Sequence Tree Modeling for Combined Accident and Feed-and-Bleed Operation

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1. Introduction

In the case of combined accident, the accident sequence is very complicated, so it is not easy to identify the accident sequence and perform the proper actions. In order to decide proper operator actions under combined accident, sequences to core damage when the specific operation are failed under combined accident are necessary to identify. If a systematic model to analyze combined accident will be developed, designers can understand accident sequences in detail and operators can perform the proper safety actions.

In order to address this issue, this study suggests the sequence tree model to analyze accident sequence systematically. Using the sequence tree model, all possible scenarios which need a specific safety action to prevent the core damage can be identified and success conditions of safety action under complicated situation such as combined accident will be also identified. Sequence tree is branch model to divide plant condition considering the plant dynamics. Since sequence tree model can reflect the plant dynamics, arising from interaction of different accident timing and plant condition and from the interaction between the operator action, mitigation system, and the indicators for operation, sequence tree model can be used to develop the dynamic event tree model easily.

Target safety action for this study is a feed-and-bleed (F&B) operation. A F&B operation directly cools down the reactor cooling system (RCS) using the primary cooling system when residual heat removal by the secondary cooling system is not available. F&B operation is very important because F&B operation is last resort to prevent the core damage for heat removal. Systems related to F&B operation are safety depressurization system (SDS) and safety injection system (SIS). The SDS provides a manual mean of rapidly depressurizing the RCS for the highly unlikely event of a total loss of feedwater (TLOFW) accident. The reduced RCS pressure allows high pressure safety injection (HPSI) flow to replenish and eventually exceed the mass flow rate out through the SDS prior to uncovering the core [1, 2].

2. Methods and Results

Sequence tree modeling is for identification of the theoretically possible sequences to core damage when target operation is failed and sampling analysis with sequence tree model is for identification of practical sequences to core damage when target operation is failed at step 1. In the step 2, designer needs to check the heat source and available heat removal mechanisms after first accident occurs. In the step 3, designer needs to categorize the plant condition using indicators to categorize the occurrence timing of second accident. In the step 4, designer should check the plant condition at timing when second accident happens, and available change points after second accident happens. In the step 5, designer identifies the theoretically possible sequences using sequence tree model. In the step 6, designer can identify the practical sequences using sampling analysis and reflect the results of sampling analysis on sequence tree model.

2.1 Indicators for Sequence Tree

Available and sufficient heat removal mechanisms is the most important factor to cool down the RCS. With insufficient heat removal mechanism, core is always damaged. Although the scenarios of combined accident is complicated, identification of reasons in a point view of heat sink can be easy to be identified, and sequences to core damage without target safety action can be identified. Therefore, it is necessary to identify the indicators which recognize the availability of heat removal mechanisms and plant conditions which are affected by heat source and heat removal mechanism.

For identification of continuous indirect cooling, the steam generator level and feedwater flow rate are used. Break timing and break size is for identification of LOCA occurrence. Success of F&B transient are related to availability of SIS and RCS pressure. To check the termination of F&B transient due to the high pressure, the RCS pressure should be checked. To identify initiation of aggressive cooldown and F&B operation, the atmospheric dump valve (ADV) opening timing and SDS opening timing are used. Core damage or successful cool down by heat removal mechanism can be identified using RCS temperature. Indications to identify plant condition affected by heat removal and heat sources should be also considered in sequence tree model.

2.2 Sequence tree model for a TLOFW accident

Based on conventional PSA model for single event, the sequence tree model can be easy to develop. Branch points are related to headings of event tree. Represent TLOFW accident sequence of PSA model (Sequence #26) is combination of auxiliary feedwater system failure and failure of opening SDS valves due to the operators or malfunction of SDS when loss of main feedwater accident happens.

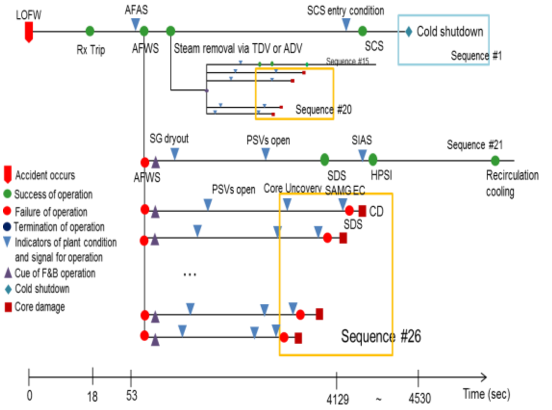

Fig. 1 Sequence tree model of a TLOFW accident

Based on sequence 26 in PSA model, a sampling analysis are performed using MARS code and MOSIQUE program [3, 4]. MOSIQUE program is a software to support the uncertainty analysis for the thermal hydraulic analysis. Key features of MOSAIQUE is to assign a distribution to a variable in a computer code input, to create samples for variables based on Latin hypercube sampling or traditional random sampling, to generate computer code's input files using samples, and to run computer codes automatically.

Target plant model is OPR1000. Reactor is tripped by RPS signal. The variable for sampling analysis is reactor coolant pump (RCP) trip timing. Since continued operation of the RCPs adds significant energy to the primary system and RCPs are tripped by operator, the timing of RCP trip is selected as variable for sampling analysis in this study. In the conventional PSA model, trip timing of RCP is fixed when the subcooling margin is less than 15℃. In real situation, there are various timing to RCP trip. From the EOP, operators can trip when subcooling margin is less than 15℃, operator follows step 4 in EOP-05 "Loss of All Feedwater" or operator follows step 3 in procedure of F&B operation in functional recovery procedure. Therefore, in this study, the trip timings of RCPs are sampled from 600 s which is timing to finish a diagnosis action procedure (reference) to depletion timing of RCS flow based on uniform distribution using Latin hypercube sampling method in MOSIQUE program. The other assumptions are same as Kim's study [1, 2].

Sampling analysis with sequence tree model can obtain the same results of dynamic event tree model if the probabilities in model such as initiating event frequency can be estimated. From the previous study, the available time for diagnosis is much more conservatively calculated in the conventional PSA model. The available time to initiate F&B operation is from the cue (auxiliary feedwater actuation signal) to PSV opening in the conventional PSA model. However, there is sufficient time between PSV opening and core damage from the thermohydraulic analysis in the previous study. Therefore the diagnosis available time for the operator to initiate F&B operation is the time from the cue to SAMG entry condition as same as the previous study [2, 5].

Fig. 1 shows the results of sampling analysis with sequence tree model for TLOFW accident. Core damage frequency (CDF) caused by sequence #26 of static conventional PSA model is 1.524e-7. CDF caused by sequence #26 of sequence tree model with sampling analysis is 3.049e-9. It is only 2% of static conventional PSA model. Branch probabilities in sequence #26 are from 3.044e-11 to 3.074e-11. The human error probability (HEP) of F&B operation in the case of TLOFW accident changes from 1.43e-1 to 2.10e-3 ~ 2.11e-3 based on K-HRA model [6, 7]. From sampling analysis, the available time for diagnosis is from 51.5 min to 54.5 min, so, diagnosis error probability is from 9.52e-5 to 1.13e-4, and execution error probability is 2.0e-3.

2.3 Sequence Tree Model for TLOFW Accident with LOCA

Dynamic event tree model is useful model to analyze the plant dynamics systematically. However, since initiating event frequency and distribution of accident timing in the case of combined accident cannot be estimated, dynamic event tree model cannot be developed.

In order to identify accident sequences for combined accident, we develop the sequence tree model based on the structure of dynamic event tree. Branch points are the change point of plant condition or accident timing.

Important factors in a combined accident include the different accident timings and the relationship between the accidents, safety functions, and operator action. The sequence tree model systematically categorizes the plant condition based on plant dynamics, where the branches can be classified according to the order of the branch points. The branch points are accident timing and the timing of indicators which inform operation timing of the mitigation system for heat removal, cues of operator, or plant condition. Subsequently, the theoretically possible sequences using the sequence tree model can be identified.

After possible sequences using the sequence tree model are identified, the sampling analysis is needed to perform to identify practical cases among the possible sequences in the further study. If the distribution of process parameters and accident timing can be estimated reasonably, occurrence probability of sampling cases can be estimated.

Sequences of core damage caused by the failure of F&B initiation under a TLOFW accident with LOCA are identified, including 97 types of sequences. The first number of sequence group means the break timing. If the second number of sequence group is 1, safety injection is not injectable due to the high pressure. On the other hands, if the second number of sequence group is 2, temporary or continuous SIS coolant injection is possible, but it is with an insufficient amount of F&B transient to cool down the RCS, and thus, F&B operation is necessary to prevent the core damage.

The first sequence group (Sequence 1) includes the sequences when LOCA occurs before reactor trip and after a TLOFW accident occurs; it has 38 type of sequences. Steam generator dryout timing precedes PSV opening, SIS actuation timing, and core uncovery. The second sequence group (Sequence 2) includes the sequences when LOCA occurs before SG dryout and after Rx trip. It also has 38 type of sequences. SG dryout timing occurs before PSV opening, SIS actuation timing, and core uncovery. The third sequence group (Sequence 3) includes the sequences when LOCA occurs before the PSVs first open and after SG dryout. It includes twelve types of sequences. The fourth sequence group (Sequence 4) includes the sequences when LOCA occurs before core uncovery and after the PSVs first open, and it has 6 type of sequences. The fifth sequence group (Sequence 5) includes the sequences when LOCA occurs before core damage and after core uncovery. In fifth sequence group, there are 3 types of sequences.

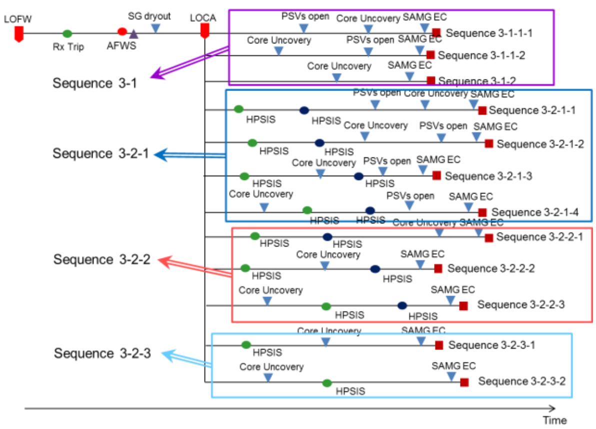

Fig. 2. Sequence 3 of sequence tree model for sequences to core damage due to failure of F&B operation under TLOFW accident with LOCA

Fig. 2 shows sequence groups 3, respectively. All sequences in Fig. 2 are that core is damaged due to failure of F&B operation. Cases of Sequence 3-1 are that no safety injection coolant is injected because of high RCS pressure and the core is damaged. Cases of Sequence 3-2-1 are that SIS injects coolant temporarily, and PSVs are opened after SI termination. Cases of Sequence 3-2-2 are that SIS injects coolant temporarily and PSVs are not opened due to RCS pressure. Cases of Sequence 3-2-3 are that SIS injects coolant continuously, but F&B transient is not sufficient to cool down RCS.

3. Conclusions

The theoretically possible accident sequences under a combined accident were identified and systematically categorized using the sequence tree model. In this study, a TLOFW accident and a TLOFW accident with LOCA were the target accidents. Based on the conventional PSA model and indicators, the sequence tree model for a TLOFW accident was developed. Based on the results of a sampling analysis and data from the conventional PSA model, the CDF caused by Sequence #26 can be realistically estimated. For a TLOFW accident with LOCA, second accident timings were categorized according to plant condition. Indicators were selected as branch point using the flow chart and tables, and a corresponding sequence tree model was developed. There are 97 types of sequences to core damage caused by the failure of F&B operation in the sequence tree model.

If sampling analysis is performed, practical accident sequences can be identified based on the sequence analysis. If a realistic distribution for the variables can be obtained for sampling analysis, much more realistic accident sequences can be described. Moreover, if the initiating event frequency under a combined accident can be quantified, the sequence tree model can translate into a dynamic event tree model based on the sampling analysis results.

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