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Key Characteristics of Combined Accident including TLOFW accident for PSA Modeling

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1. Introduction

The Probabilistic Safety Assessment (PSA) is effective to assess the risk of nuclear power plants (NPPs), and to identify the design and operational vulnerabilities. The PSA can cover all risk contributors beyond design basis accidents (DBA), e.g. an earthquake over the design criteria and related possible accident scenarios. Basically, the PSA should cover all risks from all power modes and all hazards [1]. PSA techniques are used to evaluate the relative effects of contributing event on safety or reliability [2].

The conventional PSA techniques cannot adequately evaluate all events. The conventional PSA models usually focus on single internal events such as DBAs, the external hazards such as fire, seismic. However, the Fukushima accident of Japan in 2011 reveals that very rare event is necessary to be considered in the PSA model to prevent the radioactive release to environment caused by poor treatment based on lack of the information, and to improve the emergency operation procedure. Especially, the results from PSA can be used to decision making for regulators. Moreover, designers can consider the weakness of plant safety based on the quantified results and understand accident sequence based on human actions and system availability.

This study is for PSA modeling of combined accidents including total loss of feedwater (TLOFW) accident. The TLOFW accident is a representative accident involving the failure of cooling through secondary side. If the amount of heat transfer is not enough due to the failure of secondary side, the heat will be accumulated to the primary side by continuous core decay heat [3]. Transients with loss of feedwater include total loss of feedwater accident, loss of condenser vacuum accident, and closure of all MSIVs [4]. When residual heat removal by the secondary side is terminated, the safety injection into the RCS with direct primary depressurization would provide alternative heat removal. This operation is called feed and bleed (F&B) operation.

Combined accidents including TLOFW accident are very rare event and partially considered in conventional PSA model. Since the necessity of F&B operation is related to plant conditions, the PSA modeling for combined accidents including TLOFW accident is necessary to identify the design and operational vulnerabilities.

2. Characteristics of Combined Accident including TLOFW accident

2.1 Plant conditions related to F&B operation

Plant conditions which need the F&B operation are caused by transients with loss of feedwater (Type 1 accident) or LOCA and transients with loss of feedwater (Type 2 accident). Every plant condition in the case of Type 2 accident is not necessary F&B operation. If safety injection is available continuously in the case of Type 2 accident, F&B operation is not necessary. The differences between Type 1 accident and Type 2 accident are the amount of loss of coolant inventory and the timing of loss of residual heat removal mechanism.

Plant conditions are affected by steam generator inventory, RCS inventory, core inventory, and safety injection. In the case of a Type 1 accident, the plant conditions are affected by the steam generator inventory, RCS inventory, and core inventory as shown in Table 1. As the number of the state increases, the necessity of an F&B operation increases. To prevent core damage in the case of a Type 1 accident, operators must initiate an F&B operation when the RCS condition is in State 1, State 2, or State 3. Even if the RCS condition reaches State 4, an F&B operation is still necessary to prevent the core from melting [5].

Table 1 Categorization of plant conditions requiring an F&B operation for Type 1 accidents [5]

	SG Inventory (Inv)	RCS Inv	Core Inv
State 0	Normal	Full (F)	Covered TAF (CT)
State 1	Low (L)	F	CT
State 2	None (N)	F ~ L	CT
State 3	N	L	Uncovered TAF (UT)
State 4 (core damage)	N	L	UT

In the case of a Type 2 accident, the plant conditions are also affected by the steam generator inventory, RCS inventory, and core inventory as well as the safety injection as shown in Table 2. When the RCS condition is in State 1-2, State 2-2, or State 3-2, an F&B operation is necessary [5].

Table 2 Categorization of plant conditions requiring an F&B operation for Type 2 accidents [5]

	SG Inv	Safety Injection	RCS Inv	Core Inv
State 0	Normal	Available (A)	M ~ L	-
State 1-1	L	A	M ~ L	-
State 1-2	L	Unavailable (UA)	M ~ L	-
State 2-1	N	A	M ~ L	CT
State 2-2	N	UA	M ~ L	CT
State 3-1	N	A	L	UT
State 3-2	N	UA	L	UT
State 4 (core damage)	N	-	L	UT

In the case of Type 2 accident, if the safety injection is unavailable by high pressure of RCS and steam generators dry out, 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. The availability and amount of safety injection depends on the RCS pressure and availability of the SIS. 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 F&B operation in the case of a medium or large break because they are under the low RCS pressure sequences [6].

Plant conditions in the case of Type 2 accident are affected by timing of break-up because timing of break-up affects the availability and amount of safety injection. LOCA and transient with loss of feedwater can occur simultaneously or LOCA can occur after the transient with loss of feedwater occurs. If the break occurs in State 1 of Type 1 accident, RCS pressure can be decreased below the shutoff head of HPSI pump easily because the steam generators can be removed the residual heat during State 1. If the break occurs during State 2 and 3 of Type 1 accident, the break size is needed to be large to inject the coolant by SIS because the RCS inventory is low and RCS pressure is high in State 2 and 3 of Type 1 accident.

The RCS condition which requires F&B operation depends on continuous availability of safety injection as mentioned. If a sufficient SI flow rate to the RCS is injected continuously, F&B operation is not necessary. 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 unavailability of safety injection should be checked to confirm the necessity of F&B operation in the case of Type 2 accident. State 1-2, 2-2, 3-2, and 4 of Type 2 accident is similar to the statuses of State 1, 2, 3 and 4 in the case of Type 1 accident. When the RCS condition is State 3-2, the RCS pressure and temperature is high as similar as State 3 of Type 1 accident [5].

2.2 Considerations for PSA modeling

Plant physical condition is affected by cumulative effects of type of initiating event, equipment failure, human action, and automation such as reactor trip. Sequences of event tree start from initiating event. Each heading of event tree is related to mitigation system. Fault tree model takes into account the component failures and human errors which are related to failure of mitigation system.

In the case of combined accident, cumulative effects of plant conditions such as type of initiating event, equipment failure, human action, and automation are much more complicated than the single events in PSA.

The timing of event occurrence can affect core damage occurrence. For example, if the TLOFW accident and 2 inch equi~ break LOCA occur simultaneously when the 1 HPSI pump is available, the F&B operation is not necessary because the amount of SI is enough to cool down the core. However, if TLOFW accident occurs before 2 inch break LOCA occurs, the F&B operation must be initiated to prevent core damage.

The order of events can also affect core damage occurrence. If the LOCA occurs first, and then TLOFW accident occurs, the F&B operation may not be necessary to initiate when the amount of safety injection is sufficient even though the HPSI pumps are partially available. On the other hand, if the TLOFW accident occurs first, and then LOCA occurs, the F&B operation should be initiated even though the HPSI pumps are fully available.

As mentioned above, when the amount of safety injection is not sufficient, the F&B operation is necessary to initiated. In the case of combined accident, the failure probability of F&B operation component may be changed because F&B operation components can be used according to the characteristics of accident before F&B operation is initiated by operator. These effects should be considered in PSA model.

Since a human failure probability of F&B operation is high [7], the human failure probability should be estimated reasonable. Especially, the available diagnosis time for operators under combined accident including TLOFW accident should be identified systematically.

Reactor coolant pump (RCP) is tripped by operators, and failure of RCP trip is not considered in conventional PSA model. However, the timing and failure of RCP trip much affects available diagnosis time for operators

[8]. Therefore, the effects of the timing and failure of RCP trip is necessary to be considered in PSA model.

3. Discussions & Conclusions

The PSA is significant to assess the risk of NPPs, and to identify the design and operational vulnerabilities. Even though the combined accident is very rare event, the consequence of combined accident is very hazardous. If the operator initiates F&B operation properly under the combined accident including TLOFW accident, the operators can prevent the core damage. Since F&B operation is last resort to prevent core damage and necessary conditions of F&B operation are very complicated, the consequence of these events should be considered in PSA model to improve emergency response capabilities under the rare events.

Plant physical condition is affected by cumulative effects of type of initiating event, equipment failure, human action, and automation such as reactor trip. The timing of event occurrence, the order of events, availability of F&B operation component, the available diagnosis time for operators under combined accident including TLOFW accident, the effects of the timing and failure of RCP trip should be considered in PSA model systematically.

The order of headings in conventional event tree models shows the accident sequence, however, change of heading order does not affect the results of conventional event tree because conventional event trees are static model, and the availability of mitigation systems are considered as average values and the available time to diagnosis for operator is considered conservatively with assumptions. Therefore, the static event tree model is not suitable to evaluate the risk of NPP under the combined accident.

Dynamic PSA modeling is better to estimate the effects of heading order and timing issues. Especially, dynamic PSA can model accident sequences and estimate their probabilities through integrated, time-dependent, probabilistic and deterministic models of NPPs, based on the thermal-hydraulic processes and operator behavior in accident conditions [9]. We will develop the dynamic PSA model for the combined accident including TLOFW accident in the further study.

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