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Evaluation of the Gravity-Injection Capability for Core Cooling After A Loss-of-SDC Event

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In order to evaluate the gravity-drain capability to maintain core cooling after a loss-of-shutdown-cooling event during shutdown operation, the plant conditions of the Young Gwang Units 3&4 were reviewed. The six cases of possible gravity-drain paths using the water of the refueling water storage tank (RWST) were identified and the thermal hydraulic analyses were performed using RELAP5/MOD3.2 code. The core cooling capability was dependent on the gravity-drain paths and the drain rate. 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. However, in the cases with the injection path and opening on the cold leg side, the core coolant continued boiling although the system pressure remains atmospheric after gravity-injection because the cold water injected from the RWST was bypassed the core region. In the cases with the higher pressurizer opening than the RWST water level, the system was also pressurized by the water-hold in the pressurizer and the core was uncovered because the gravity-injection from the RWST stopped due to the high system pressure. In addition, from the sensitivity study on the gravity-injection flow rates, it was found that about 54 kg/s of RWST drain rate was required to maintain the core cooling. Those analysis results would provide useful information to operators coping with the event.

I. Introduction

Recently, a loss-of-shutdown-cooling event (a loss-of-SDC event), experienced several times during reactor shutdown operation in PWR plants [1,2], have been considered as an important safety concern [3]. In general, two types of operator actions are required to cope with the event in a proper time. One action is to restore a decay heat removal capability, including the recovery of SDC system and the alignment of injection flow path for core cooling. The other action is to protect personnel working in the containment and to prevent an uncontrolled release of fission products to atmosphere, including the evacuation of non-essential personnel from the containment and the closure of the containment. The operator action time could be determined from the results of thermal hydraulic analysis for the plant transient with various reactor coolant system (RCS) conditions. In a previous study, the containment closure time after event was estimated for typical plant conditions under the worst event sequence with no RCS makeup and unavailable steam generators (SG) [4]. It revealed that the core could be uncovered within 42 minutes after event, and then the containment must be closed within the time to prevent an uncontrolled release of fission products. In a present study, the gravity-drain capability to maintain core cooling are evaluated after a loss-of-SDC event under shutdown operation of the Young Gwang Units 3 & 4 (YGN 3/4). The plant conditions are reviewed to identify the possible gravity-drain pathways following the event, and the 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-drain flow rate is performed to investigate a minimum mass flow rate needed to prevent coolant boiling in the core region.

II. Possible Pathways for Gravity-Drain

II.1 Drain Paths from the RWST

Following the loss-of-SDC event, the gravity-drain of the cold water in the refueling water storage tank (RWST) could be a process with potential to delay core boiling and damage. If the RWST water level is sufficiently higher than the RCS water level, the hydrostatic elevation head forces the RWST cold water into the RCS and then the core cooling could be maintained for a long-term transient under a situation of the loss of SDC flow. However, there exist various flow paths between the RWST and the RCS, and some action time are required to make an alignment for the gravity-drain process. In the YGN 3/4, the possible and prominent paths for the gravity-injection are as follows;

- The cold leg injection path through a high pressure safety injection system or a charging and letdown system, with high hydraulic resistance
- The cold leg injection path through a SDC system, with moderate hydraulic resistance
- The hot leg injection path through a SDC suction line, with low hydraulic resistance, etc.

Because the injection flow paths are generally long and complex, and fitted with various components such as flow orifices, valves, pumps, or heat exchangers, the gravity flow is constrained by the hydraulic resistance. Among the possible flow paths, the hot leg injection path through a SDC suction line has relatively low resistance because there are no pumps and a few numbers of valves on the flow path. In addition, the gravity flow could be delayed if the accessibility to the local site to open a valve or supply ac power to control the valve is not ensured in a proper time.

II.2 Drain Paths out of the RCS

To maintain the gravity-injection flow into the RCS, a drain 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 coolant discharging or steam venting in a boiling phase. The effectiveness of the RCS drain path depends on the opening location relative to the RCS water level and the opening size. During shutdown operation 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
- The pressurizer safety or relief valves with 6 inches diameter
- The hot leg, pressurizer, or vessel head vent lines with 3/4 to 1 inches 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, etc.

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 size of the opening is the manways on the SG inlet plenum or the top of the pressurizer except the opening of the reactor vessel head-off.

III. Thermal Hydraulic Analysis

III.1. Analysis Method

Based on the typical plant configurations, the six cases of the gravity-drain paths are identified to evaluate the gravity flow behavior and the core cooling capability after event. Two gravity-injection lines, the cold leg and the hot leg injection, are available, and three of large RCS openings, pressurizer manway, SG inlet plenum manway, and cold leg opening, are considered as the RCS drain paths. Figure 1 represents the locations of the possible gravity-drain paths and the YGN 3/4 plant configurations.

- 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

In the YGN 3/4 design, the volume and height of the RWST are 3,271 m^3 (115,530 ft^3) and 10.7 m (35 ft), respectively. When the RWST water level is assumed 70 % of full height, it is about 7.0 m (23 ft) above the hot leg centerline. The pressure and the water temperature in the RWST are assumed to be atmospheric and 307 K (93 °F), respectively. A pipe diameter from the RWST to the RCS injection point is assumed 10 inches, based on the safety injection system line. In actual, the pipe size is varied depending on the flow path chosen and the gravity flow is constrained by a hydraulic resistance on the flow path. Thus, the sensitivity study on the gravity-injection flow rates is discussed in a separated section III.4. The plant is assumed to be in a mid-loop operation. The RCS water is in the hot leg centerline and the SG secondary side is conservatively assumed emptied. The major initial conditions are represented in Table 1.

The system transient analysis code, the RELAP5/MOD3.2 recently released by the U.S. NRC [5], is used to analyze the plat transient. 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 [6], which was based on the ROSA-IV/LSTF experiment simulating the loss-of-residual-heat-removal event during mid-loop operation [7]. It revealed that the code was capable of simulating appropriately 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 about 240 hydrodynamic volumes connected by 269 junctions and 228 heat structures. The steady state conditions are obtained from new transient run up to 1,000 seconds, and the loss-of-SDC event is initiated at that time by isolating the SDC flow. The gravity-injection is assumed to begin at 20 minutes after event, based on the typical operator action time.

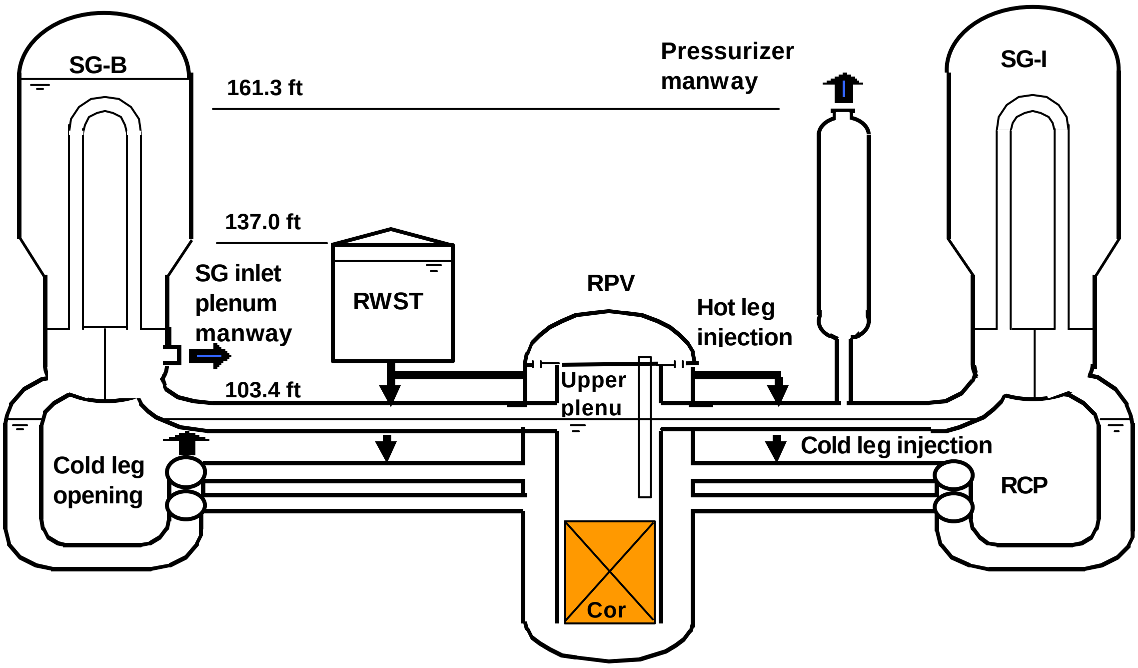

Fig. 1. Gravity-Drain Pathways and RCS Configurations of the YGN 3/4

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 temperature [K]	• 327.6, 313.1, and 313.1
• Primary and secondary water level	• Mid-level of loop and emptied
• RWST 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

III.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 RWST begins at 2,200 seconds. After the gravity-injection due to the differential elevation head between the RCS and the RWST water levels, the Case A indicates a continuous pressure increase, but the Cases B and C remain nearly constant. Such a difference of the pressure behavior is resulted from the different RWST drain 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 700 seconds after gravity-injection, while the injection flows for the Cases B and C continue to remain high mass flow rates. In the Case A with the higher elevation opening than the RWST water level, the RCS water directly moves toward the pressurizer and the water is held in the bottom of the pressurizer. The water-hold results in preventing the two-phase mixture from discharging through the pressurizer manway. Eventually, the system pressure continuously increases and it makes the gravity-driven flow stopped when the pressure reaches about 180 kPa corresponding to the hydrostatic head of the elevation difference. After the gravity-injection flow is lost, the pressure further increases because of the steaming in the core region. When the pressure reaches about 310 kPa at about 4,800 seconds, the two-phase mixture begins to be discharged through the opening by the driving force of the high system pressure. Thereafter, the pressure moderately decreases. Meanwhile, in the Cases B and C with the lower elevation openings than the RWST water level, the cold water injected into the RCS is well mixed with the hot water of the core region, and the RCS outflow through the opening is well established. Eventually, the system pressure remains atmospheric for a long-term transient after gravity-injection.

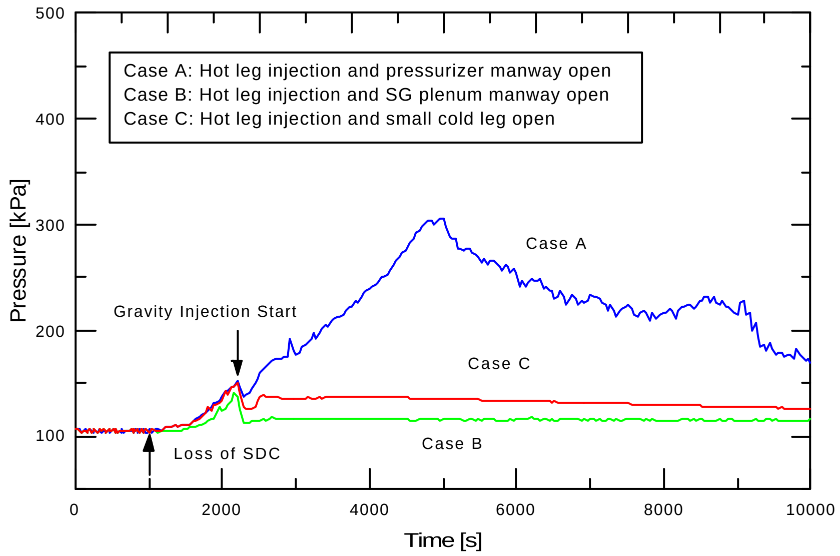

Fig. 2 Pressure Behavior in the Upper Plenum for the Cases A, B and C

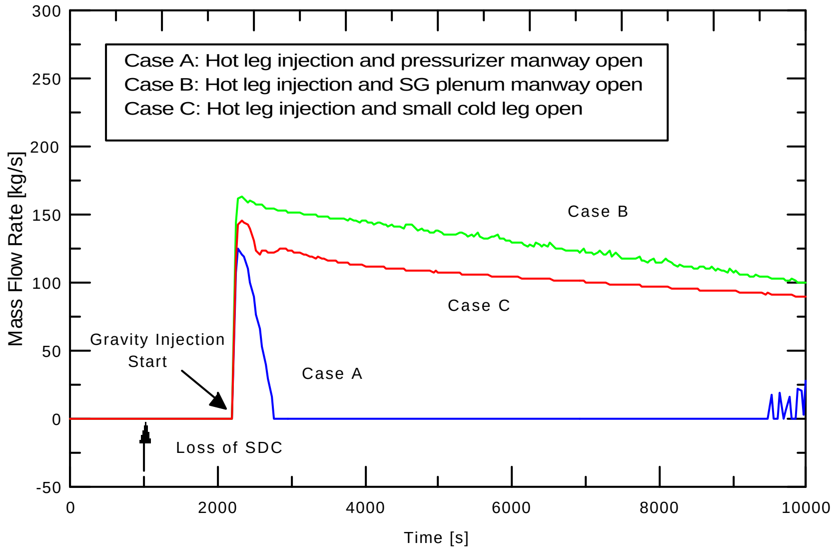

Fig.3 Mass Flow Rates from the RWST for the Cases A, B and C

Figure 4 indicates the water temperatures above the core region. The coolant temperature increases shortly after a loss-of-SDC event. When the RWST cold water is injected into the RCS, the temperatures immediately drop 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 in the pressurizer as previously discussed, indicates that it reaches a saturated temperature within a short time after gravity-injection. Meanwhile, the Case C with the cold leg opening that the RWST cold water passes through the core region remains a lower subcooled temperature than the Case B with the hot leg opening that only some of the cold water pass the upper plenum of the RPV. As a result, it indicates that the core boiling after event is prevented by the gravity-drain using the RWST water for the Cases B and C, but the core coolant is again boiled off even though the gravity-injection for the Case A.

Figure 5 shows the collapsed water levels in the RPV. The water level increases rapidly after gravity-injection for the all cases. Thereafter, the water level of the Cases B and C remains nearly constant with the stable RCS inflow and outflow. However, the Case A indicates the continuous decrease of the water level. The initially rapid decrease is due to the movement of the coolant toward the pressurizer, and the lately moderate decrease is due to the two-phase mixture discharging through the opening. As above discussed, the two-phase mixture begins significantly discharging through the opening at about 4,800 seconds, and then the water level decreases moderately from that time. The continuous discharging makes the water level reduced below the top of the core, and eventually the core is uncovered at about 6,800 seconds, that is 96.6 minutes after event.

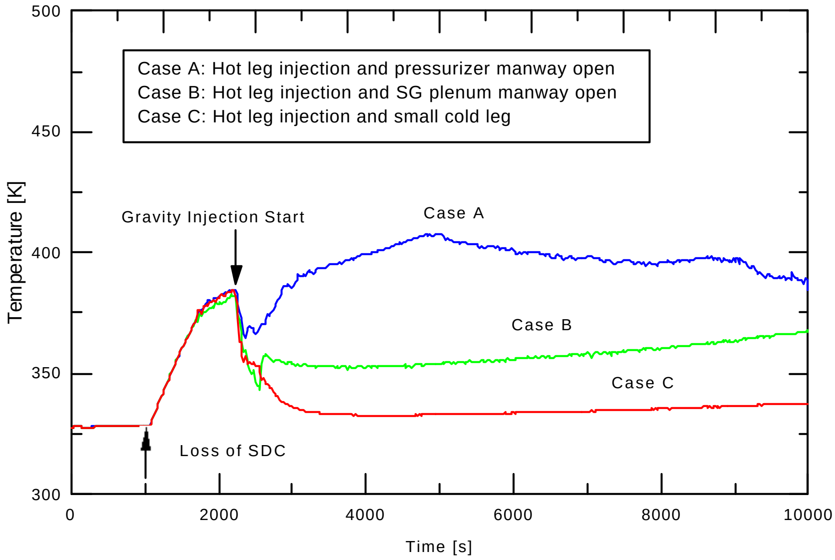

Fig. 4 Water Temperatures above the Core Region for the Cases A, B and C

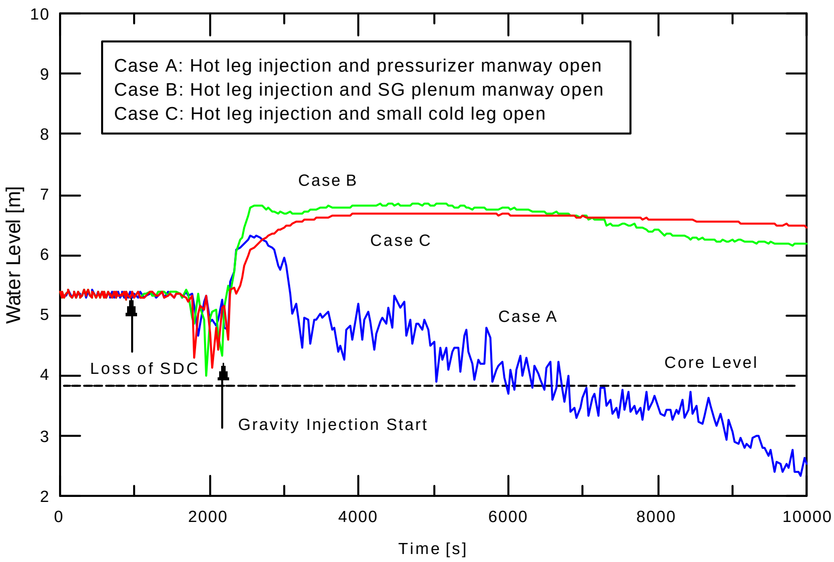

Fig.5 Collapsed Water Levels in the RPV for the Cases A, B and C

III.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 openings have the thermal hydraulic behavior similar to the cases of the hot leg injection. As shown in Figs. 6 and 7, the Case D with the pressurizer opening indicates that the system pressure continues to increase and the core is boiled off after gravity-injection. As similar to the Case A, the gravity flow completely stops within a short time after gravity-injection. Also, the water level in the RPV decreases below the top of the core by the continuous discharge through the opening, and then the core is uncovered at the nearly same time as the Case A.

The Case E with the SG inlet plenum opening indicates that the pressure remains sufficiently low to maintain the nearly same RWST drain rate as the Case C. The core is also successfully cooled for a long-term transient. As a result, the core boiling is prevented by the well-established RCS inflow and outflow. 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, some of the cold water passes the upper part of the core region. As a result, the core water of the Case F is saturated by the insufficient core flow.

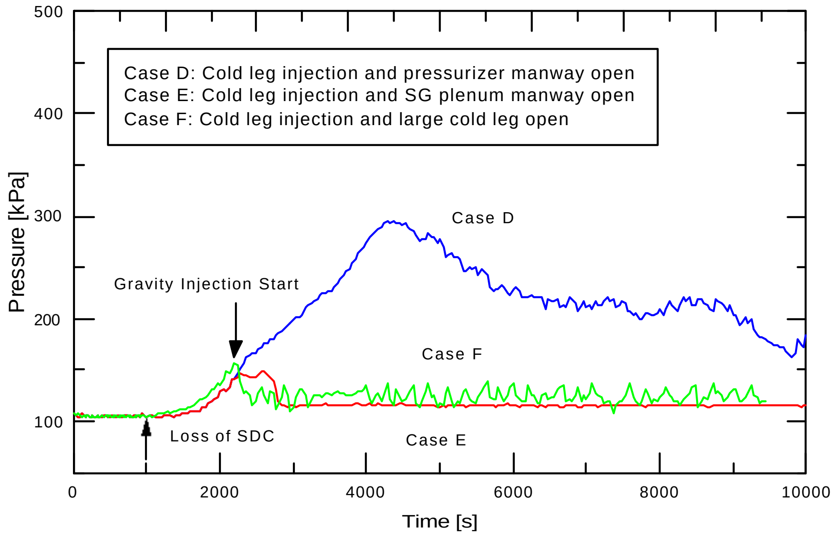

Fig.6 Pressure Behavior in the Upper Plenum for the Cases D, E and F

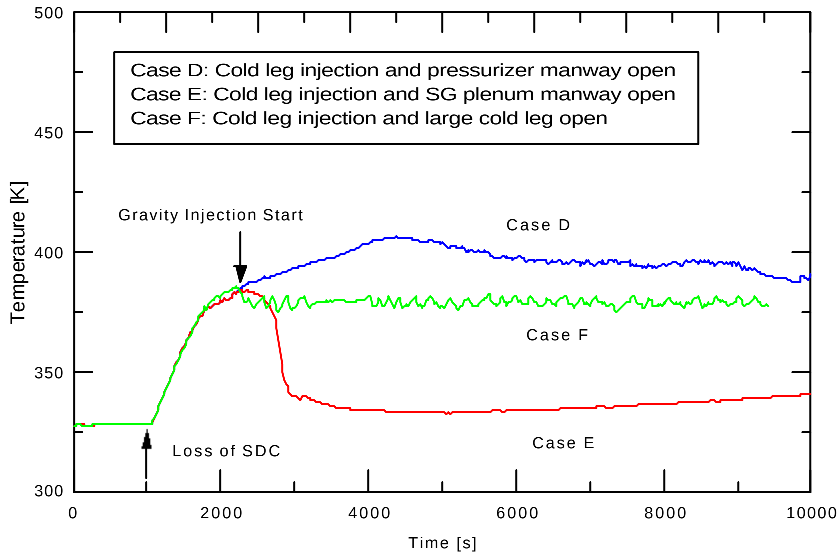

Fig. 7 Water Temperatures above the Core Region for the Cases D, E and F

III.4. Sensitivity Study on the Gravity-Injection Flow Rates

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. Therefore, it is totally dependent on the differential elevation between the RWST and the RCS water levels, the losses of the flow paths, and the RCS opening size and location. In order to determine the gravity-injection rate required to prevent core boiling after a loss-of-SDC event, the calculation is performed in varying the injection line size for a specific RCS configuration. Figure 8 shows the gravity-injection flow rates depending on the injection line sizes, 5 inches up to 10 inches diameter, for the Case C with the hot leg injection and the cold leg opening. It indicates that the RWST drain rate decreases as the flow area reduces. In particular, the more than 6 inches of the line size indicates a uniform injection flow for a long-term transient after gravity-injection because the RCS inflow from the RWST is balanced with the RCS outflow through the opening. However, for the less than 5 inches of diameter, the coolant in the core region continues boiling off because of the insufficient RCS inflow from the RWST. Eventually, it loses the gravity-injection flow around 8,000 seconds due to the system pressurization. As shown in Fig. 9, the water temperature in the RPV remains saturated condition after gravity-injection for the 5 inches diameter, while it remains subcooled for the more than 6 inches diameters.

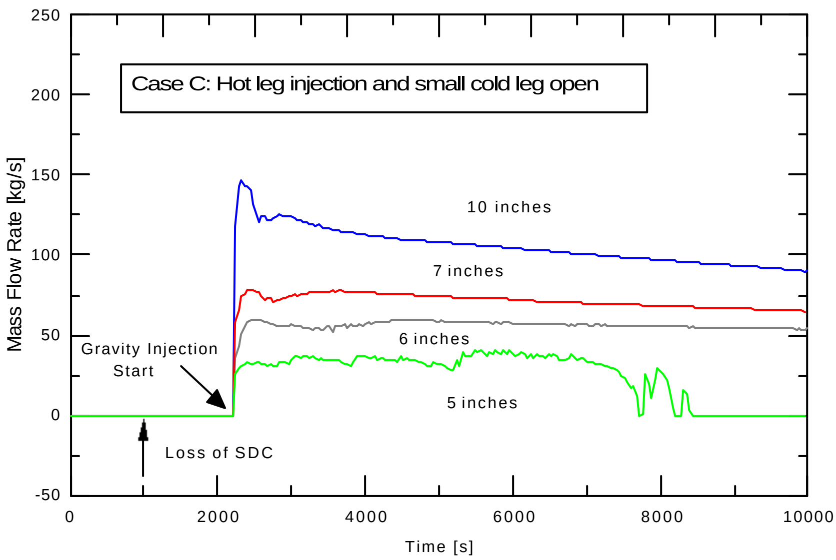

Fig.8 Mass Flow Rates from the RWST for the Various Line Size

The RWST drain rate corresponding to the 6 inches diameter is average about 54 kg/s. This mass flow rate is the gravity-injection rate needed to prevent the core boiling, which means a minimum mass flow rate for maintaining the core cooling after event. In addition, based on the minimum flow rate, the RWST drain duration which could delay the core boil-off is estimated to be maximum 11.5 hours if the 70% of the RWST water is assumed available. As a result, it can be found that the RWST drain is capable of providing the core cooling for a sufficient long-term transient for the Case C after the loss-of-SDC event. Also, in the calculation for the Case E with the cold leg injection and the SG plenum manway opening, the minimum mass flow rate and the gravity-drain duration are estimated to be nearly same.

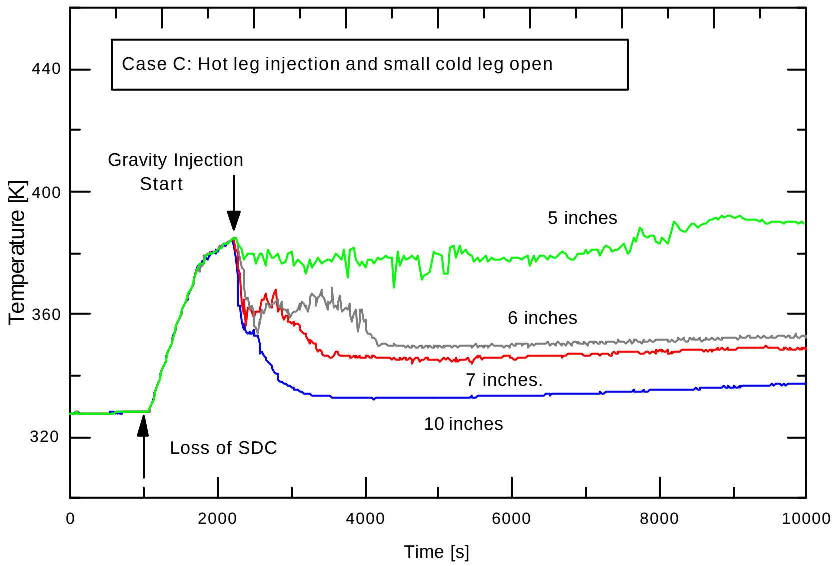

Fig.9 Water Temperatures above the Core Region for the Various Line Size

IV. Conclusions

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

(1) The Cases A and D with either the hot leg or the cold leg injection path along with the pressurizer opening; because of the high elevation of the opening relative to the RWST water level, the core coolant continues boiling after gravity-injection and then the system is pressurized continuously. The water is held in the pressurizer and the gravity-injection flow completely stops at about 700 seconds after gravity-injection. Eventually, the core is uncovered at about 96.6 minutes after event.

(2) The Cases B and F with the injection point and opening on the same leg side; the system is depressurized after gravity-injection. However, for the Case F, the core coolant is boiled because the cold water injected from the RWST is bypassed the core region. Meanwhile, for the Case B, the core boiling is prevented because some of the cold water are mixed with the hot water in the core region.

(3) The Cases C and E with the injection point and opening on the different leg side; the

system is well depressurized after gravity-injection and the core boiling is successfully prevented for a long-term transient. It is because the RWST cold water passes through the core region and uniformly flows out the RCS opening. As a result, these drain paths are evaluated to be suitable to avoid the core boiling for the long-term period after event.

(4) From the sensitivity study on the gravity-injection flow rates, it is estimated that about 54 kg/s of the RWST drain rate is required to maintain the core cooling for the Cases C and E after event. Also, it indicates that the RWST drain is capable of providing the core cooling for maximum 11.5 hours in the same cases.

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