An Estimation of Operator's Diagnostic Time for Feed-And-Bleed Operation under Various Scenarios

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1. Introduction

A probabilistic safety assessment (PSA) model has been commonly employed to systematically quantify the safety of nuclear power plants (NPPs). A static event tree model and a static fault tree model are most popular models of PSA models. Using two models, core damage frequency (CDF) can be calculated to quantify the risk of NPP based on the accident scenarios. However, static PSA model cannot be easily reflected the plant dynamics, which derive from the interaction of different plant components and the interaction between the operator and plant control equipment. In order to assess realistic safety of plant, effects of interactions between components, operator, and plant condition are needed to be considered in the PSA model [1][2].

One of the important issues to estimate the CDF is the estimation of human error probability (HEP). When an accident occurs, operators follow the emergency operating procedure and check various alarm, parameters, and signals [3]. In the conventional Korean PSA model, the Korean standard HRA (K-HRA) method is used. In this method, the HEP is the sum of diagnosis error probability and execution error probability. A diagnosis error probability is expressed by the available time for diagnosis and adjusting performance shaping factors, and an execution error probability is a function of task type and stress level [4]. Available time for diagnosis is very important factor of HEP. If the available time for diagnosis is short, the HEP becomes high.

In order to obtain the realistic risk assessment results, we first focus on the estimation of HEP considering the plant dynamics under various scenarios. Target operation and scenarios are feed-and bleed operation (F&B operation) and total loss of feedwater (TLOFW) accident with/without loss of coolant accident (LOCA). One of the highest HEP is HEP of F&B operation. In additional, Scenarios, which are related to combination secondary heat removal failure and primary heat removal failure, are most critical core damage scenario of the combined accident except scenarios related to station black out (SBO). In these scenarios, the F&B operation is last resort to prevent core damage.

2. Relationship between accidents, mitigation functions and plant condition

An F&B operation directly cools the RCS using the primary cooling system when residual heat removal by the secondary cooling system is not available. Plant conditions that need an F&B operation are caused by transients with a loss of feedwater (Type 1 accident) or LOCA and transients with a loss of feedwater (Type 2 accident). In the case of a Type 2 accident, an F&B operation is only needed for certain plant conditions. If safety injection is continuously available in the case of a Type 2 accident, an F&B operation is not necessary. The differences between a Type 1 accident and Type 2 accident include the loss of coolant inventory and the timing of the loss of the residual heat removal mechanism [5].

Operators follow the emergency operating procedures (EOP) to initiate F&B operation to mitigate accidents. EOPs are plant specific procedures containing instructions for operators to implement preventive measures for managing accidents. There are two types of EOPs: optimal recovery procedures (ORPs) and functional recovery procedures (FRPs). The ORPs are designed to mitigate an accident when the operators can diagnose the specific event. The FRPs are designed for plant specific functional recovery EOPs which the operators would use to verify the satisfactory control or restoration of all critical safety functions. They provide actions to control events which cannot be identified or misdiagnosed, or for which the ORPs are not adequately treating the symptoms [6].

F&B operation is in the FRP and includes a number of steps following the opening of the safety depressurization system (SDS) valves. The steps of F&B operation can be categorized into two parts: diagnosis for necessity of F&B operation and performance of F&B operation from initiation to termination F&B operation.

Entry conditions of F&B operation in EOP are [7]:

- Failure to recover the steam generator levels (when both wide range level and feedwater flow rate are too low)
- Temperature of primary side (Tc) rises uncontrollably because the heat removal of the RCS is unavailable

- Core exit temperature (CET) is less than 650℃ (Entry condition of Severe Accident Management Guideline)
- Pressurizer safety valve (PSV) opens

Scenario of Type 1 accident is simpler than scenario of Type 2 accident. A TLOFW accident is used to represent Type 1 accident. Fig.1 shows the relationship between accidents, mitigation functions and plant condition when the TLOFW accident occurs.

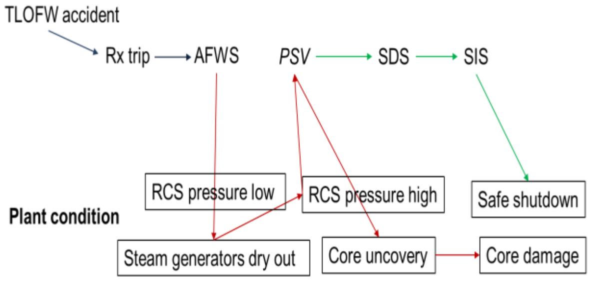

Fig. 1 Relationship between accidents, mitigation functions and plant condition in the case of TLOFW accident

When the TLOFW accident and LOCA are combined, the sequence is changed shown in Fig. 2. If the LOCA occurs when pressure is high, according to the break size the pressure will be drop and according to the flow rate from SIS next step is decided If the SI flow rate is insufficient, the SDS valves need to be opened.

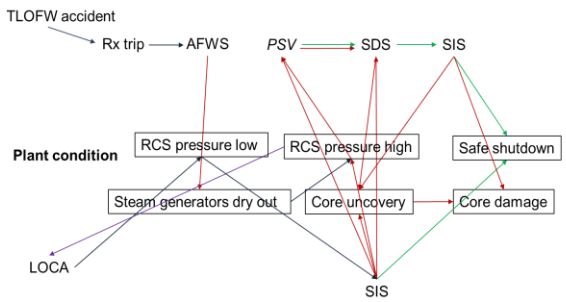

Fig. 2 Relationship between accidents, mitigation functions and plant condition in the case of TLOFW accident with LOCA

Based on Fig 2, relationship between plant component, operator action, and plant condition can be illustrated as shown in Fig. 3. Each mitigation affects plant condition and next mitigation condition. Accident type and timing also affect plant condition and next mitigation condition.

After accident happens, the reactor is tripped and auxiliary feedwater system (AFWS) is failed. Any time the break occurs, pressure will be drop according to the break size and timing. After break occurs, if pressure is low and amount of SI is enough, the plant condition becomes safe shutdown. But if pressure is high, operator need to open the SDS valves. Finally, the success of F&B operation is decided the core damage or not.

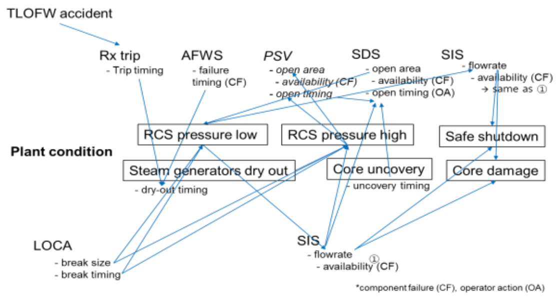

Fig. 3 Relationship between plant component, operator action, and plant condition in the case of TLOFW accident with LOCA

The timing of the reactor coolant pump (RCP) trip is an important factor of the heat source after the reactor trip. Continued operation of the RCPs adds significant energy to the primary system [8]. After the accident, the RCPs are tripped by operators based on the EOP. Step 4 in EOP-00 in OPR1000 directs the operators to trip the RCPs if the subcooled margin is less than 15℃; in EOP-05, Step 4 directs the operators to trip the RCPs without conditions.

3. Estimation of available time distribution for diagnosis of F&B operation

In the conventional PSA model, the available time for diagnosis is much more conservatively calculated when the secondary side fails. The conventional PSA considers that all HEPs of F&B operation are the same. From the Jung et al.'s results, the available time for F&B operation is 21 minutes and available time for diagnosis is 12 minutes [3]. However, the HEPs of F&B operation should be considered separately according to the accident type. Available time for diagnosis is re-estimated according to the accident scenarios based on thermohydraulic (TH) analysis. TH analysis is performed using the MARS (Multi-dimensional Analysis of Reactor Safety) code [9][10].

As mentioned previously, the available time for diagnosis is affected by accident scenarios, so the minimum available time for diagnosis is chosen to be conservative. From the Jung's study, the available time to initiate F&B operation is from cue (auxiliary feed water actuation signal) to PSV opening [3][4]. However, the core is still not damaged after PSV opening from the TH analysis. Therefore, we estimated the available time of diagnosis for F&B operation as the time from cue to SAMG entry condition.

In order to reflect the relationship between plant component, operator action, and plant condition, we obtain the distribution of available time of diagnosis using the MOSAIQUE developed by KAERI. Key Features of MOSAIQUE are to assign a distribution to a variable in a computer code input, to create samples for variables and to create input files for the given number of samples [11].

Based on the Fig. 3, the variables are break size (0 in. ~ 3 in. break), break timing (0 sec ~ 4500 sec), trip timing of RCP (0 sec ~ 1500 sec after reactor trip), and availability of high pressure safety injection (HPSI) pump (1, 2 pumps) under the TLOFW accident with LOCA. For Type 1 accident, trip timing of RCP (0 sec ~ 1500 sec after reactor trip) is chosen for variable under TLOFW accident without LOCA. This paper shows the results when the one HPSI pump is available in the case of TLOFW accident with LOCA as shown in Fig. 4, and the results when the TLOFW occurs. In the case of Fig.4, 68 % cases need F&B operation. Average available time for diagnosis in Fig. 4 is 3538 sec. Average available time for diagnosis in Fig. 5 is 3743 sec. The range of distribution in Fig. 4 is much larger than the range of distribution in Fig. 5. We expected that the available time of diagnosis in the case of Type 2 accident is longer than the time in the case of Type 1 accident. However, some cases in Fig. 4 are shorter than Fig. 5. Therefore, we need to check effects of variable on the accident scenarios in detail.

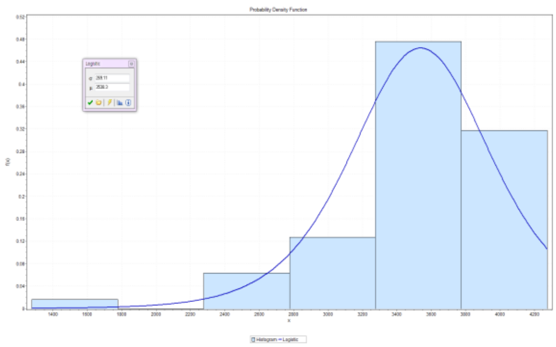

Fig. 4 Distribution of available time for diagnosis to initiate F&B operation when one HPSI pump is available under TLOFW accident with LOCA.

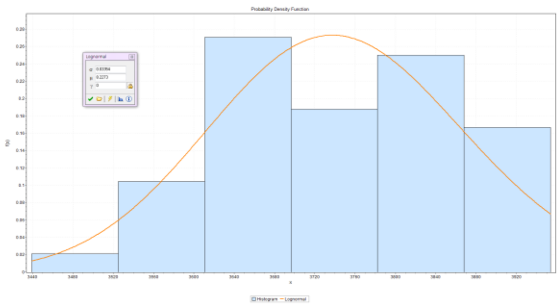

Fig. 5 Distribution of available time for diagnosis to initiate F&B operation under TLOFW accident without LOCA.

4. Conclusions and Further study

To estimate available operator diagnosis time, we identify the relationship between accidents, mitigation function, and plant condition. Distribution of available time of diagnosis was estimated using the MOSAIQUE. The variables are break size, break timing, trip timing of RCP, and availability of high pressure safety injection (HPSI) pump under the TLOFW accident with LOCA. For Type 1 accident, trip timing of RCP is chosen for variable under TLOFW accident without LOCA. Average available time for diagnosis under TLOFW accident with LOCA is 3538 sec. Average available time for diagnosis under TLOFW accident without LOCA is 3743 sec.

Some cases in Fig. 4 are shorter than Fig. 5. Effects of variables on the accident scenarios should be identified in detail. Moreover, method to reflect the distribution of available time for diagnosis in PSA model will be studied in further.

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