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Containment Closure Time Following the Loss of Shutdown Cooling Event 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 (SDC) event. For the five cases of typical reactor coolant system (RCS) configurations under the worst event sequence, such as unavailable secondary cooling and no RCS inventory makeup, the thermal hydraulic analyses were performed using the RELAP5/MOD3.2 code to investigate the plant behavior following the event. The thermal hydraulic analyses include the estimation of time to boil, time to core uncovery, and time to core heat up to determine the containment closure time to prevent the uncontrolled release of fission products to atmosphere. The result indicates that the containment closure is recommended to be achieved within 42 minutes after the loss of SDC for the steam generator (SG) inlet plenum manway open case or the large cold leg open case under the worst event sequence. The containment closure time is significantly dependent on the elevation and size of the opening and the SG secondary water level condition. It is also found that the containment closure needs to be initiated before the boiling time to ensure the survivability of the workers in the containment. These results will provide useful information to operators to cope with the loss of SDC event.

1. Introduction

During hot shutdown operation, the decay heat is generally removed by dumping steam to main condenser or to atmosphere and restoring inventory in steam generators (SGs) with auxiliary feedwater (AFW) system. Because of the relatively high reliability of AFW system, loss of the decay heat removal has infrequently occurred. However, during cold shutdown operation and refueling, the decay heat is removed by the residual heat removal (RHR) system. The loss of decay heat removal has been a continued safety concern because of the relatively high possibility of the event [1,2]. For example, the loss-of-RHR events, which caused by RHR pump failure during mid-loop operation at the Diablo Canyon 2 plant in 1987 [3] and by a loss of vital ac power during refueling at the Vogtle 1 plant in 1990 [4], resulted in requiring to improve the reliability of the decay heat removal system and to cope appropriately with the event [5]. Also, the loss-of-RHR event caused by RHR pump failure during mid-loop operation and refueling had been experienced at KORI Units 2 and 3 in 1984 and 1987, respectively [6].

During shutdown operation and refueling, there are three events considered as initiating events leading to core damage; loss of RHR event (loss of shutdown cooling event in CE-typed plant), loss of inventory event, and loss of offsite power event. The loss of inventory event could be caused by two dominant contributors, overdrain while going to reduce inventory and failure to maintain a water level during reduced inventory such as mid-loop operation. The loss of inventory would eventually lead to the loss of shutdown cooling (SDC) flow. The loss of offsite power would also cause a failure of the SDC system. As a result, the loss of SDC event is considered as the most serious initiating event during shutdown operation. In particular, because the event would lead quickly to bulk boiling and core uncovery if the shutdown cooling is not restored in a proper time, it is required an evacuation of the personnel working in the containment and a fast containment closure to prevent the uncontrolled release of the radiological materials to atmosphere. Therefore, the plant behavior after the event should be analyzed in detail to take actions in a proper time to mitigate the event.

The purpose of this study is to estimate the time to close the containment following the loss of SDC event under shutdown operation. In general, the containment closure time is dependent on the plant configurations and operating states and thermal hydraulic processes in the reactor coolant system (RCS). Thus, the YGN Units 3&4 plant conditions during shutdown operation are reviewed to identify the possible event scenarios following the event and the thermal hydraulic analyses are performed for various RCS configurations using the RELAP5/MOD3.2 code to investigate the plant behavior following the event. The thermal hydraulic analyses include the estimation of time to boil, time to core uncovery and time to core heat up following the event to determine the containment closure time to prevent the uncontrolled release of fission products to atmosphere.

2. Possible Event Scenarios Following the Loss of SDC Event

2.1. Identification of Possible Event Sequences

If a loss of SDC occurs as an initiating event during shutdown operation, various scenarios following the event are possible according to operating states and plant conditions. Depending on the mitigation measures following the event, nine possible and prominent event sequences could be identified as shown in Fig. 1 [7]. If the SDC 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 SDC 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 make up 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

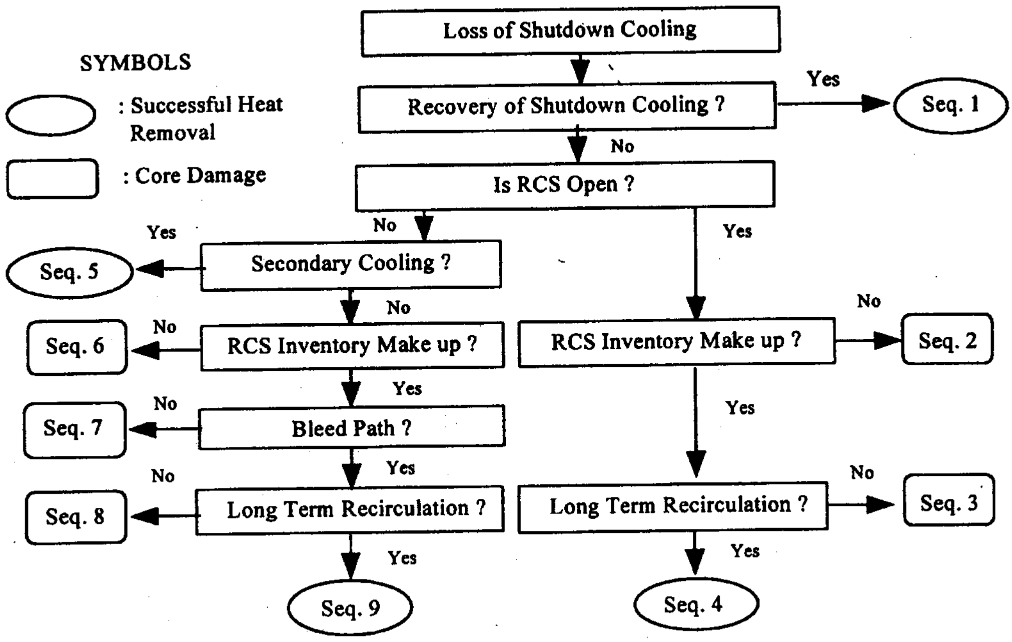

Fig. 1. Possible Event Scenarios Following the Loss of Shutdown Cooling

(sequence 2). Also, if the long term recirculation in the RCS is not possible even with inventory make up, the core could be challenged (sequence 3). In case of the closed RCS, if the secondary cooling with available SGs (sequence 5), or RCS inventory make up and long term recirculation (sequence 9) are available, then the core decay heat would be also removed. However, with the secondary cooling not available by installation of nozzle dams or maintenance of AFW system, either the water feeding into the RCS or the steam bleeding outside the RCS is inoperable, then the core would be uncovered and damaged (sequences 6, 7 and 8).

In general, the closed RCS configuration, as compared to the open RCS, provides an additional fission product barrier and a longer time for personnel to work in the containment. In case of the open RCS, if the core is damaged, the fission products would be released through the RCS opening to the containment and jeopardize the personnel to work in the containment. Also, if the containment is open, the radiological materials would be released to atmosphere. Therefore, the open RCS gives more serious consequences and the size and location of the RCS opening may have significant effect on the containment closure time. Table 1 represents the potential RCS openings during shutdown operation and refueling of the YGN Units 3&4. The largest RCS opening is the pressurizer manway and the SG plenum manways, except the reactor pressure vessel (RPV) head off for refueling. The highest opening is the manway or vent line on the top of the pressurizer. In addition, if the reactor coolant pump (RCP) seal or impeller is repaired during plant outage, the cold leg side

Table 1. Potential RCS Openings During Shutdown Operation

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 cross area	- for repair

could be considered to open.

2.2. The Worst Event Sequence

From the evaluation of the nine event sequences, in view point of the early core damage and containment challenge, the sequence 2 is selected as the worst event sequence. In this event sequence, the SG secondary cooling by natural circulation is not available and the forced water feeding into RCS using a safety injection pump or a gravity drain from the RWST to make up the inventory is inoperable throughout the transient. The RCS configurations such as the opening size and location are conservatively assumed. In the aspect of the early coolant discharging through the opening to containment, two locations of the opening in the hot leg side, pressurizer manway and SG inlet plenum manway, and two sizes of the opening in the cold leg side, 5 % and 30 % of cold leg cross area, are considered. In addition to the RCS openings, the SG secondary water level conditions would affect on 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 following the loss of SDC event as follows;

- Case 1 : Pressurizer manway open with water-filled SGs but without auxiliary feedwater
- Case 2 : Pressurizer manway open with emptied SGs
- Case 3 : SG inlet plenum manway open with emptied SGs
- Case 4 : Small cold leg open with emptied SGs
- Case 5 : Large cold leg open with emptied SGs

3. Thermal Hydraulic Analyses

3.1. Analysis Method

To analyze the thermal hydraulic behavior following the loss of SDC event, the system transient analysis code, RELAP5/MOD3.2 recently released by USNRC [8], is used. The code is run on DEC 5000/240 workstation. The applicability of the code to the loss of SDC event under shutdown conditions was assessed in previous study [9,10], which includes comparisons of the calculation with the LSTF experiment simulating the loss of RHR event during mid-loop operation in Japan [11]. It revealed that the code was capable of simulating appropriately the major thermal hydraulic

Table 2. Initial Conditions Used in Calculation

Major Parameters	YGN Units 3 & 4 Conditions
• Core power (3 days after reactor shutdown) [MWt]	• 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 hot leg / air
• Initial mass inventory [kg]	• 104,618
• Pressurizer / SG plenum manway area [m^2]	• 0.13 / 0.13
• Cold leg opening area of 5 % and 30 % [m^2]	• 0.0228 / 0.1368

processes following the event including noncondensable gas behavior with proper calculation time steps. The same code and models are used in the present analyses. Also, S. Banerjee et al. [12] reported that the code gave a good qualitative agreement between the measured and the calculated data by evaluating the RELAP5/MOD3 with the same experiment data.

The nodalization for the simulation of the event consists of about 214 hydrodynamic volumes connected by 242 junctions and 228 heat structures. It includes a reactor pressure vessel (RPV) with two channel core and downcomer, two loops represented by intact loop with pressurizer and broken loop, two SGs and four RCPs, and SDC system connected to both the hot legs and the cold legs. The initial conditions used in the calculation are represented in Table 2. 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 also assumed to be in mid-level of the hot leg. The pressure in the primary and secondary system remains atmosphere and the gas space is filled with the noncondensable gas, air. The steady state conditions are obtained from new transient run up to 1,000 seconds and the loss of SDC event is initiated by isolating the SDC flow and by opening the pressurizer or SG manways or cold leg opening.

In general, the containment closure time is estimated based on the time to boil, the time to core uncovery, and the time to core heat up after the loss of SDC. The time to boil is defined as the time for the water in reactor vessel upper plenum to reach a saturation temperature under atmospheric pressure. The time to core uncovery is defined generally as the time that it takes the water above the top of the core to drop to the top of the core. But, in the analysis, it is determined from the time for the collapsed water level to reach top of the core. Also, the time to core heat up is defined as the time for the fuel surface temperature to begin to rapidly increase.

3.2. Analysis Results for Hot Leg Side Openings (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 occurs at 1,000 seconds during mid-loop operation. The Case 1 shows that the pressure moderately increases

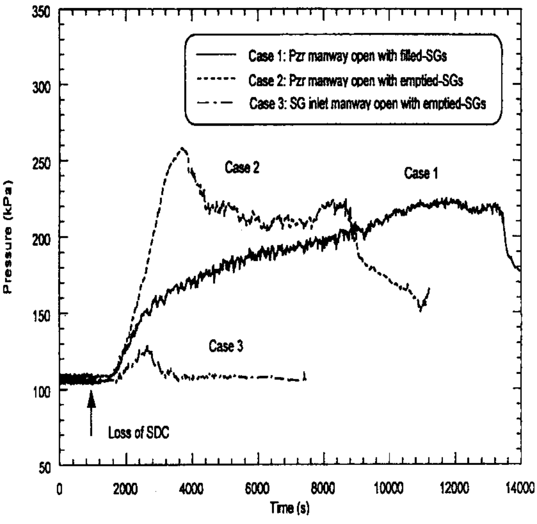

Fig. 2. Pressure Behavior in Upper Plenum for the Cases 1, 2 and 3

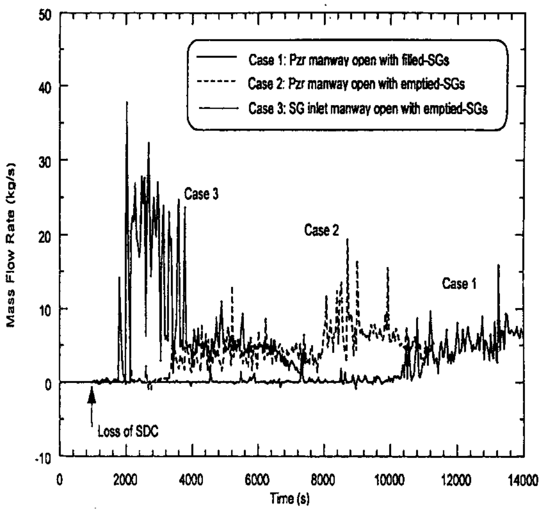

Fig. 3. Discharging Flows Through the RCS Opening for the Cases 1, 2 and 3

throughout the transient except the early boiling phase and reaches a maximum value of 220 kPa at about 11,600 seconds. Meanwhile, the Case 2 shows the pressure rapidly increases in short interval after boiling and reaches a maximum value of 265 kPa at about 3,600 seconds. This difference on the pressurization rate is because the Case 1 with water-filled SGs transfers more decay heat into secondary side by reflux condensation on SG U-tube than the Case 2 with emptied SGs. More than 8 MW among the total of 14.125 MW core decay heat is removed throughout the transient. On the contrary, the Case 3 with SG inlet plenum manway opening located at the relatively low elevation shows low pressurization since the steam is discharged to the containment much earlier than that for the pressurizer manway opening with the water held up in the bottom of the pressurizer. Figure 3 shows the initiating times of the discharging flow through the opening. For the Cases 1 and 2 with the same opening and different secondary condition, the discharging flow has a similar flow pattern just with a time delay of about 7,200 seconds. The significant discharging flow to the containment is formed at about 10,400 seconds for the Case 1 and at about 3,200 seconds for the Case 2. For the Case 3 with the relatively low elevation of the opening, the steam and liquid coolant is discharged more vigorously in the early phase of the event. The discharging is initiated from 1,800 seconds just after boiling. As a result, the calculation 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 at the bottom of the pressurizer or at the vertically inclined portion of the hot leg. Thus, the water level in the RPV decreases due to the water held up and the coolant discharging through the opening. Figure 4 represents the collapsed water levels in the RPV between the core bottom and the upper plenum. Before the boiling, the level swelling due to the temperature increase of the water is not

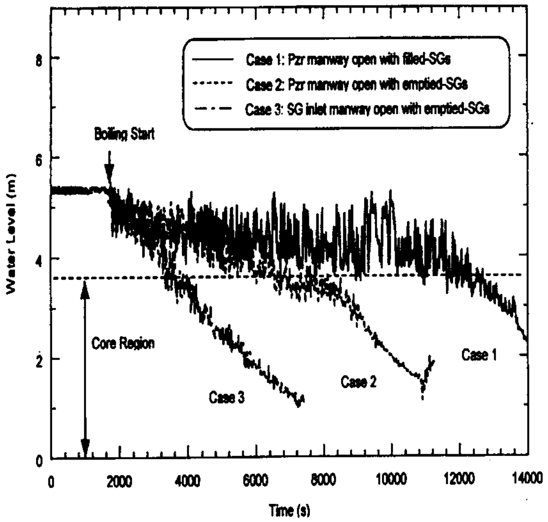

Fig. 4. The Collapsed Water Lavels in RPV for the Cases 1, 2 and 3

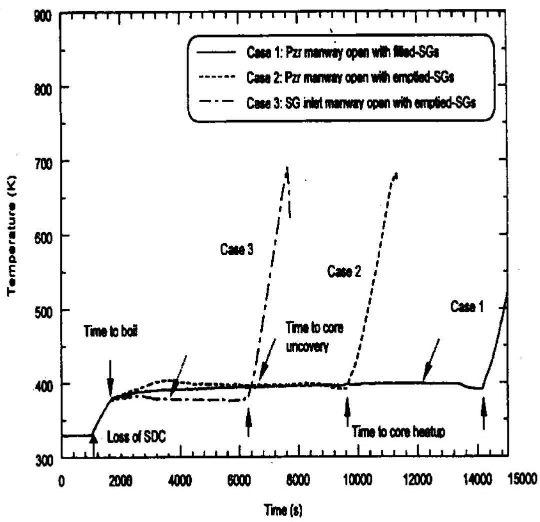

Fig. 5. Fuel Cladding Temperatures for the Cases 1, 2 and 3

significant for all cases. In the Case 3, the water level rapidly decreases due to the early coolant discharging through the opening. On the contrary, for the Case 1, the water level remains constant with somewhat oscillating for a long time since the coolant is discharged much late after the initial decrease due to 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 occurs and the core heat up is eventually initiated if the RCS inventory is not made up. As shown in Fig. 5, the time to core uncovery and the time to core heat up were estimated to be about 11,200 and 13,200 seconds after the event for the Case 1, about 5,600 and 8,600 seconds for the Case 2, and about 2,600 and 5,300 seconds for the Case 3, respectively. In general, the core heat up is initiated over 2,000 seconds after the core uncovery and it has similar trends with some time delay for all cases. In particular, the Case 2 with emptied SGs indicates 5,600 seconds earlier core uncovery than the Case 1 with water-filled SGs. Also, the Case 3 with the SG inlet plenum manway opening located at the relatively low elevation indicates 3,000 seconds earlier core uncovery than the Case 2 with the pressurizer manway opening. These results indicate that the time to core damage is significantly affected by the SG secondary water level and the elevation of the opening.

3.3. Analysis Results for Cold Leg Openings (Cases 4 and 5)

The Cases 4 and 5 simulating the cold leg openings show some different system behaviors from the Cases 1, 2, and 3 simulating the openings of the hot leg side. First, the reactor coolant in the cold leg begins to discharge to the containment in the early phase of the event because the opening is located at the relatively low elevation in the cold leg side. After the boiling at about 1,610 seconds for both cases,

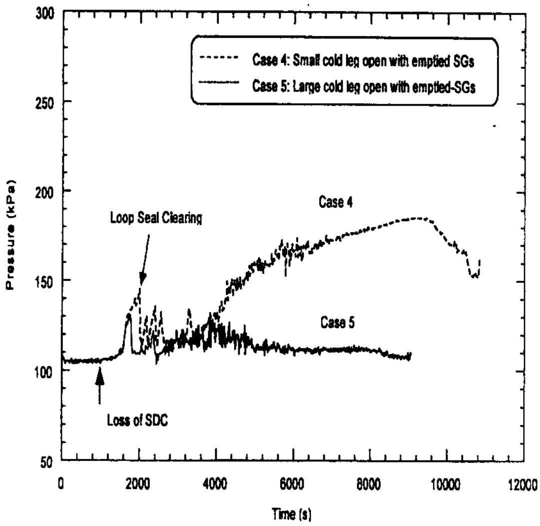

Fig. 6. Pressure Behavior in Upper Plenum for the Cases 4 and 5

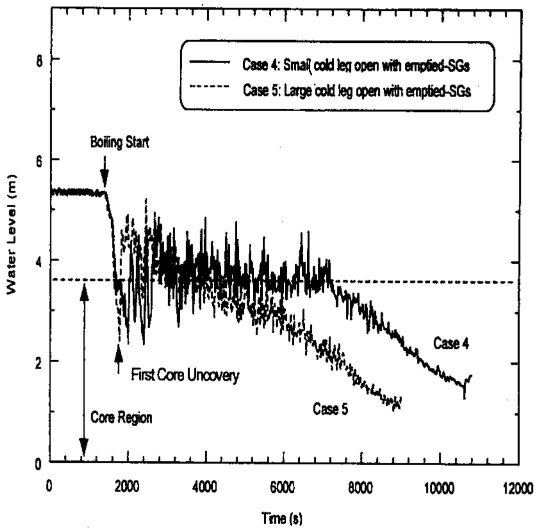

Fig. 7. The Collapsed Water Levels in RPV for the Cases 4 and 5

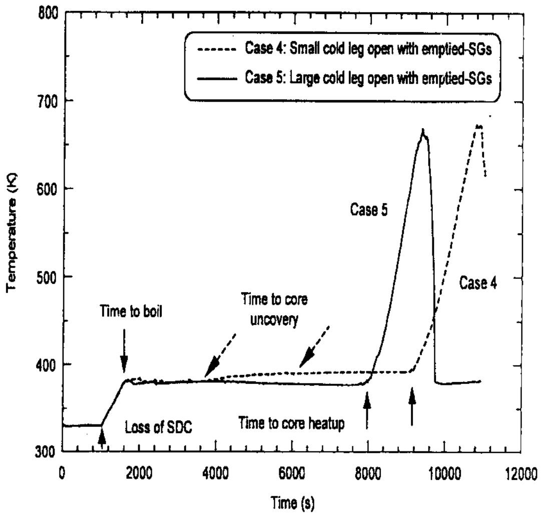

Fig. 8. Fuel Cladding Temperatures for the Cases 4 and 5

the pressure in the upper plenum rapidly increases as shown in Fig. 6 and eventually 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 the RPV toward the cold leg with opening and the coolant is rapidly discharged to the containment. Thus, 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. 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 crossover leg is immediately cleared, which is called loop seal clearing (LSC). Simultaneously, the pressure in the hot leg and upper plenum drops to the cold leg pressure. The pressure drop quickly increases the water level in the RPV because the compression force in the steam space above the water in the reactor core is disappeared. Eventually, the core is recovered again. The LSC phenomenon and the restoration of the RPV water level had also been found in H. Nakamura and Y. Kukita' s experiment simulating the same event [11]. 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. After the LSC, the discharging flow through the opening decreases to nearly zero due to the low system pressure and the core remains covered by the water even though intermittently occurred.

Due to the continuous steaming, the pressure in the upper plenum increases again after the formation of the loop seal in the crossover leg, especially showing much higher pressurization rate for the Case 4 with the small cold leg opening. As the RCS is pressurized again, the steam is discharged through the opening and the water level in the RPV continues to decrease moderately as shown in Fig. 7. Eventually, the core is uncovered again at about 5,200 seconds after the event for the small opening case and about 2,800 seconds for the large opening case. Also, the core heat up is initiated from about 8,200 seconds after the event for the small opening and about 7,000 seconds for the large opening as shown in Fig. 8. As a result, the calculation indicates that the first core uncovery is initiated from about 1,600 seconds regardless of the size of the cold leg opening and the core heat up does not occur. However, the second core uncovery time is significantly dependent on the size of the opening. For the large opening case, the core uncovery is initiated about 2,400 seconds earlier than that for the small opening case. It is because there is more coolant discharging to the containment through the large opening.

4. Time to Close Containment After the Loss of SDC Event

4.1. Abnormal Procedure Against the Event

In YGN Units 3&4, in order to cope with the loss of SDC event under shutdown conditions, Abnormal-45 Operating Procedure, "Actions Following Loss of SDC System", was recently developed [13]. The procedure includes various provisions to restore the core heat removal function and to protect against the radiological release following the event. In the procedure, three initiators are considered as major causes of the loss of SDC event; loss of RCS inventory, loss of SDC flow and loss of support systems. The loss of inventory is perceived from abnormal symptoms that a current or flow on SDC pump in service is fluctuating or the water level in pressurizer or RPV is rapidly decreasing. The loss of SDC flow takes place when the SDC flow requirements, in which the flow must be maintained greater than 4,000 gpm (or 3,290 gpm under low coolant temperature condition) for one pump in service, are not met. The loss of support systems is caused by a failure of SDC heat exchanger or pump.

The operator is required in the procedure to take two types of actions to mitigate the event. One is to restore the removal capability of the core decay heat, including the recovery of the SDC system, the alignment of the RCS make up flow path and bleed path, the control of the RCS inventory and so on. The other is to protect personnel working in containment and to prevent the uncontrolled release of fission products to atmosphere, including the evacuation of the non-essential personnel from the containment, the closure of the containment opening and so on. Thus, the times to take actions for the RCS make up or the containment closure should be determined from the results of the thermal hydraulic analyses for the various plant conditions and operating states.

4.2. Containment Closure Time

The results of the thermal hydraulic analyses for the five cases of typical RCS configurations

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

RCS Openings (units : minutes)	Time to boil	Time to core uncovery	Time to core heat up
• Pzr manway open with water-filled SGs (Case1)	12.5	186.7	220.0
• Pzr manway open with emptied-SGs(Case2)	12.3	91.7	144.0
• SG inlet manway open with emptied-SGs(Case3)	13.2	41.7	88.3
• Small cold leg open with emptied-SGs(Case4)	10.2(13.6)	86.3(91.5)	136.7
• Large cold leg open with emptied-SGs(Case5)	9.8(13.6)	45.8(59.9)	116.3

• ( ) is CE-typed PWR data

under the worst event sequence were summarized in Table 3 and compared with the available data on the CE-typed PWR [14, 15]. The time to core uncovery of the YGN Units 3&4 was estimated to be slightly earlier than that of the CE-typed PWR. It is due to the difference of the calculation models and plant geometries. In overall, the time to boil was estimated to be about 10 to 13 minutes regardless of the opening size and location and the SG secondary water condition. It is because the boiling time is just dependent on the initial conditions such as the decay heat load, the amount of RCS coolant in and above the core and the bulk temperature of the coolant. On the contrary, the times to core uncovery and the times to core heat up are strongly dependent on the size and the location of the opening and the SG secondary water level condition. The Case 3 indicates the earliest core uncovery and core heat up, 41.7 minutes and 88.3 minutes after the loss of SDC event, respectively.

In general, the time to close the containment is dependent on the operating states during maintenance activities and there are two important factors to be considered for the containment closure, the initiating time and the completion time of the containment closure. First, it is necessary to initiate the containment closure before the time to boil, within about 10 minutes, because the steam and coolant in the RCS begin to discharge to the containment through the opening just after the coolant boiling. If the containment closure is initiated after the boiling time, it would be required to evaluate the in-containment environment and the survivability of the workers to perform the necessary containment closure actions in the containment. It is because the core could be instantaneously uncovered and damaged in the early phase of the boiling. Second, the containment closure should be achieved at the latest before the core damage to prevent the uncontrolled release of fission products to atmosphere. As the core is uncovered, the core damage is possible. Thus the containment closure is recommended to achieve before the time to core uncovery after the event. For example, if there is a large opening such as the SG inlet manway (Case 3) or the removal of the RCP impeller assembly (Case 5), the containment closure should be achieved within about 42 minutes after the event. Also, if the pressurizer manway is open (Case 2), the containment closure should be completed within 92 minutes. However, if the SG secondary is filled with water for the same opening (Case 1), it could be delayed by 187 minutes.

5. Conclusions

The YGN Units 3&4 plant conditions during shutdown operation were reviewed to identify the possible event scenarios following the loss of SDC event. Based on the operating states and plant conditions, the worst event sequence with unavailable secondary cooling and no RCS make up was identified from the nine possible event sequences. The thermal hydraulic analyses were performed for the five cases of typical RCS configurations under the worst event sequence, using the RELAP5/MOD3.2 code, to investigate the plant behavior to determine the containment closure time following the event.

1) The time to boil was estimated to be about 10 to 13 minutes regardless of the opening size and location and the SG secondary water level condition. It is because the boiling time is just dependent on the decay heat load and the amount of water in and above the core.
2) Time to core uncovery was significantly affected with the location and size of the opening and the SG secondary water level condition. In case of the SG secondary filled with water, as compared to the emptied SG, the time to core uncovery was delayed about 95 minutes by the late coolant discharging through the opening because the upper plenum is moderately pressurized by the reflux condensation on the SG U-tube. The core uncovery for the opening of the SG inlet manway located at the relatively low elevation was initiated about 50 minutes earlier than that for the opening of the pressurizer manway discharging much late the coolant due to the water held up in the bottom of the pressurizer. Also, the core uncovery for the large size of the cold leg opening was initiated about 40 minutes earlier than that of the small size opening.
3) The containment closure is recommended to achieve before the time to core uncovery to prevent the uncontrolled release of fission products to atmosphere. In this analysis, the times to core uncovery for the five cases of typical RCS configurations under the worst event sequence were provided and those results provide useful information to operator to cope with the event. In particular, it was estimated the containment closure should be achieved within 42 minutes after the event for the SG inlet manway opening case or the large cold leg opening case. In addition, if the containment closure is initiated after the boiling time, about 10 minutes, it is necessary to evaluate the in-containment environment and the survivability of the workers in the containment because the steam and coolant in the RCS are discharged through the opening just after the coolant boiling.

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