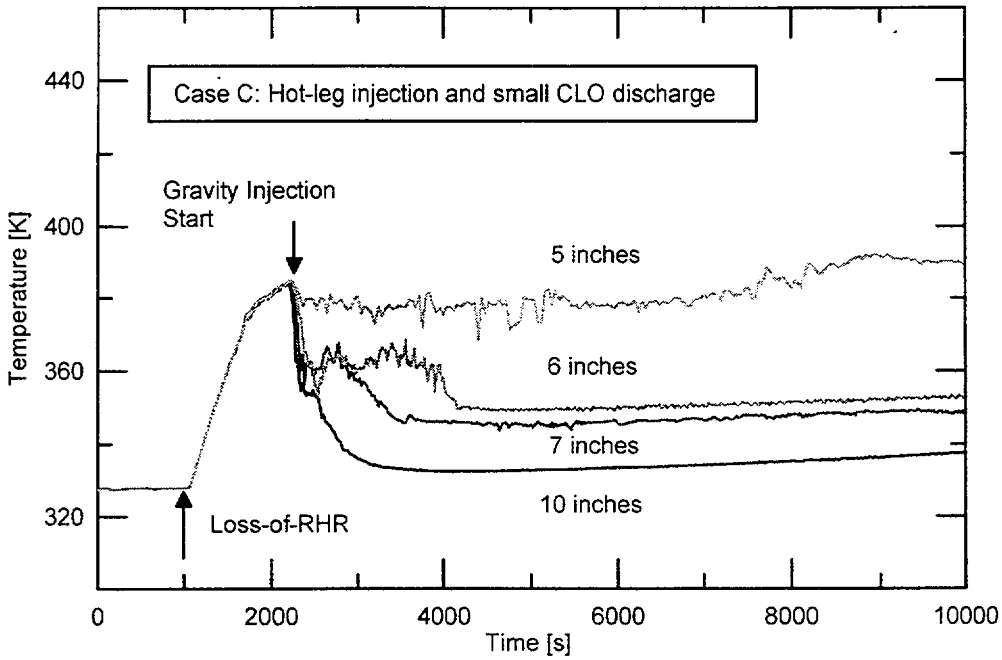

Fig. 31. Water temperature above the core region (sensitivity)

IV.B. Run Statistics

In the previous study on the assessment of RELAP5/MOD3.2 code with the LSTF experiment for the loss-of-RHR event, it was reported that the MOD3.2 version was capable of simulating the transient following the event with appropriate time step and CPU time [10, 11]. Even though there were some flow oscillations during boiling process in the core region, the major thermal-hydraulic phenomena such as a loop seal clearing, water holdup in the pressurizer, and a non-condensable gas migration were reasonably predicted with an appropriate computational time. In addition, the transient run was successfully performed without any failure. This plant application using the same code and modeling scheme as the LSTF simulation also gives a similar calculation characteristics.

Figure 32 shows the required CPU times for simulating the transient in case of pressurizer manway open. The LSTF case represents the CPU time for the previous transient calculation of the LSTF simulation, and the YGN 3/4 cases represent the Case 1 of the CCT analysis and Case A of the GIPR analyses, respectively. It indicates that the similar CPU time is required for all the transient calculation.

In addition, it was reported that the RELAP5/MOD3 code predicted too large system mass errors during the transient. In the previous calculation for the LSTF simulation, the mass error in the primary system was estimated about 90 ~ 100 kg for the transient of 2.8 hours, that was nearly 4% of initial coolant mass inventory. As similar to that, in the YGN 3/4 simulation, the mass error is estimated about 2,700 ~ 3,100 kg for the same duration, that is nearly 3% of initial coolant inventory. Figure 33 shows the estimated mass error behavior during the transient. It shows that the mass error is rapidly generated in the phase of coolant boiling and thereafter it gradually rises. Because the large mass error could significantly reduce the reliability of the calculation data, these mass errors should be reduced up to the negligible value. Thus, the efforts to reduce the system mass error are needed in the future to improve the reliability of the code.

The main computer used in the calculation was a DEC workstation 5000/240 with UNIX operating system. During the transient, it indicates that the CCT and GIPR analyses require the similar calculation time steps. Figure 34 shows the Courant time limit and advanced time step size for the Case A of GIPR analysis. The maximum time step is 0.1 s. It shows that the calculation is reasonably conducted with appropriate time steps below the Courant Limit. In this case, the required CPU time to simulate the transient of 10,000 s is 152,094.1 s including 10.4 s for input processing. For that time interval, the attempted advancement is 172,683 time steps. Then, the grind time can be calculated as follows. It will be 4.10 CPU msec/vol/step. This value is similar to that of the LSTF simulation, 3.673 ~ 4.036 CPU msec/vol/step.

- CPU time	CPU = 152,094.1 – 10.4 = 152,083.7 sec
- Number of time step	DT = 172,683 - 10,084 = 162,599
- Number of Volume	C = 228
- Transient Real Time	RT = 10,000 sec
- Grind Time	GT = CPUx1000/(CxDT) = 4.10 CPU msec/vol/step

As a result, it is found that the real plant simulation of the RELAP5/MOD3.2 version gives the similar calculation characteristics to the LSTF simulation of the loss-of-RHR event in the CPU time, calculation time step, and estimated system mass error.

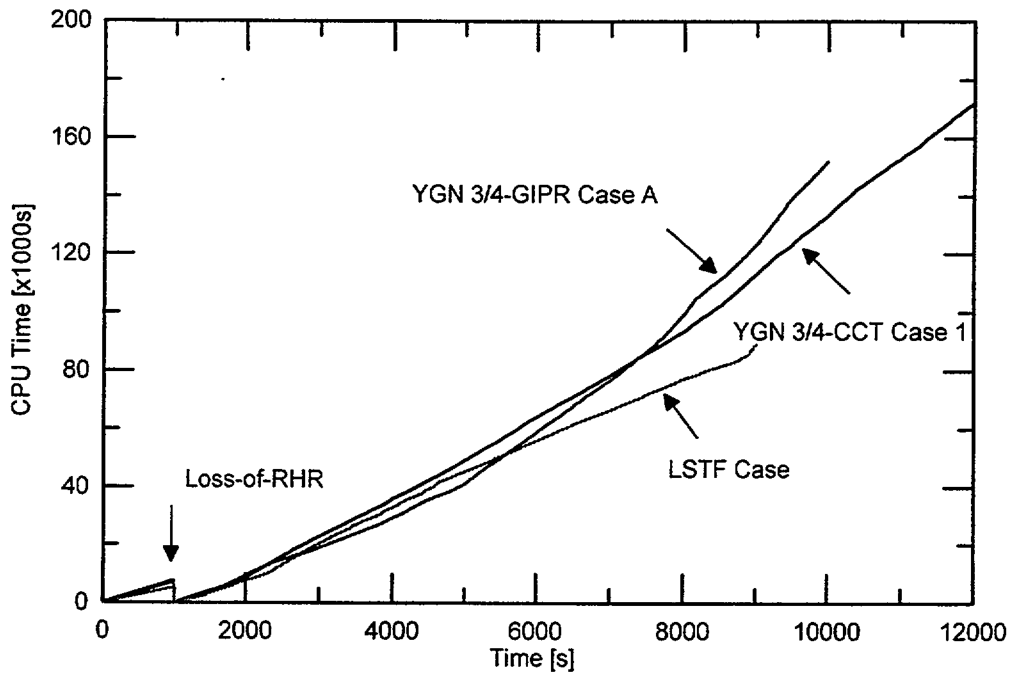

Fig. 32. Comparison of CPU time

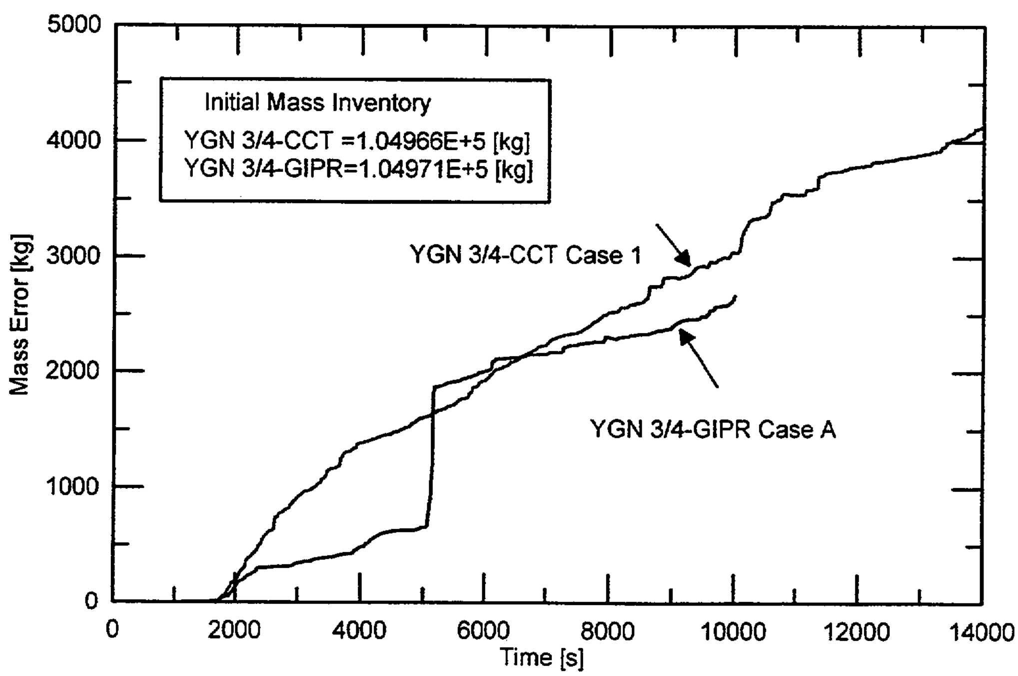

Fig. 33. Estimated mass error

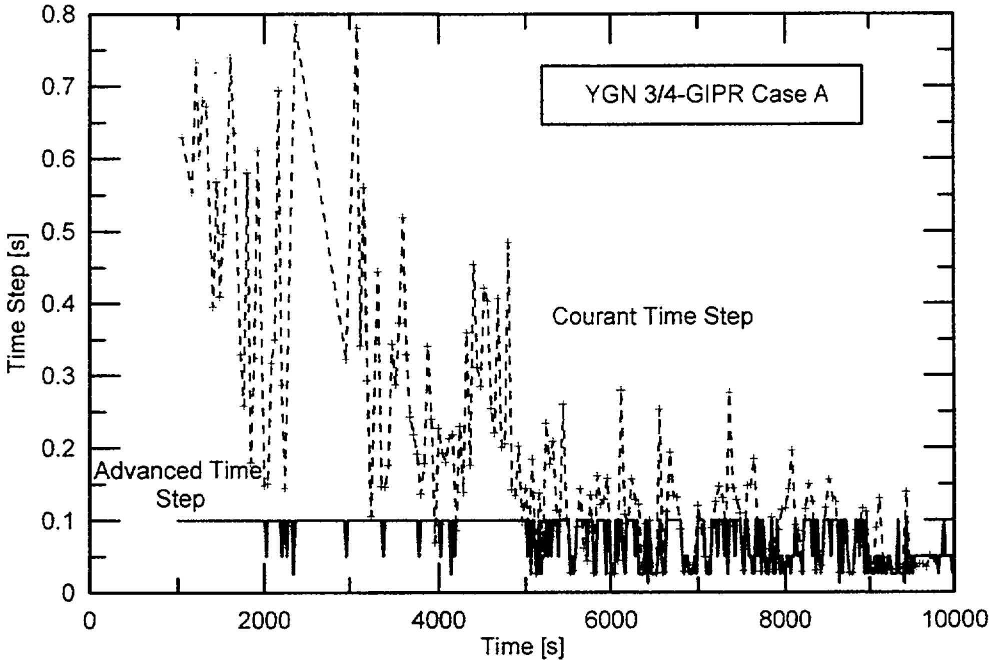

Fig. 34. Advanced time step (case A)

V. CONCLUSIONS

To investigate the mitigation measures following the loss-of-RHR event during reactor shutdown, the plant operating conditions of the Yonggwang Units 3 and 4 (YGN 3/4), PWR type of 2,815 MW thermal power in Korea, were reviewed. The possible event sequences were identified and the long-term transient analyses were performed using the standard version of RELAP5/MOD3.2 code. This analysis is finally to determine the containment closure time (CCT) to prevent the release of fission products to environment and the gravity-injection path and rate (GIPR) to effectively cool the core after event. The findings from the transient analysis can be summarized as follows:

(1) The loss-of-RHR event of the YGN 3/4 plant was analyzed using the RELAP5/MOD3.2 code and model which was assessed with the LSTF experiment in the previous study. As a result, the real plant simulation gives the similar calculation characteristics to the LSTF simulation in the required CPU time, computational time step, and system mass error. Thus, it was found that the RELAP5/MOD3.2 code was capable of appropriately simulating the loss-of-RHR event of the real plant.

(2) From the CCT analysis for the five cases of typical RCS configurations with no RCS makeup and unavailable secondary cooling, the time to boil after event was estimated to be about 10 to 13 minutes regardless of the opening size and location. Meanwhile, the time to core uncovery was estimated to be about 40 to 183 minutes depending on the elevation and size of the opening and the SG secondary water level condition. Particularly, in case with the water-filled SG, it was delayed about 100 minutes by the reflux condensation on SG U-tubes, as compared to the emptied SG case. However, it also indicated that the first core uncovery could occur in the early phase of the event by the loop seal clearing phenomenon in the crossover leg for the cold-leg opening case. As a result, it was found that the earliest CCT was 40 minutes after event for the SG-inlet-plenum-manway opening or the large cold-leg opening cases with the emptied SG. Besides, the containment closure is needed to initiate before the coolant boiling because the discharge via the opening after boiling could threaten the workers in the containment.

(3) From the GIPR analysis for the six possible gravity-injection paths from the RWST, the following conclusions were obtained. In cases with the PMO, located at higher elevation than

the RWST water level, the system pressure continued increasing due to the water holdup phenomenon in the pressurizer, and then the core was uncovered at about 96.6 minutes despite of the gravity-injection process. In cases with the injection point and opening on the same leg side, the core cooling was dependent on the core flow. For instance, as most of the water injected from the RWST bypassed the core region, the core cooling could not be effectively maintained. Meanwhile, in the cases with the injection point and opening on the different leg side, the RCS was well depressurized and the core boiling was successfully prevented for a long-term transient. As a result, these injection paths were estimated to be the most suitable paths in avoiding core boiling for a long-term period. In addition, about 54 kg/s of minimum injection rate was required to maintain core cooling. Such an injection rate was capable of providing the core cooling for about 10.6 hours if 70% of the RWST water was available.

(4) These results will provide useful information to operators to understand the plant behavior and to cope with the event in timely manners. However, to apply them to the emergency and recovery procedures against the loss-of-RHR event during shutdown operation, additional case studies are needed in the future for wide range of operating conditions such as RCS inventory, RWST water temperature, and core decay heat rate.

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Appendix A

Input Decks for the Steady State Calculation: Loss-of-RHR Event in Yonggwang Units 3 & 4 Plants

1) Input Deck for the CCT Analysis
2) Input Deck for the GIPR Analysis

(Not Included by the Proprietary Information)

Appendix B

Input Decks for the Transient Calculation: Loss-of-RHR Event in Yonggwang Units 3 & 4 Plants

1) Input Deck for the CCT Analysis
2) Input Deck for the GIPR Analysis

(Not Included by the Proprietary Information)

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

The long-term transient following a loss-of-residual-heat-removal (loss-of-RHR) event during reactor shutdown was analyzed to determine the containment closure time (CCT) to prevent the release of fission products to environment and the gravity-injection path and rate (GIPR) to effectively cool the core. The thermal-hydraulic analysis was carried out using the RELAP/5/MOD3.2 code and relevant modeling scheme, which was assessed with the LSTF experiment in a previous study (NUREG/IA-0143). Based on the plant-specific geometry data including various operating conditions, the possible event sequences were identified for the Yonggwang Units 3 and 4 plant (YGN3/4), which is CE-typed PWR of 2,815 MW thermal power in Korea. As a result, the real plant simulation gives the similar calculation characteristics to the previous LSTF simulation, and then it was found that the RELAP5/MOD3.2 code is capable of appropriately simulating the loss-of-RHR event of the real plant.

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