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Gravity-Injection Core Cooling After a Loss-of-SDC Event in the YGN Units 3 & 4

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Abstract

In order to evaluate the gravity-injection capability to maintain core cooling after a loss-of-shutdown-cooling event during shutdown operation, the plant conditions of the Yong Gwang Units 3&4 were reviewed. The six cases of possible gravity-injection paths from the refueling water tank (RWT) were identified and the thermal-hydraulic analyses were performed using the RELAP5/MOD3.2 code. The core cooling capability was significantly dependent on the gravity-injection path, the RCS opening, and the injection rate. In the cases with the pressurizer manway opening higher than the RWT water level, the coolant was held up in the pressurizer and the system pressure continued increasing after gravity-injection. The gravity injection eventually stopped due to the high system pressure and the core was uncovered. In the cases with the injection path and opening on the same leg side, the core cooling was dependent on whether the water injected from the RWT passed the core region or not. However, in the cases with the injection path and opening on the different leg side, the system was well depressurized after gravity-injection and the core boiling was successfully prevented for a long-term transient. In addition, from the sensitivity study on the gravity-injection flow rate, it was found that about 54 kg/s of injection rate was required to maintain the core cooling and the core cooling could be provided for about 10.6 hours after event with that injection rate from the RWT. Those analysis results would provide useful information to operators coping with the event.

Key Words : loss-of-shutdown-cooling event, gravity-injection core cooling, RELAP5/MOD3.2 code.

1. Introduction

A loss-of-shutdown-cooling event (loss-of-SDC event) during shutdown operation and refueling, often called a loss-of-residual-heat-removal event (loss-of-RHR event), has been experienced several times in pressurized water reactors (PWR) [1]. The typical examples of the loss-of-RHR event include a RHR pump failure during shutdown at Davis Besse plant in 1980, a loss of RHR flow during mid-loop operation at Diablo Canyon plant in 1987 [2], and a loss of ac power during refueling at Vogtle plant in 1990 [3]. The loss-of-RHR event by the RHR pump failure had been also experienced at Kori Units 2 and 3 in 1984 and 1987, respectively [4]. Although the plants were 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.

To understand the plant behavior after event, S. A. Naff, et al.[5] investigated the important thermal hydraulic processes and phenomena 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 reactor coolant system (RCS) using steam generators (SG) as a heat sink and the other is a gravity-injection cooling using water of the refueling water tank (RWT). 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, 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 outage. Because of the complexity and variety of the gravity-injection processes from plant to plant, an appropriate injection path and injection rate should be determined from the detailed thermal-hydraulic analysis based on the plant-specific conditions and configurations.

If the RHR capability is lost and alternate heat removal means cannot be established, the heat-up of the coolant leads to core boil-off, core uncovery, and core damage. In case that the RCS is open, the RCS coolant could be discharged into containment and threaten the personnel working in the containment. If there are also containment openings such as personnel or equipment hatches, an uncontrolled release of fission products to environment is possible in the early phase of the transient. K.W. Seul, et al. [6] studied the containment closure time determined from the time to boil and the time to core uncovery after event for various plant conditions. They revealed that the core could be uncovered within 42 minutes after event under the worst event sequence with no RCS makeup and unavailable secondary cooling, and then the containment must be closed within the time to prevent the release of fission products. However, if an alternate cooling scheme using a forced or gravity injection into the RCS is available, then the core boil-off and damage could be prevented or delayed for some time period. In the present study, the gravity-injection capability to maintain core cooling is evaluated as an alternate core cooling method after a loss-of-SDC event under shutdown operation of the Yong Gwang Units 3 & 4 (YGN 3/4). The plant conditions are reviewed to identify the possible gravity-injection paths following the event, and detailed thermal-hydraulic analyses are performed using the RELAP5/MOD3.2 code to investigate the plant responses. In addition, a sensitivity study on the gravity-injection flow rate is performed to investigate the minimum mass flow rate needed to prevent coolant boiling in the core region.

2. Possible Paths for the Gravity-Injection

2.1. Injection Paths from the RWT

When the RCS is open, two sources of borated water for the RCS cooling may be available without offsite assistance, i.e., the accumulators and the RWT. It is known that the gravity-injection from the accumulators is not a practical method because it is difficult to control manually the injection flow, even they could be pressurized by the gas [5]. Meanwhile, the gravity-injection from the RWT to the RCS could be an effective measure if there is a net positive differential pressure between the RWT and the RCS. In the YGN 3/4, the RWT water level during mid-loop operation is generally higher than the RCS water level. However, if the RCS water level is higher than about 30% of the pressurizer, the net positive elevation head for the gravity-injection could not be assured. Also, because the injection paths are generally long and complex, even fitted with various components such as flow-orifices, valves, pumps, or heat exchangers, the injection-gravity flow could be constrained by the hydraulic resistance. Then, it is important to identify the possible and effective injection paths for core cooling. The YGN 3/4 have multiple flow paths from the RWT 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 SDC system
- The hot leg injection path through SDC suction lines, etc.

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

2.2. Drain Paths out of the RCS

To maintain the gravity-injection into the RCS, the drain or vent path out of the RCS into the containment must be assured. Depending on the RCS configurations and operating states, the various openings could be used for the coolant drain or steam venting. Particularly, the RCS opening elevation relative to the RCS water level and the opening size were found to significantly affect the thermal hydraulic processes after event [5,6]. During shutdown or refueling of the YGN 3/4, the potential and prominent RCS openings are as follows:

- The pressurizer manway with 16 inches diameter
- The SG inlet/outlet plenum manways with 16 inches diameter in case without nozzle dams
- Three pressurizer safety valves with 6 inches diameter
- The hot leg, pressurizer, or vessel head vent lines with 3/4 to 1 inch diameter
- The cold leg side opening with 5 to 30% of the cold leg cross sectional area while a reactor coolant pump (RCP) seal or impeller is repaired.

Among the RCS openings, the highest elevation of the opening is about 17.6 m (58 ft) of the pressurizer manway above the centerline of the hot leg, and the lowest opening elevation is the cold leg opening. Also, the largest opening size is the manways in the SG inlet plenum or the top of the pressurizer except the opening of the reactor vessel head-off.

3. Thermal Hydraulic Analysis

3.1. Analysis Method

Based on the typical plant configurations, 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 injection, and three of large RCS openings as a RCS drain path, the pressurizer manway, the SG inlet plenum manway, and the cold leg opening. The six cases of the identified injection paths are as follows:

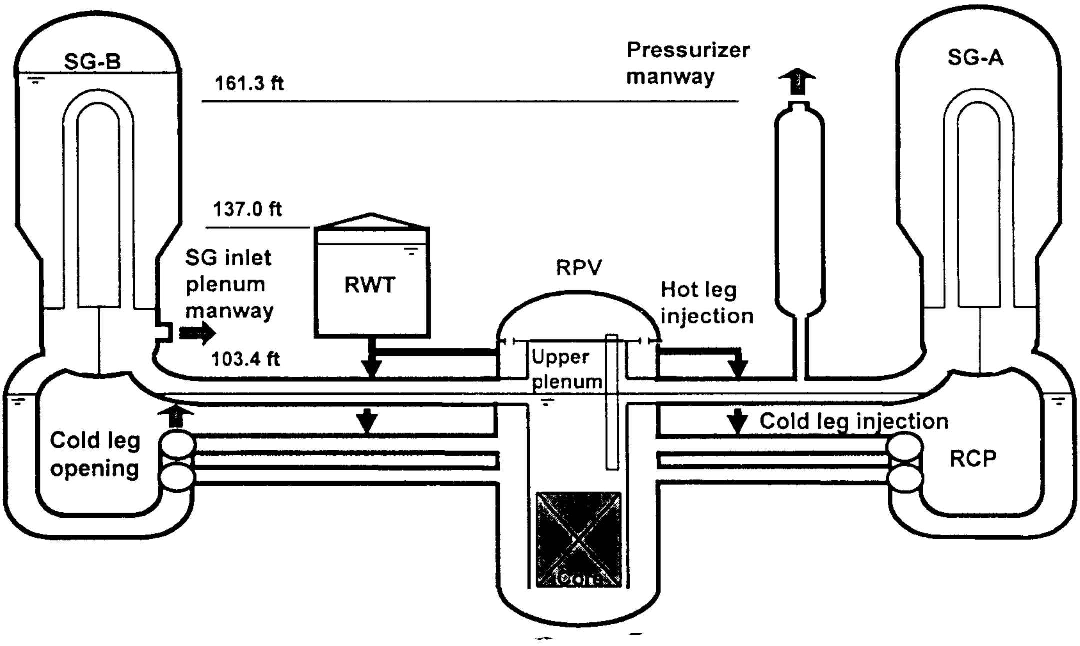

Fig. 1. Gravity-Injection Paths and RCS Configurations of the YGN 3/4

- Case A: the hot leg injection and the pressurizer manway open
- Case B: the hot leg injection and the SG inlet plenum manway open
- Case C: the hot leg injection and the small cold leg open
- Case D: the cold leg injection and the pressurizer manway open
- Case E: the cold leg injection and the SG inlet plenum manway open
- Case F: the cold leg injection and the large cold leg open

Figure 1 represents the possible gravity-injection paths and the locations of the RCS openings in the YGN 3/4 plant configurations.

In the YGN 3/4 design, the total of useful water volume of the RWT is 2,978 m^3(787,000 gal) [7]. When 70% of the RWT water is available during plant outage, the water level of the RWT is about 7.0 m(23 ft) above the hot leg centerline. The pressure and the water temperature in the RWT are assumed to be atmospheric and 307 K (93 °F), respectively. A diameter of the pipe from the RWT to the RCS injection point is assumed 25.4 cm (10 inches), based on the pipe diameter of safety injection system. In practice, the pipe size varies depending on the flow path, and 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 3.4. The plant is assumed to be in a mid-loop operation. The RCS water level is in the hot leg centerline and the SG secondary side is conservatively assumed empty. The major initial conditions used in calculation are represented in Table 1.

The system transient analysis code, the RELAP5/MOD3.2 recently released by the U.S. NRC [8], is used to analyze the plant transient.

Table 1. Initial Conditions for Transient Analysis

Major Parameters	YGN 3/4 Conditions
• Core power (3 days after reactor shutdown) [MWt]	• 14.125 (0.5% of full power)
• Primary and secondary pressures	• Atmosphere
• Hot leg, cold leg, and secondary water temperatures [K]	• 327.6, 313.1, and 313.1
• Water level in primary and secondary sides	• Mid-level of loop and emptied
• RWT water level and water temperature [K]	• 70% of full height and 307.0
• Initial mass inventory [kg]	• 104,618
• Pressurizer and SG plenum manways area [m^2]	• 0.13
• Cold leg opening area of 5% and 30% [m^2]	• 0.0228 and 0.1368

The code is run on a DEC 5000/240 workstation. The applicability of the code to the loss-of-SDC event under shutdown conditions was assessed in a previous study [9], which was based on the ROSA-IV/LSTF experiment simulating the loss-of-RHR event during mid-loop operation [10]. It revealed that the code was capable of simulating the major thermal hydraulic processes following the event with proper calculation time steps. The same models are used in the present analyses. The nodalization for the simulation of the event consists of 240 hydrodynamic volumes connected by 269 junctions and 228 heat structures. The steady state conditions for the six cases of transients are obtained from new transient run up to 1,000 seconds, and the loss of the SDC system occurs by isolating the SDC flow. The gravity-injection from the RWT is assumed to begin at 20 minutes after event, based on the typical operator action time.

3.2. Analysis Results for the Hot Leg Injection Cases

Figure 2 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. The SDC function is lost at 1,000 seconds and the gravity-injection from the RWT begins at 2,200 seconds. After the gravity-injection by the differential elevation head between the RCS and the RWT water levels, the Case A indicates a continuous pressure increase, but 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. 3, the gravity-injection flow for the Case A completely stops at about 550 seconds after gravity-injection, while the injection flow for the Cases B and C continues to remain high mass flow rates. In the Case A with the higher elevation opening than the RWT water level, the water injected from the RWT fills the hot legs, the reactor pressure vessel (RPV), and the surge line. Then, the system pressure again increases because the pressurizer opening is blocked by the water hold-up in the bottom of the pressurizer. Eventually, it makes the gravity-driven flow stopped when the pressure reaches about 172 kPa corresponding to the hydrostatic head of the elevation difference. After the gravity-injection flow is lost, the pressure further increases because the water in the core region continues boiling off and the water in the hot leg moves into the pressurizer. When the pressure reaches about 300 kPa at about 4,700 seconds, the water movement into the pressurizer nearly stops due to the emptied hot legs, and the two-phase mixture

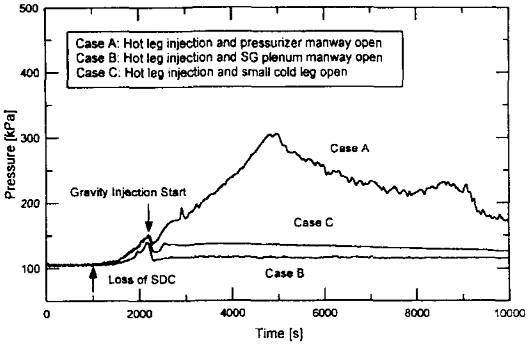

Fig. 2. Pressure Behavior in the Upper Plenum for the Cases A, B and C

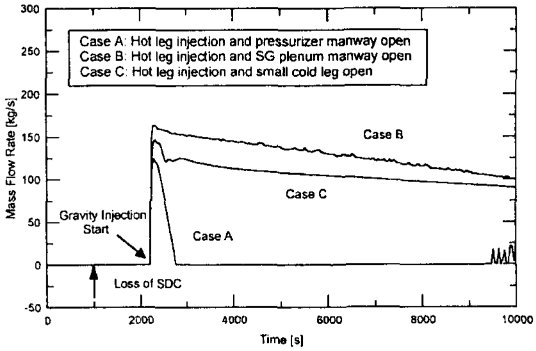

Fig. 3. Mass Flow Rates from the RWT for the Cases A, B and C

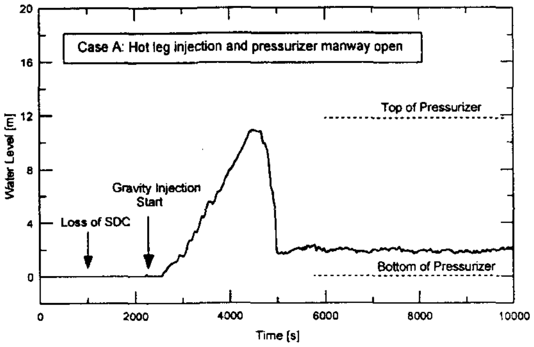

Fig. 4. Collapsed Water Level in the Pressurizer for the Cases A

begins to be discharged through the opening by the driving force of the high system pressure. Thereafter, the pressure moderately decreases. Figure 4 shows the water hold-up in the pressurizer after gravity-injection and the rapid reduction of the water level after discharging through the opening. Meanwhile, in the Cases B and C with the lower elevation openings than the RWT water level, the cold water of the RWT is well injected into the RCS and the RCS outflow through the opening is well established. Eventually, the system pressure remains atmospheric for a long-term transient after gravity-injection.

Figure 5 indicates the water temperatures above the core region. The coolant temperature increases shortly after the loss-of-SDC event. When the RWT cold water is injected into the RCS, the temperature immediately drops due to the mixing with the RCS hot water. Depending on the mixing effect, the water in the core region remains either a subcooled or a saturated condition. The Case A with the pressurizer manway opening, in which the discharging flow through the opening is blocked by the water hold-up in the pressurizer as previously discussed, indicates that it reaches saturation temperature within a short time after gravity-injection. Meanwhile, the Case C with the cold leg opening, in which the RWT cold water passes through the core region, remains low subcooled temperature. The Case B with the hot leg opening, in which part of the cold water passes the upper plenum of the RPV, also remains subcooled. 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 RWT water, but the core coolant is boiled off again in the Case A and then the gravity-injection is ineffective in avoiding core boiling.

Figure 6 shows the collapsed water levels in the RPV. The water level increases rapidly after gravity-injection for all cases. Thereafter, the water

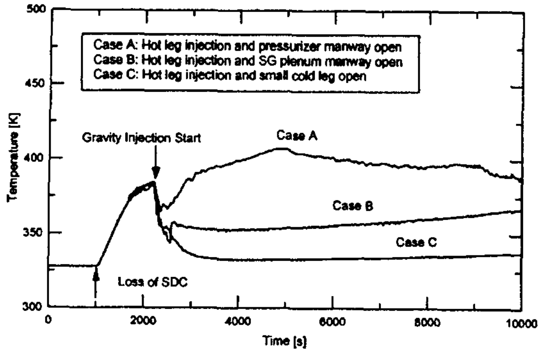

Fig. 5. Water Temperatures Above the Core Region for the Cases A, B and C

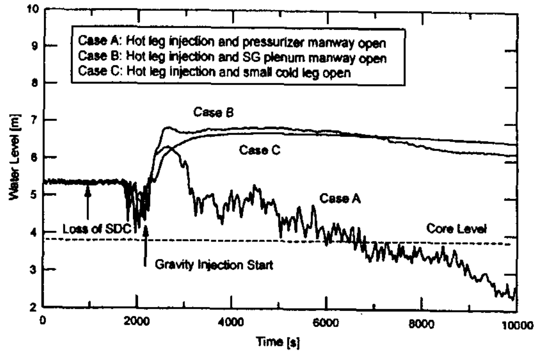

Fig. 6. Collapsed Water Level in the RPV for the Cases A, B and C

levels of the Cases B and C remain nearly constant due to the stable RCS inflow and outflow. However, the Case A indicates the decrease of the water level with some oscillatory behavior. 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. As discussed above, the two-phase mixture begins significantly discharging at about 4,700 seconds. The continuous discharging leads to reduce the water level below the top of the core, and then the core is uncovered after about 6,800 seconds, that is 96.6 minutes after event. As a result, the core would be damaged in the Case A due to the failure of the gravity-injection.

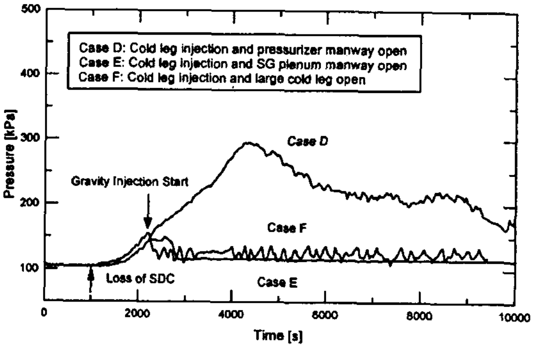

Fig. 7. Pressure Behavior in the Upper Plenum for the Cases D, E and F

3.3. Analysis Results for the Cold Leg Injection Cases

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. 7 and 8, the Case D with the pressurizer opening 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 about 500 seconds after gravity-injection, as shown in Fig. 9. Thus, the water level in the RPV decreases below the top of the core by the continuous discharge via the opening and the core is uncovered at the nearly same time as the Case A. These results indicate that the core cooling could not be maintained by the gravity-injection process, regardless of the injection path in the case of the pressurizer manway opening, because of the relatively higher elevation opening than the RWT water level.

The Case E with the SG inlet plenum opening shows that the pressure remains sufficiently low to maintain the injection rate as the Case C after

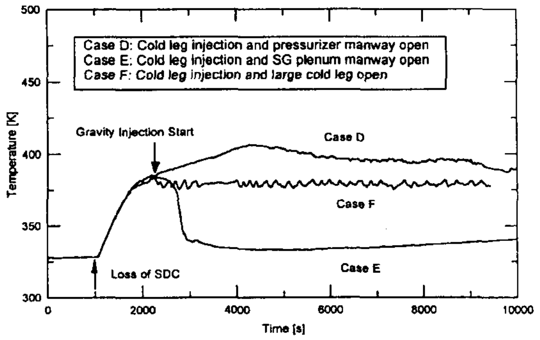

Fig. 8. Water Temperatures Above the Core Region for the Cases D, E and F

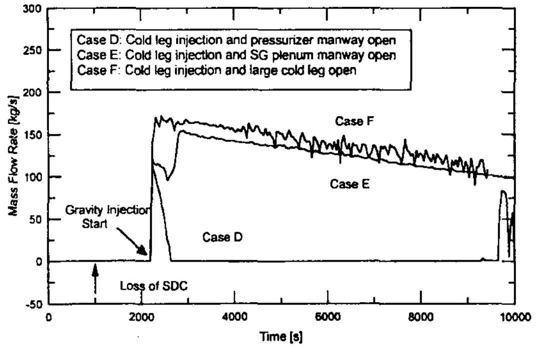

Fig. 9. Mass Flow Rates from the RWT for the Cases D, E and F

gravity-injection, as shown in Fig. 9. 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 are the most suitable gravity-injection paths to avoid the core boiling after event. It is because the water injected into the RCS from the RWT directly passes through the core region and successfully removes the decay heat.

The Case F with the cold leg opening also indicates low pressure as the Case B, but the water in the core region is saturated and boiled off after gravity-injection. It is because most of the cold water injected through the cold leg is directly discharged through the cold leg opening 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.

3.4. Sensitivity Study on the Gravity-Injection Flow Rate

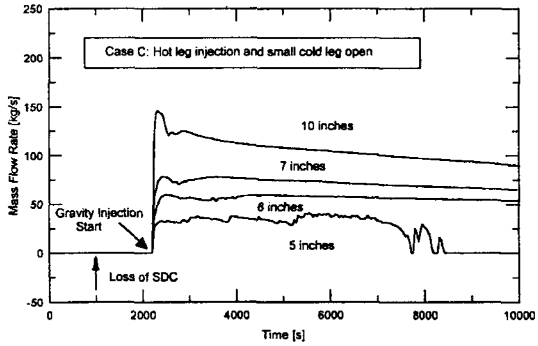

Fig. 10. Mass Flow Rates from the RWT for the Various Line Size

The gravity-injection flow rate is determined by the driving head and the resistance of the flow path through the injection lines and fittings, reactor core, and discharging paths to the containment. In other words, it is totally dependent on the differential elevation between the RWT and the RCS water levels, the pressure losses of the flow paths, and the RCS opening size and location. In addition, the gravity flow rate could be throttled by operator for proper cooling or inventory control of the RCS. In the present study, to determine the minimum flow rate needed to maintain core cooling after event, the calculation is run by varying the injection line size

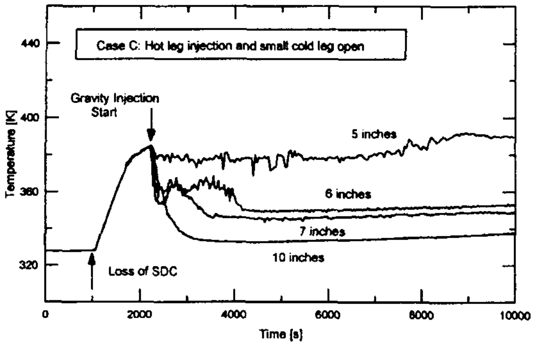

Fig. 11. Water Temperatures Above the Core Region for the Various Line Size

for the Case C with the hot leg injection and the cold leg opening. Figure 10 shows the gravity-injection flow rates depending on the injection line sizes, 5 inches up to 10 inches diameter. It indicates that the RWT injection rate decreases as the line size reduces. In particular, more than 6 inches of the line size indicates a uniform injection flow for a long-term transient after gravity-injection. The reason is that the RCS inflow from the RWT is balanced with the RCS outflow through the opening. However, for less than 5 inches of diameter, the coolant in the core region continues boiling off because of the insufficient RCS inflow from the RWT. Eventually, it loses the gravity-injection flow around 8,000 seconds due to the system pressurization. As shown in Fig. 11, the water temperature above the core region for the 5 inches diameter remains saturated condition after gravity-injection, whereas for more than 6 inches diameter it remains subcooled.

The injection rate corresponding to the 6 inches diameter averages about 54 kg/s. It is minimum gravity-injection rate needed to prevent the core boiling after event. Based on the minimum injection rate and the nominal capacity of the RWT, the injection duration which could delay the core boil-off is estimated to be about 10.6 hours if 70% of the RWT water is available. As a result, it indicates that the gravity-injection using the RWT water is capable of providing the core cooling for a sufficient long-term transient for the Case C after the loss-of-SDC event. The results are similar to the Case E with the cold leg injection and the SG inlet plenum manway opening, even not presented in this paper.

4. Conclusions

The gravity-injection capability to maintain core cooling was evaluated as an alternate core cooling method following a loss-of-SDC event under shutdown operation. Based on the typical plant conditions of the YGN 3/4, the six possible gravity-injection paths were identified and the termal-hydraulic analyses were performed using the RELAP5/MOD3.2 code to investigate the plant behavior following the event.

(1) For the cases with the pressurizer manway opening, located at higher elevation than the RWT, the RCS coolant was held up in the pressurizer and the system pressure continued increasing despite of gravity-injection. Eventually, the injection stopped and the core was uncovered after about 96.6 minutes after event. In the cases with the injection point and opening on the same leg side, the system was well depressurized by the gravity-injection, however, the core cooling was dependent on the core flow. For instance, in the case that most water injected from the RWT bypassed the core region, the core cooling could not be maintained effectively.

(2) For 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. It is because the cold water injected from the

RWT passed through the core region and removed effectively decay heat. As a result, these injection paths were evaluated to be most suitable in avoiding core boiling for the long-term period after event.

(3) From the sensitivity study on the gravity-injection flow rate, it was estimated that about 54 kg/s of the injection rate is required to maintain core cooling after event. It also indicated that the injection rate is capable of providing the core cooling for about 10.6 hours if 70% of the RWT water is available.

(4) These analysis results would provide an useful information on the gravity-injection path, flow rate, and duration to operators to cope with the event in a timely manner.

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