Development of state categorization model for necessity of feed and bleed operation and application to OPR1000

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Abstract: Since nuclear power plant (NPP) has lots of functions and systems, operated procedure is much complicated and the chance of human error to operate the safety systems is quite high when an accident occurs. There are two approaches to cool down the reactor coolant system (RCS) after an accident in a NPP. One is heat removal by a secondary side and the other is heat removal by a feed-and-bleed (F&B) operation. The F&B operation provides residual heat removal when secondary system is not available. It is difficult to decide initiating the F&B operation because the radioactive coolant is released to the containment during F&B operation. A state categorization model to qualitatively analyze the necessity and effect of F&B operation was developed. Sequences of RCS conditions when heat removal by secondary side fails are identified to two events: non-LOCA and LOCA. The proposed model has five levels to inform the necessity and effect of F&B operation qualitatively and component failure state to inform the unavailability of F&B operation. Thermal hydraulic analysis is performed to ascertain the boundary of each level in OPR1000. The boundary of successful F&B operation of OPR1000 was identified.

Keywords: Feed-and-Bleed operation, success boundary, OPR1000, operator decision support.

1. INTRODUCTION

In the case of an accident on a nuclear power plants (NPPs), a safety function to remove residual heat of core and coolant is one of the most important safety functions to prevent the core damage. The purpose of the safety function is to remove the decay heat generated in the core and to transfer the residual heat from primary side to secondary side or to some other heat sink [1]. In order to perform the safety function, various safety systems have been installed in the NPPs.

There are two approaches to remove the residual heat in reactor coolant system (RCS) after an accident in a pressurized water reactor (PWR): residual heat removal by a secondary side and residual heat removal by safety injection into the RCS with direct depressurization of primary side [2]. Residual heat can be transferred from the primary to the secondary side through the steam generators if the secondary side is available. If the steam generators transfer a small amount of or no heat from the primary side, the heat will be accumulated to the primary side by continuous core decay heat [3]. When residual heat removal by the secondary side fails, the RCS needs another residual heat removal mechanism by safety injection into the RCS with depressurization of primary side. There are two ways to decrease the RCS pressure directly for injection of the coolant: (i) break in the RCS occurs; (ii) the operator manually opens the valves for feed and bleed (F&B) operation.

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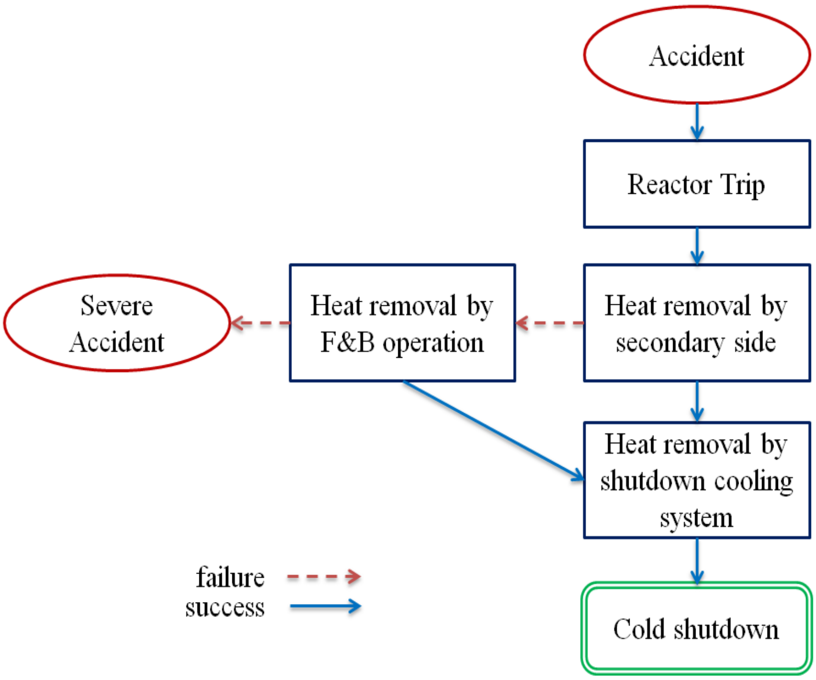
Fig. 1: Process of safety cooldown in OPR1000



F&B operation is a process to cool the reactor by the primary side directly. If adequate residual heat removal through the secondary side is not available, the heat can be removed from the RCS by F&B operation as shown in Fig. 1. F&B operation consists of the safety depressurization system (SDS) and safety injection system (SIS) in OPR1000. F&B operation includes steps from the opening of SDS valves to reach the entry condition of shutdown cooling system (SCS). The SDS is adopted in OPR1000s to enable F&B operation to mitigate beyond design basis accidents (BDBAs). The SDS is designed to perform the combined function of overpressure protection and rapid depressurization. The SDS consists of two separate lines connected to the top of the pressurizer and each line discharges to the containment atmosphere through a rupture disc. The SIS is designed to inject the coolant to RCS during the transient. Reduced RCS pressure allows high pressure safety injection (HPSI) flow to replenish and eventually exceed discharged steam flow rate out through the SDS prior to uncovering the core. An extended residual heat removal capability is provided by a feed (HPSI) and bleed (SDS) process [1,4,5]. In order to perform F&B operation, operators need to manually open the SDS valves and safety injection actuation signal (SIAS) should be generated.

Previous studies of F&B operation have focused on a total loss of feedwater (TLOFW) accident to demonstrate the of F&B operation [2,5,6,7,8]. The TLOFW accident is a representative accident involving the failure of cooling through secondary side. Several studies have investigated the effects of F&B operation in the case of TLOFW accident. Although considerable researches have been devoted to F&B operation, operators still have problems to decide the initiating F&B operation. The operators may hesitate to initiate F&B operation if a clear cue is not provided, since its initiation implies the radioactive coolant releases into the containment. OPR1000 has an optimized recovery procedure (ORP) to diagnose TLOFW accident and functional recovery procedure (FRP) to initiate F&B operation. Even though emergency operating procedure (EOP) is designed to guide the operator’s mitigation actions against TLOFW accident in OPR1000, the available time for a diagnosis of the F&B operation is very short and the human failure probability of initiating F&B operation is very high [9]. In the case of a combined accident including the failure of cooling through the secondary side, it is difficult for operators to notice the necessity of F&B operation because the numerous process parameters and alarms are needed to be checked before decision making and operators spend much time to entry into steps in the FRP to initiate F&B operation. Most previous studies have focused on the TLOFW and few studies took into account of the combined accident including the failure of cooling through the secondary side because the probability that the combined accident occurs is very low.

In order to solve these problems, the aim of the present paper is to develop a method to identify the necessity and effects of F&B operation condition in various reactor conditions. In this study, the analysis of the necessity and effects of F&B operation was performed. A state categorization model is developed to identify the necessity and effects of F&B operation condition. The boundary of each state in OPR1000 is identified to support the operator's decision making on the initiation of F&B operation in various reactor conditions.

2. STATE CATEGORIZATION MODEL

2.1. Characteristics of State Categorization Model

A state categorization model is developed to determine the necessity of F&B operation for systematic operation and the possibility of safe cooldown by F&B operation. Degree of necessity of F&B operation depends on the existence of residual heat removal mechanism and amount of inventory in the core. Effects of F&B operation depends on availability of F&B operation and core damage. The state categorization model has five states to inform the necessity and effect of F&B operation qualitatively and component failure state to inform whether F&B operation is available or not. Table 1 shows the characteristics of states and state in the model. As the number of states increases, the degree of necessity of F&B operation increases.

Table 1: Characteristics of states in the state categorization model

	Existence of residual heat removal mechanism	Availability of F&B operation	Amount of inventory in core	Necessity of F&B operation	Core damage
State 0	Yes (continuous)	possible	sufficient	No	No
State 1	Yes (temporary)	possible	sufficient	necessary	No
State 2	No	possible	sufficient	necessary	No
State 3	No	possible	insufficient	essential	No
State 4	No	possible	insufficient	essential	Yes
Component failure state	No	impossible	-	-	-

State 0 means that the secondary side is available and can continuously remove the residual heat if the inventory of primary side is enough to transfer the residual heat from primary to secondary side. The RCS can be cooled down by secondary system without F&B operation.

During State 1, the RCS still has the residual heat removal mechanism temporarily even though the secondary side fails. For example, the residual heat can be transferred from the primary to secondary side until the steam generator dry out even though the feedwater is not supplied to the steam generators. State 1 indicates that F&B operation will be needed after the termination of the residual heat removal by the secondary side or under the condition that high pressure blocks safety injection into the system. F&B operation is not essential during State 1.

After entry of State 2, there is no residual heat removal mechanism in RCS. During State 2, the residual heat be accumulated and RCS pressure increases. State 2 indicates that the RCS is necessary to be cooled down by F&B operation or secondary side when the secondary side is recovered. If the secondary side recovers the capacity of residual heat removal, the RCS can be cooled down without core damage and core uncovery.

State 3 indicates that core is uncovered and RCS should be cooled down by F&B operation to prevent core damage. During State 3, the coolant becomes superheated and RCS temperature increases dramatically. F&B operation is more appropriate operation to prevent core damage and to supply the coolant in the RCS during State 3. The procedure of initiating F&B operation is much simpler than that of recovering the secondary side. Therefore, F&B operation should be initiated in State 3.

State 4 means that core will be damaged or is already damaged even though F&B operation is initiated. The RCS temperature can increase even after F&B operation is initiated according to the availability of systems related to F&B operation. State 4 indicates that F&B operation cannot prevent core damage.

Component failure state means that the related components of F&B operation fail; hence F&B operation is impossible. When SDS valves fail to open or components of the SIS fail to operate, F&B operation cannot be initiated. If the NPP loses all power supply, F&B operation cannot be initiated because HPSI pumps are the active system.

2.2 Boundary of States in OPR1000

Boundary of each state in OPR1000 should be identified to support the operator's decision making on the initiation of F&B operation in various reactor conditions. As mentioned in previous section, RCS condition when the core is damaged can be classified as high RCS pressure and temperature without break (Type 1) or high RCS pressure and temperature with break (Type 2).

In the case of Type 1, if the secondary side fails to remove the heat, the RCS loses the entire heat sink. The components of secondary side are available to transfer the residual heat. If these requirements are not satisfied, the residual heat cannot transfer from primary to secondary side. The heat of the RCS is always positive by the residual heat when the residual heat removal through secondary side becomes zero.

In the case of Type 2, if the safety injection is unavailable by high pressure of RCS, the RCS loses its entire heat sink. The leakage of fluid by break releases the residual heat. The cold coolant can be injected by the SIS to cool down the RCS. If a break in any part of the primary side occurs, the RCS pressure decreases. As the RCS pressure decreases below the shutoff head of HPSI pump, the HPSI pumps can inject cold coolant to the primary side. However, if the break size is small, the RCS pressure remains above shutoff head of HPSI pump and safety injection is not available. If the amount of residual heat removal is insufficient by the SIS and the secondary side, the RCS pressure increases and F&B transient is terminated. After safety injection is unavailable, the core will be damaged. On the other hand, it is not necessary to depressurize the RCS in the case of a medium or large break because they are under the low RCS pressure sequences [2].

The RCS condition changes in the case of Type 1 as shown in Table 2. The RCS condition changes in the case of Type 2 as shown in Table 3. When the components of secondary side fail, RCS condition becomes State 1. The boundary between State 0 and State 1 is the failure of secondary side. Examples of the failure of secondary side include failure of components of the secondary side such as failure of the main steam line valves and TLOFW accident.

Table 2: Relationship between the RCS condition and states in the case of Type 1

State	RCS conditions
1	Reactor trips Secondary side fails (boundary; steam generator level decreases) RCPs trip Safety injection by depressurization of secondary side is available (optional)
2	Steam generators dry out or safety injection is unavailable (boundary; RCS pressure increases) PSVs open (RCS inventory loses)
3	Core is uncovered (boundary) Coolant is superheated Peak cladding Temperature (PCT) increases dramatically
4	Core is damaged (boundary)

Table 3: Relationship between the RCS condition and states in the case of Type 2

State	RCS conditions
1	Break occurs (RCS inventory loses, RCS pressure decreases) Secondary side fails (boundary; steam generator level decreases) RCPs trip Safety injection is activated
2	Safety injection is unavailable (boundary; RCS pressure increases) PSVs open (RCS inventory loses)
3	Core is uncovered (boundary) Coolant is superheated PCT increases dramatically
4	Core is damaged (boundary)

The boundary between State 1 and State 2 in the case of Type 1 is the timing of dry out of the steam generator without safety injection or the timing of inability of safety injection after the steam generator pressure is depressurized by operator.

Duration of State 1 is related to the amount of heat transfers from the primary to secondary sides and the remaining inventory in steam generators at the reactor trip. The amount of heat transfers from the primary to secondary sides is affected by the reactor and reactor coolant pumps (RCPs) trip. In the case of a TLOFW accident, the reactor and the RCPs are generally tripped due to the low steam generator level and coolant sub-cooling margin. The steam generators have more water masses and the duration of State 1 can be prolonged if the reactor and RCPs are tripped quickly. If the reactor and RCPs trip is delayed, the duration of State 1 becomes much shorter.

The inventory of the steam generators is the main factor influencing State 1. As the steam generator level at a reactor trip becomes higher, the duration of State 1 increases. If a little amount of feedwater is supplied to steam generator, it can increase the duration of State 1. The cooldown rate by the secondary side also influences the remaining inventory of feedwater in steam generators and the amount of heat transfers from the primary to secondary sides. The cooldown rate is related to feedwater enthalpy and steam generator pressure [10]. As the cooldown rate increases, the time until the steam generators dry out decreases and the duration of State 1 increases because the RCS pressure can be decreased below the HPSI shutoff head and SIS can inject the coolant. Consequently, the depressurizing the steam generator increases the duration of State 1.

The boundary between State 1 and State 2 is timing of unavailability of safety injection in the case of Type 2. The SI flow rate is the main factor influencing State 1. If a sufficient SI flow rate to the RCS is injected, the duration of State 1 becomes longer. SI flow rate depends on the RCS pressure and the availability of SIS components. The RCS pressure is affected by the break size, SI flow rate, and flow enthalpy. The statuses of State 2 to 4 in the case of Type 2 are the same as in the case of a Type 1. The unavailability of safety injection should be checked to confirm the necessity of F&B operation in the case of Type 2.

The boundary between State 2 and State 3 is the core uncovery. During State 2, the PSVs of pressurizer can be opened to protect the reactor vessel and the RCS inventory is lost. As the amount of loss of RCS inventory increases after the PSVs of pressurizer are opened, the duration of State 2 decreases. In the case of State 2, the RCS inventory is also lost by the break. The core can be uncovered before the steam generators dry out in the case of situation that the SI flow is not sufficient to fill up the RCS. In this case, RCS condition directly changes from State 1 to State 3 after the safety injection is not available any more. If all PSVs of pressurizer are not opened, RCS pressure increase over the pressure limit of vessel. In this case, RCS condition is changed from State 2 to State 3 quickly, and the duration of State 2 and 3 is very short.

As time passes, a large amount of RCS coolant is lost. The upper part of the RCS will be occupied by saturated vapor, and then the top of core will become uncovered. During State 3, the coolant is superheated, and then RCS temperature increases dramatically as mentioned. When the peak cladding temperature (PCT) rises to 1000 K, fuel cladding oxidation begins. Following this, the PCT rises abruptly due to heat generation associated with fuel cladding oxidation. Substantial fuel cladding oxidation occurs when the fuel cladding temperature rises over 1200 K [2]. If this goes on the reactor core will be damaged. We assume that core damage occurs when PCT exceeds 1477 K. Although a more conservative model could use core uncovery as a core damage criterion, the PCT incorporates the duration of the core uncovery into core damage criterion [11].

The boundary between State 3 and State 4 is the RCS temperature and pressure, which is named deadline and corresponds with the avoidable limitation of core damage by F&B operation. The deadline can be decided by the maximum RCS temperature at starting time of F&B operation. F&B operation should be initiated before the deadline.

The availability of the SDS and the SIS is the main factors influencing deadline. The mass flow rate of SDS valves depends on total opened area of SDS valves and the pressure difference between RCS and containment pressure. The RCS inventory is lost through the SDS valves and is filled by SIS. If the duration from the opening of SDS valves to safety injection prolongs, the core can be damaged after F&B operation is initiated. Consequently, the deadline can be lower than 1477 K of PCT according to the availability of the SDS and the SIS. The RCS pressure increases dramatically when all pressurizer PSVs fail to open. To prevent damage of the reactor vessel, the SDS should be opened before the pressure margin of the reactor vessel.

3. EXAMPLE ANALYSIS FOR APPLICATION TO OPR1000

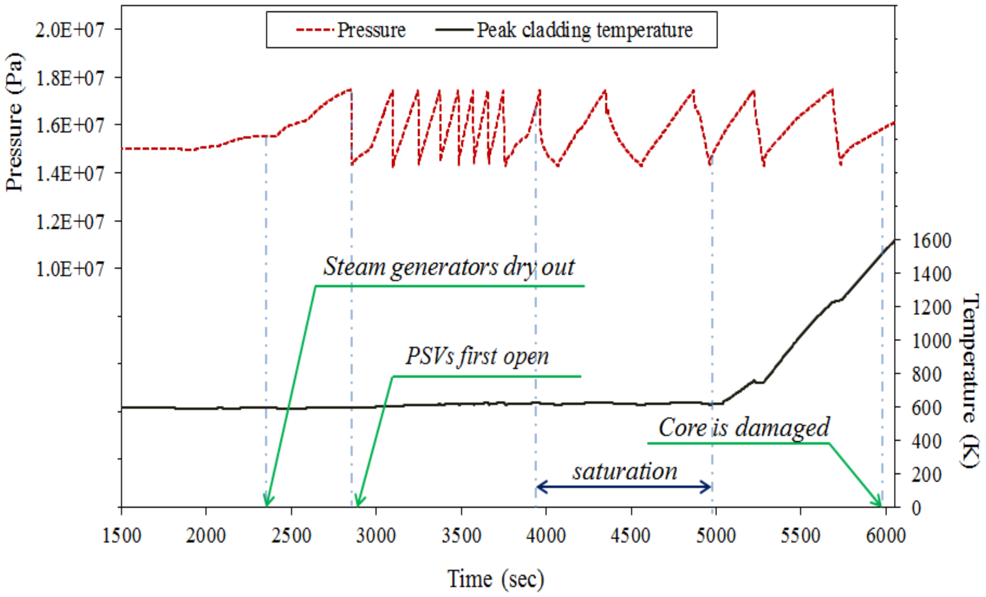
In the case of the failure of secondary side, the RCS condition can be changed by various events. In order to ascertain boundary of each state in the proposed model, a thermohydraulic analysis was performed using the MARS (Multi-dimensional Analysis of Reactor Safety) code [12]. Initiating events for examples are assumed as: (i) TLOFW accident for Type 1; (ii) TLOFW accident and a loss of coolant accident (LOCA) for Type 2. It is assumed that the break and reactor and RCPs trip occurs at 0 sec. Feedwater was assumed that it is not supplied in the secondary side after the reactor trips. Table 4 shows the design values and the calculated results of the steady state for OPR1000 [13]. OPR1000 has two separate lines located at the top head of the pressurizer in the SDS and two HPSI pumps, two low pressure safety injection (LPSI) pumps, and four safety injection tanks (SITs) in the SIS. Four PSVs of pressurizer are adopted in OPR1000.

Table 4: Comparison of design values and calculated results at steady-state for the OPR1000 [13]

	Parameters	OPR1000 (Designed)	MARS
Primary side	Core power [MWt]	2815	2815
	Hot leg flow rate [kg/s]	7700	7717
	Hot leg temperature [K]	600.3	600.5
	Cold leg temperature [K]	569.2	569.0
	Pressurizer Pressure [MPa]	15.51	15.51
Secondary side	Feedwater mass flow rate [kg/s]	721.02	721.13
	Steam generator pressure [MPa]	7.38	7.38

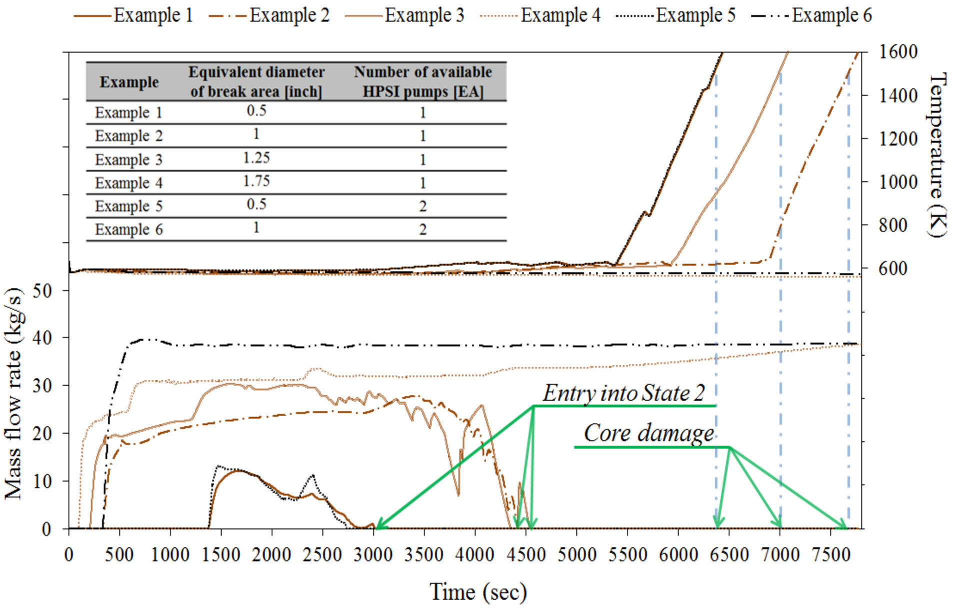
The RCS temperature and pressure change in the case of TLOFW accident without F&B operation as shown in the Fig. 2. The RCS pressure increases because the residual heat is not eliminated by the secondary side. To ensure the integrity of the RCS vessel, PSVs of pressurizer are repeatedly opened and closed according to the RCS pressure. The inventory of the RCS coolant loses as PSVs of pressurizer open repeatedly.

Fig. 2: PCT and RCS pressure in the case of Type 1 when F&B operation is not initiated.



To ascertain the effects of break size and availability of SIS components on State 1 in the case of TLOFW accident and LOCA, six examples were chosen. For equivalent diameters of break sizes are 0.5 in., 1.0 in., 1.25 in. and 1.75 in. One HPSI pump or two HPSI pumps can be used. Fig. 3 shows the mass flow rate from SIS and PCT without F&B operation.

Fig. 3: Mass flow rate from SIS and peak cladding temperature according to break size and availability of SIS components when F&B operation is not initiated.

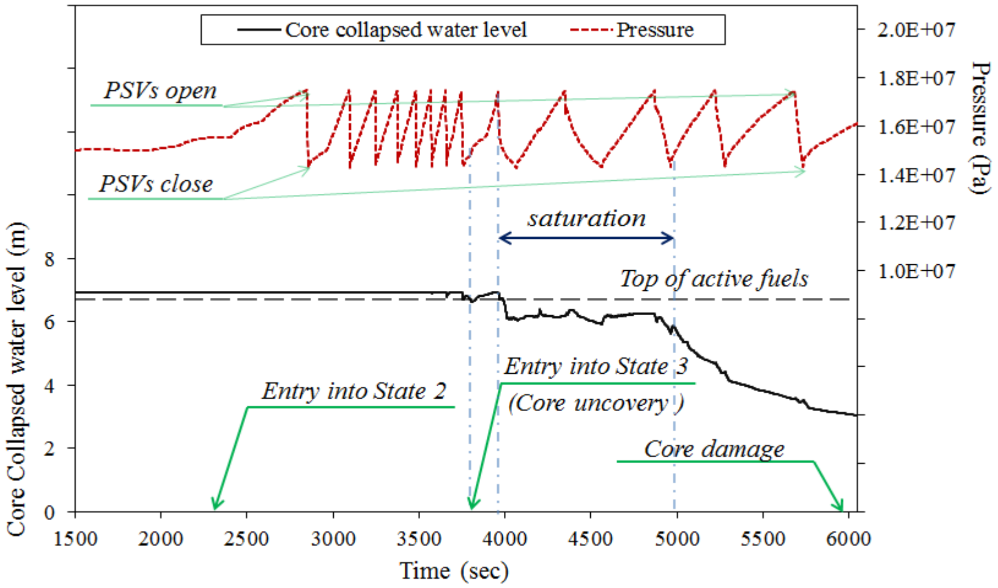


Example	Equivalent diameter of break area [inch]	Number of available HPSI pumps [EA]
Example 1	0.5	1
Example 2	1	1
Example 3	1.25	1
Example 4	1.75	1
Example 5	0.5	2
Example 6	1	2

If the equivalent diameter of the break size is smaller than 1.25 in. and one HPSI pump is available, safety injection is not enough to prevent the core damage. If the equivalent diameter of break size is 0.5 in. and two HPSI pumps are available, safety injection is also unavailable. Eventually the core is damaged after F&B transient is terminated. On the other hand, if the equivalent diameter of the break size is more than 1.25 in. and one HPSI pump is available, safety injection is continued. If the equivalent diameter of the break size is more than 0.5 in. and two HPSI pumps are available, the SIS is also continued. In these cases, the RCS condition does not transfer from State 1 to State 2 or State 3.

Fig. 4 shows the core level and RCS pressure in the case of Type 1. From the results of Fig. 2 and 4, the RCS pressure repeatedly increases and decreases between the set point of PSVs of pressurizer and RCS temperature is not changed during State 2. After the core is uncovered, the coolant becomes saturated. When the coolant is superheated, the core collapsed water level decreases dramatically. More than half of water inventory in core is lost when the core is damaged.

Fig. 4: Core collapsed water level and RCS pressure in the case of Type 1 when F&B operation is not initiated.



To ascertain the effects of break size and availability of SIS components on the boundary between State 2 and State 3, Example 1, 2, 3 and 5 in Fig. 3 were selected.

Fig. 5: Core collapsed water level according to break size and availability of SIS components in the case of Type 2 when F&B operation is not initiated.

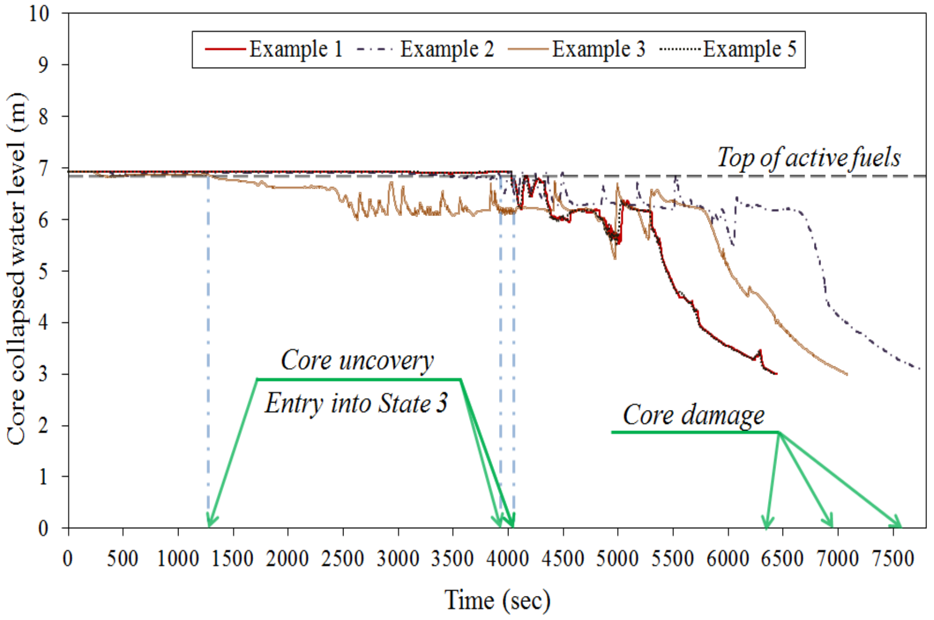


Fig. 5 shows the core collapsed water level without F&B operation in the case of Type 2. As mentioned in previous section, if core collapsed water level is below top of active fuels, the RCS condition is changed from State 2 to State 3. From the results of 0.5 in equivalent diameter of the break size as shown in Fig. 3 and 5, the core was uncovered after inability of safety injection. In these cases, the RCS condition is changed from State 1 to State 2 after inability of safety injection. From the results of 1.0 in and 1.25 in equivalent diameter of the break size with one available HPSI pump as shown in Fig. 3 and 5, the core was uncovered before inability of safety injection. In these cases, the RCS condition is changed from State 1 to State 3 after inability of safety injection. As break size increases, the possibility of direct transient from State 1 to State 3 increases.

The deadline can be decided by the maximum RCS temperature at starting time of F&B operation without core damage as mentioned in previous section. A sensitivity analysis was performed to ascertain the effects of availability of the SIS and the SDS on the deadline. Six examples were selected, and the initiating event is TLOFW accident. Examples had different conditions: opened area of SDS valves, available HPSI pumps, and PCT at initiating F&B operation. The design area of one valve in SDS is $0.008107m^2$ (KHNP, 2011). Core damage is assumed that a PCT is above 1477 K as mentioned in previous section.

Fig. 6: Peak cladding temperature when F&B operation is initiated in Level 3 in case of Type 1

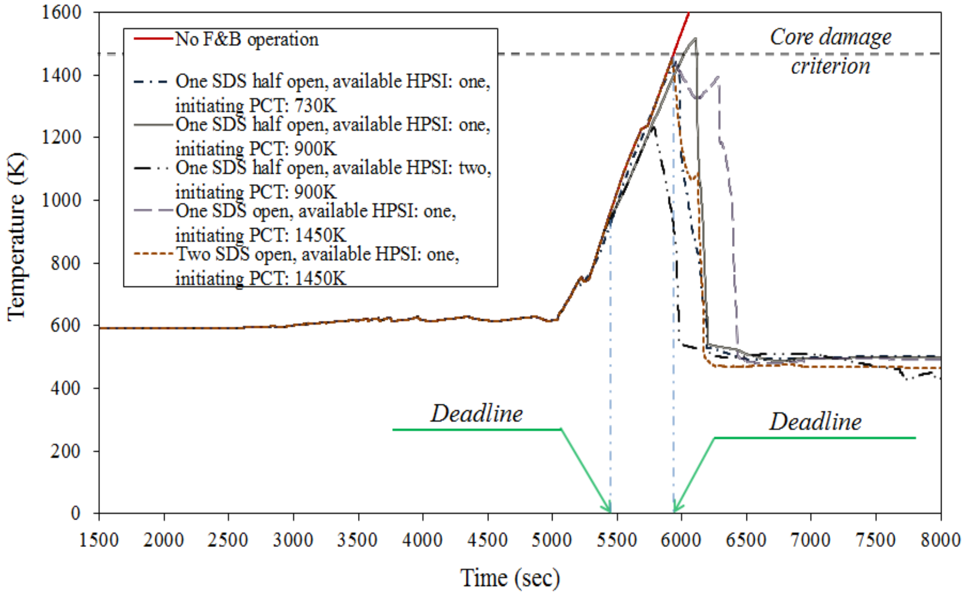


Fig. 6 shows PCT with F&B operation according to the examples' conditions. The duration of State 3 was changed according to the opened area of SDS and the availability of HPSI pumps as shown in Fig 6. Deadline became over 1450 K when one or two SDS valve open SDS valve with one available HPSI pump. As opened area of SDS becomes smaller, the degree of pressure drop decreases. The duration from the opening the SDS valves to safety injection can be prolonged due to the small opened area of the SDS and the SI flow rate. The results from examples, which conditions are one and two available HPSI pumps with one SDS valve half open and initiating PCT at 900 K show much different outcome due to condition of SIS components. When one HPSI pumps are available in the case of one SDS valve half open and initiating PCT at 900 K, core was damaged even though F&B operation is initiated. When two HPSI pumps are available in the case of one SDS valve half open and initiating PCT at 900 K, the core was not damaged because SI flow is sufficient in spite of small opened area of SDS. If F&B operation is initiated quickly, the core will not be damaged when one HPSI pumps are available in the case of one SDS valve half open and initiating PCT at 730 K. To prevent the core damage, two available HPSI pumps and fast initiation of F&B operation are needed when the opened area of SDS valves is too small.

4. CONCLUSION

Cooling the RCS after a scram is one of the most important safety functions to prevent core damage. To support the operator's decision making on the initiation of F&B operation in various reactor conditions, the state categorization model is developed. Boundary of each state in OPR1000 was identified. The proposed model has five states to inform the necessity and effect of F&B operation qualitatively and component failure state to inform the unavailability of F&B operation. The proposed model explains the necessity of F&B operation even when the situation is complicated due to a combined accident.

Component failure state can be categorized to three types; (i) failure of the SDS, (ii) failure of the SIS, and (iii) failure of both the SDS and the SIS. Even though the SIS is available, F&B operation cannot be initiated when the SDS valves fail to open. However, when the SIS fails, the SDS valves should not be opened to prevent the loss of primary inventory. In order to confirm component failure state, the monitoring system for the SIS and the SDS should be needed.

Time for operators to mitigate the accident can be changed according to the events in the RCS. The duration of states can be increased or decreased according to the type of events. The main events which can affect the duration of states need to be identified in further study.

To apply the proposed model to the NPP, process parameters related boundary of each state need to be monitored. However, some parameters such as PCT are difficult to be measured due to absence of direct measuring method. If the process parameter cannot be measured directly, alternative parameters need to be utilized in order to predict the boundary. A new model for estimating the RCS condition based on the alternative parameters will be also developed in further study.

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