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Containment Closure Time Following Loss of Cooling Under Shutdown Conditions of YGN Units 3&4

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Abstract

The YGN Units 3&4 plant conditions during shutdown operation were reviewed to identify the possible event scenarios following the loss of shutdown cooling. The thermal hydraulic analyses were performed for the five cases of RCS configurations under the worst event scenario, unavailable secondary cooling and no RCS inventory makeup, using the RELAP5/MOD3.2 code to investigate the plant behavior. From the analyses results, times to boil, times to core uncovery and times to core heat up were estimated to determine the containment closure time to prevent the uncontrolled release of fission products to atmosphere. These data provide useful information to the abnormal procedure to cope with the event.

I. Introduction

During shutdown conditions and refueling, the residual heat removal (RHR) system is used to remove the decay heat and a loss of decay heat removal (a loss of shutdown cooling (SDC) in CE-typed plant) has been a continuing problem because the possibility of the event is relatively high [1]. For example, the loss of RHR event was caused by RHR pump failure during mid-loop operation at the Diablo Canyon 2 plant in 1987, and the reliability of the decay heat removal capability was required to improve. In 1990, the loss of RHR event was occurred by a loss of vital ac power during refueling outages at the Vogle 1 plant and it was required to appropriately cope with the event during an extended period without any ac power. In YGN Units 3&4, Abnormal-45 Operating Procedure, "Actions Following Loss of SDC System", was developed in 1994 [2]. The procedure includes various mitigative procedures to restore the core heat removal and to protect workers from the uncontrolled release of fission products following the event. However, in order to take actions in a proper time for the RCS makeup or the containment closure, the plant behavior is necessary to be evaluated. The purpose of this study is to estimate the containment closure time following the event. To do this, the YGN Units 3&4 plant conditions during shutdown operation is reviewed to identify the possible scenarios following the event and the thermal hydraulic analyses are performed for the various RCS configurations using the RELAP5/MOD3.2 code to investigate the plant behavior.

II. Possible Scenarios Following the Loss of SDC Event

When a loss of SDC event occurs as an initiating event during shutdown operations, various event scenarios are possible according to operating states and plant conditions. If the RCS is assumed to be in reduced inventory or mid-level of the hot leg and the decay heat rate depending on the time after reactor shutdown is conservatively assumed, the possible and prominent event sequences would be identified as shown in Fig.1 [3]. Depending on the mitigative measures, 9 event sequences are possible. Some sequences show the successful removal of the core decay heat by recovery of the SDC (Seq.1), secondary cooling using available SGs (Seq.2), or feed-and-bleed and recirculation if needed (Seq.6 and 9). However, if the recovery of the SDC is delayed for a long time, the secondary cooling is not available by installation of nozzle dams or no auxiliary feedwater, and either the water feeding into RCS including long term recirculation (Seq.3, 5, 7 and 8) or steam bleeding to the RCS outside (Seq.4) are inoperable, then the core would be uncovered and damaged. Eventually, the fission products would be released through the RCS opening to the containment.

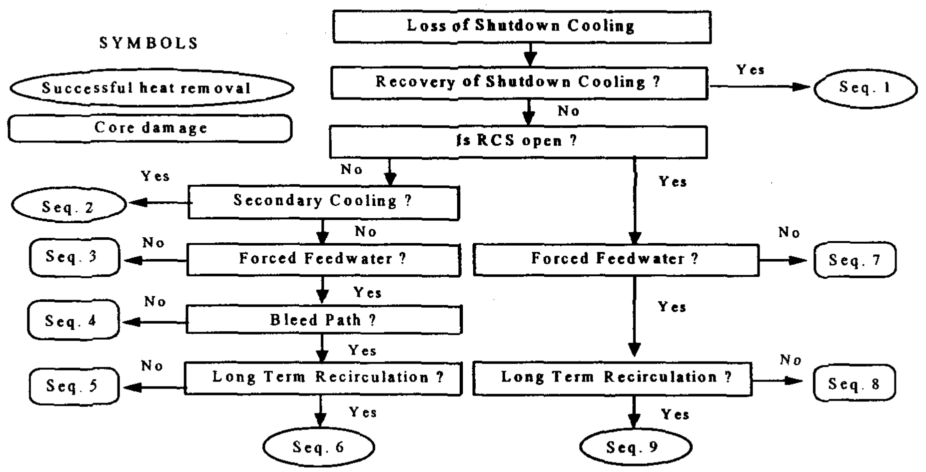

Fig. 1 Possible Scenarios Following the Loss of Shutdown Cooling Systems

The plant behavior following the event 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 is established if the opening size is sufficient. The closed RCS provides an additional fission product barrier and an ability to work in the containment for a longer time. Because the opening size and location affects significantly on the plant response to the event, two locations of the opening with the largest size in the hot leg side and two sizes of the openings in the cold leg side, 5 % and 30 % of cold leg cross area to simulate the RCP repair or SG outlet plenum manway, are analyzed in this analysis. Also, the water level in the SG secondary would has influence on the thermal hydraulic process in the RCS. Thus, based on the combination of the RCS openings and the SG secondary water level condition, five cases of RCS configurations are selected to analyze the plant behavior for the worst event sequence (Seq.7), unavailable SG secondary cooling and no RCS inventory makeup; Pressurizer manway open with water-filled SGs but no auxiliary feedwater (Case 1), Pressurizer manway open with emptied SGs (Case 2), SG inlet plenum manway open with emptied SGs (Case 3), Small cold leg open (Case 4) and Large cold leg open with emptied SGs (Case 5).

III. Thermal Hydraulic Analyses

The containment closure time is determined from time to boil and time to core uncovery or core heat up following the loss of SDC event. To analyze the thermal hydraulic behavior for the five cases of RCS configurations, the system transient analysis code, RELAP5/MOD3.2 is used on DEC 5240 workstation. The applicability of the code to the loss of SDC event under shutdown conditions was assessed in previous study [4] and it revealed that the code was capable of simulating appropriately the event and the thermal hydraulic processes including noncondensable gas behavior were reasonably predicted with proper calculation time step. The same code and models are used in these analyses. The initial conditions used in calculation are represented in Table 1 and the loss of SDC event is initiated at 1,000 seconds by isolating the SDC flow and by opening the manways or the cold leg opening.

Table 1. Initial Conditions and Assumptions for RCS Transient Analyses

Major Parameters	YGN Units 3/4 Conditions
• Core power (3 days after reactor shutdown) [kWt]	• 14,125 (0.5 % of full power)
• Primary / Secondary pressure	• atmosphere / atmosphere
• Hot leg / Cold leg / Secondary water temperature [K]	• 327.6 / 313.1 / 313.1
• RCS water level / Noncondensable gas	• mid-level of the hot leg / air
• Initial mass inventory [kg] / RHR flowrate [kg/s/loop]	• 104,618 / 126.0
• Pressurizer / SG plenum manways area [m^2]	• 0.13 / 0.13
• Cold leg open area of 5 % and 30 % [m^2]	• 0.0228 / 0.1368

1. Analysis Results for the Cases 1, 2 and 3

After the loss of SDC, the coolant temperature in the RPV begins to increase and the water boils off at a saturation temperature. The coolant boiling and steaming eventually pressurizes the upper plenum and the upper head. Figure 2 shows the pressure behavior in the upper plenum for the Cases 1, 2 and 3, in which the loss of shutdown cooling occurred at 1,000 seconds. The Case 1 shows moderate pressure increase throughout the transient except the early boiling phase and reaching a maximum value of 220 kPa at about 11,600 seconds, while the Case 2 shows rapid pressure increase in short interval after boiling and reaching a maximum value of 265 kPa at about 3,600 seconds. This difference on the pressurization rate is due to the primary-to-secondary heat transfer rate because the Case 1 with the water-filled SGs transfers more decay heat into secondary side by reflux condensation phenomenon on the SG U-tube wall than the Case 2 with the emptied SGs. More than 8 MW among the total of 14.125 MW core power was estimated to be removed throughout the transient. On the contrary, the Case 3 with the SG inlet plenum manway open shows relatively low system pressurization since the steam is discharged to the containment much earlier than that for the pressurizer manway open located at the relatively high elevation.

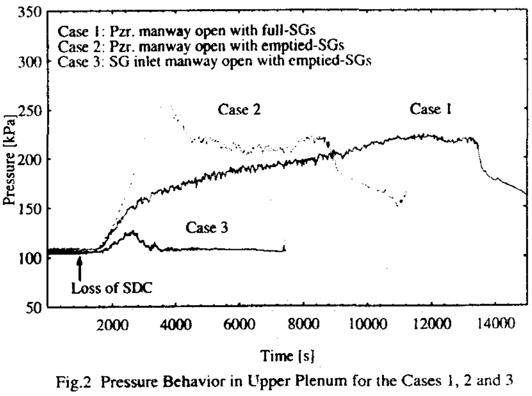

Fig.2 Pressure Behavior in Upper Plenum for the Cases 1, 2 and 3

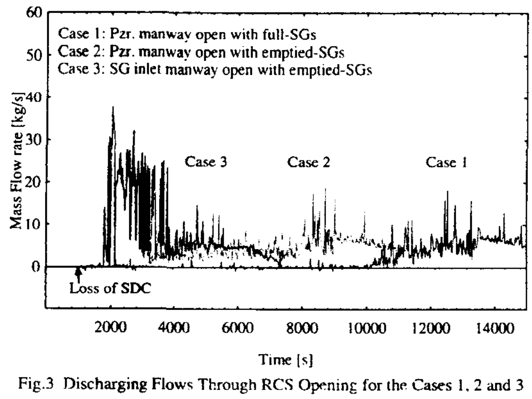

Fig.3 Discharging Flows Through RCS Opening for the Cases 1, 2 and 3

Figure 3 shows the different initiation times of the discharging flow through the opening. For the Cases 1 and 2 with the same opening and different secondary water condition, the significant discharging flow has a similar pattern just with a time delay, which is begun at about 10,400 seconds for the Case 1 and at about 3,200 seconds for the Case 2. It implies that the water-filled SGs, even though the auxiliary feedwater is not supplied, can delay the coolant discharging by about 2 hours. Also, for the Case 3 with the relatively low location of the opening, the liquid coolant is discharged much vigorously in the early phase of the event. The discharging is initiated from 1,800 seconds just after the boiling. It indicates that the coolant discharging is strongly dependent on the location of the opening as well as the SG secondary water level condition.

In addition to the coolant discharging, the water is held up by flooding phenomenon at the bottom of the pressurizer or at the vertically-inclined portion of the hot leg. Thus, the water level in the RPV decreases as shown in Fig. 4. The Case 3 shows the rapid decreasing of the water level due to the early discharging through the opening, while the Case 1 shows the remaining of the water level for a long time due to the late discharging after it's initial decrease by the liquid hold up in the bottom of the pressurizer. When the water level is reduced to the top of the core, the core uncovery is initiated. As shown in Fig. 5, the time to core uncovery was estimated to be about 11,200 seconds after the event for the Case 1, about 5,600 seconds for the Case 2, and about 2,600 seconds for the Case 3. Also, the core heat up is initiated over 2,000 seconds after the core uncovery. As a result, the Case 2 with the emptied SGs indicates 93 minutes earlier core uncovery than the Case 1 with the water-filled SGs. The Case 3 with the cold leg open indicates 55 minutes earlier core uncovery than the Case 2 with the pressurizer manway open. These results indicates that the core damage time after the event is significantly affected by the SG secondary water level condition and the elevation of the opening as well as the initiation of the coolant discharging.

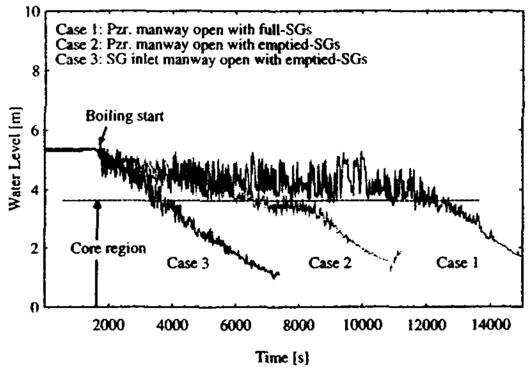

Fig. 4 The Collapsed Water Levels in RPV for the Cases 1, 2 and 3

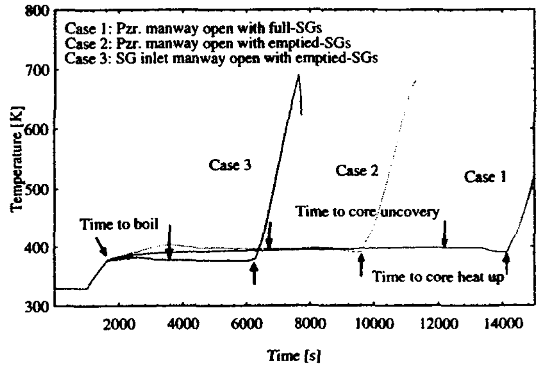

Fig. 5 Fuel Cladding Temperatures for the Cases 1, 2 and 3

2 Analysis Results for the Cases 4 and 5

The Cases 4 and 5 simulating the cold leg openings show some different system behaviors with the cases simulating the openings of the hot leg side. The reactor coolant in the cold leg begins to discharge through the opening before the boiling because the elevation of the opening is relatively low. After the boiling, the pressure in the upper plenum rapidly increases as shown in Fig. 6 and eventually the pressure difference between the hot leg side and the cold leg side becomes increasing. The high differential pressure expels the coolant in the crossover leg and the RPV toward the cold leg with the opening and the coolant is rapidly discharged to the containment. Thus, the water level in the downside of the crossover leg drops to the bottom of the leg and the water level in the RPV decreases below the top of the core in the early phase of the boiling as shown in Fig. 7. When the pressure reaches a maximum value, 147 kPa for the Case 4 and 130 kPa for the Case 5, the water in the upside of the crossover leg is immediately cleared, which is called loop seal clearing (LSC), and the pressure in the upper plenum drops simultaneously to the cold leg pressure. The pressure drop quickly restores the water level in the RPV because the compression force in the gas portion above the water in the RPV is disappeared. These LSC phenomenon and the restoration of the RPV water level were also found in H. Nakamura and Y. Kukita's experiments simulating the same event [5]. In addition, the experiment indicated a local core heat up at the top part of the core by the rapid decrease of the RPV water level. However, the calculation did not predict the local phenomena because the core is modeled as an averaged volume. Anyway, the cold leg opening causes the large amount of the discharging flow and the instantaneous core uncovery in the early phase of the boiling and, just after the LSC, the discharging flow is dropped to nearly zero and the core is recovered.

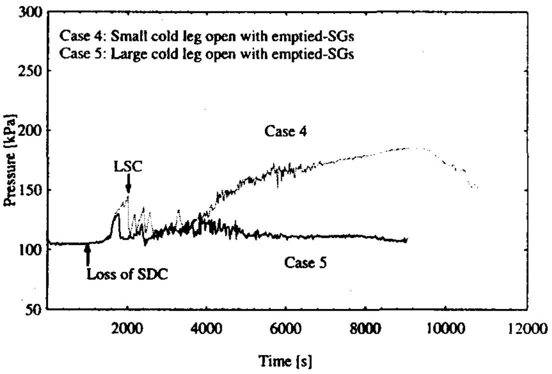

Fig.6 Pressure Behavior in Upper Plenum for the Cases 4 and 5

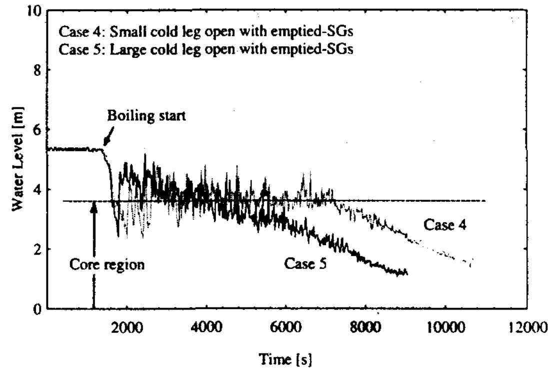

Fig. 7 The Collapsed Water Levels in RPV for the Cases 4 and 5

Due to the continuous steaming, the pressure in the upper plenum increases again, especially predicting high pressurization rate for the Case 4 with the small opening. As the RCS is again pressurized, the steam is discharged through the opening and the water level in the RPV continues to decrease. Eventually, the core is uncovered again at about 5,200 seconds after the event for the small open case and about 2,800 seconds for the large open case. The core heat up is initiated much late over one hour after the core uncovery because the pressurization rate is relatively low after the LSC. As a result, the calculation indicates that the first core uncovery occurs at around 1,600 seconds for very short time interval with regardless of the size of the cold leg open, but the core heat up does not occur because the collapsed water level is not enough low to cause the core heat up. However, the second core uncovery time was significantly dependent on the size of the opening.

IV. Time Available for Mitigation after the Loss of SDC Event

From the above thermal hydraulic analyses results for the five cases of RCS configurations, the time to close the containment after the event can be determined. Table 2 represents the times to boil, the times to core uncovery, and the times to core heat up and the some cases were compared with the available data of the CE-typed PWR [6]. In general, the containment closure should be achieved at least before the time to core uncovery following the event to prevent the uncontrolled release of fission products to atmosphere. Thus, if the maintenance activities are performed with a large opening on the hot leg side such as the SG inlet manway or on the cold leg side such as the removal of the RCP impeller assembly, then the containment closure should be achieved within about 46 minutes after the event for the worst event scenario. However, if SG secondary is filled with water, the achievement of the containment closure could be significantly delayed, by 187 minutes for the pressurizer manway open. Also, the containment closure is necessary to be initiated before the time to boil because the steam with high enthalpy begins to discharge through the opening after the boiling time. The discharging flow could include the radiological materials since the core is instantaneously uncovered and damaged in the early phase of the boiling as the case of the cold leg opening. Therefore, if the containment closure is initiated after the boiling time, it is necessary to evaluate the in-containment environment and the ability of personnel to work in that environment to perform the necessary containment closure operations.

Table 2. Results of Thermal Hydraulic Analyses for YGN Units 3&4

RCS openings (units: minutes)	Time to boil	Time to core uncovery	Time to core heatup
• Pzr manway open with water-filled SGs (C1)	12.5	186.7	220.0
• Pzr manway open with emptied-SGs (C2)	12.3	91.7	144.0
• SG inlet manway open with emptied-SGs (C3)	13.2	41.7	88.3
• Small cold leg open with emptied-SGs (C4)	10.2 (13.6)*	68.3 (91.5)*	131.0
• Large cold leg open with emptied-SGs (C5)	9.8 (13.6)*	45.8 (59.9)*	116.3

* CE typed-PWR data [6], Pzr : Pressurizer, C1: Case 1

V. Conclusions

The YGN Units 3&4 plant conditions during shutdown operation were reviewed to identify the possible event scenarios following the loss of SDC. The thermal hydraulic analyses were performed for the five cases of RCS configurations under the worst event sequence, unavailable secondary cooling and no RCS inventory makeup, using the RELAP5/MOD3.2 code to investigate the plant behavior to determine the containment closure time. These results could provide useful data to the abnormal procedure to cope with the event.

1) Time to boil was estimated to be about 10 to 13 minutes with regardless of the location and size of the opening because it is dependent on the decay heat load and the mass inventory in the RVP.

2) Times to core uncovery were significantly affected with the location and size of the opening and the thermal hydraulic process. The water-filled SG secondary delayed the core uncovery due to the reflux condensation on the SG U-tube wall and the SG inlet manway open caused the earlier core uncovery than the pressurizer manway open located at the relatively high elevation. The large opening of the cold leg was initiated earlier than the small opening.

3) The containment closure should be achieved within 46 minutes after the event for the worst case If the SG secondary is filled with water, it is delayed by 187 minutes for the pressurizer manway open. In addition, if the containment closure is initiated after the boiling time, it is necessary to evaluate the in-containment environment and the ability of personnel to close the containment.

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