Analysis on Failure of Feed-and-bleed Operation under TLOFW accident with LOCA

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Combined accident is defined that two initiating events occur simultaneously or differently. In the case of combined accident, the accident sequence is very complicated and dynamic, so it is difficult to identify the accident sequence clearly. Sequence tree model is developed to analyze the sequences of combined accident when the safety action is failed by operator or system. This 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 is branch model to divide plant condition considering the plant dynamics. The branch points are accident timing, operation timing of related mitigation system, and indicators for operator action and for identifying plant condition.
Using the sequence tree model, all possible scenarios requiring a specific safety action to prevent core damage can be identified, and success conditions of the safety actions performed during a complicated situation, such as a combined accident, will be also identified. Possible type of sequences of core damage caused by the failure of F&B initiation under a TLOFW accident with LOCA are identified, including 95 types of sequences. Important factor of combined accident is different accident timing and relationship between accident, safety functions, and operator's action. However, conventional static PSA model cannot reflect the effect of the order or timing of events. With sampling analysis, the realistic and possible sequences can be identified. If a systematic model to analyze combined accident can be developed, designers can understand accident sequence in detail and consider the weakness points of plant safety based on the results. Moreover, the results from model can be used to decision making for regulators.

I. INTRODUCTION

The 2011 Fukushima accident in Japan revealed that even a very rare event must be considered in order to prevent radioactive release to the environment from poor treatment based on a lack of information [1, 2]. A combined accident, defined as two initiating events occurring at the same or different times, is one of these very rare events and thus is not considered in current safety analyses.

In a combined accident, the accident sequence is very complicated and it is therefore not easy to identify and perform the proper actions. In order to decide the proper operator actions in a combined accident, it is necessary to identify the sequences to core damage when specific operations fail. With the development of a systematic model to analyze combined accidents, designers can understand accident sequences in detail and operators can perform the proper safety actions.

This study addresses this issue by suggesting a sequence tree model to systematically analyze accident sequences. A sequence tree model is a type of branch model that categorizes the plant condition by considering plant dynamics. Using the sequence tree model, all possible scenarios requiring a specific safety action to prevent core damage can be identified, and success conditions of the safety actions performed during a complicated situation, such as a combined accident, will be also identified. As the sequence tree model can reflect the plant dynamics that arise from the interaction of different accident timings with the plant condition, and also from the interactions between operator action, mitigation systems, and the indicators for operation, the model can be used to develop a dynamic event tree model [3, 4, 5].

This study develops a sequence tree model to core damage requiring a Feed-and-Bleed (F&B) operation under the combination of a total loss of feedwater (TLOFW) accident with a loss of coolant accident (LOCA).

II. Sequence tree model for F&B operation under TLOFW accident with LOCA

In the present study, sequence tree modeling is adopted to identify the theoretically possible sequences to core damage when target operation fails, and a sampling analysis with the sequence tree model is used to identify the practical sequences to core damage when target operation fails. Fig. 1 shows the accident sequence analysis method for a combined accident [6]. In step 2, the designer needs to check the heat source and available heat removal mechanisms after the first accident occurs. In step 3, the designer needs to identify the plant condition using indicators to categorize the occurrence timing of a second accident. In step 4, the designer should check the plant condition after the second accident occurs and the available change points (indicators) after the second accident. The available change points are assigned in each sequence group. In step 5, the indicators are permutated to develop the sequences in the sequence tree model. In step 6, the designer eliminate impossible sequences based on a thermohydraulic analysis.

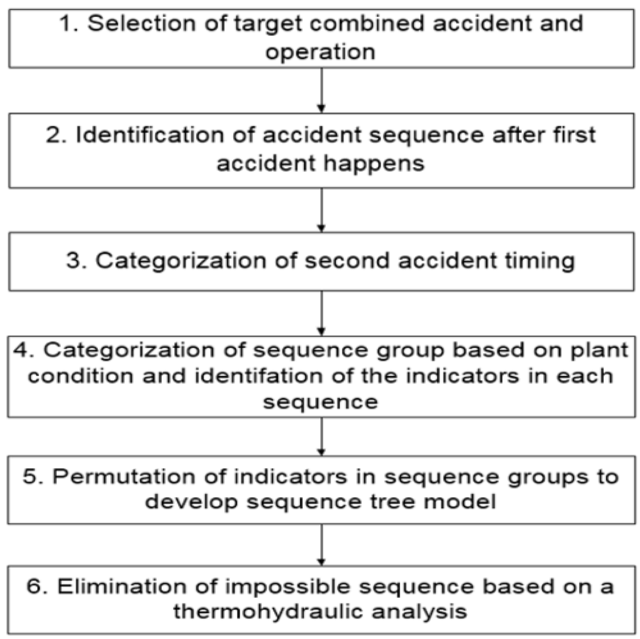

Fig. 1 Process of accident sequence analysis for a combined accident [6]

The sequence tree is a branch model to divide plant conditions considering plant dynamics. The branch points (condition change points) are accident timing, operation timing of related mitigation system for heat removal, and indicators for operator action and for identifying plant condition. In the sequence tree model, safety system starting, termination, and failure timing are the branch points in the sequence tree model, represented by green, dark blue, and red circles, respectively. Signals for the safety systems and process parameters to identify the plant condition are used as indicators in model as inverted triangles. Usually, indicators to identify plant condition are not used as branch points in PSA models; however, in the sequence tree, indicators are important factors to understand plant condition when a second accident occurs. Triangles represent the cue for target operation by operators.

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. As mentioned in the previous section, 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.

In this study, the target combined accident is an initial TLOFW accident followed by LOCA. Based on the branch of Sequence #26 of event tree model of TLOFW accident [7], plant condition can be categorized as shown in Fig. 2. The first condition is maximum heat release to the primary side after a TLOFW accident occurs. The second condition is steam generator inventory decrease and decay heat release. The third condition is secondary side heat removal depletion and reactor coolant system (RCS) pressure increase. The fourth condition is RCS pressure between the PSV opening and closing set points. The fifth condition is core uncovery under very high pressure. After LOCA occurs, sequences (including the amount of heat removal by F&B transient (safety injection (SI) - break)) are strongly affected by the RCS condition at break timing, the break size, and SIS availability.

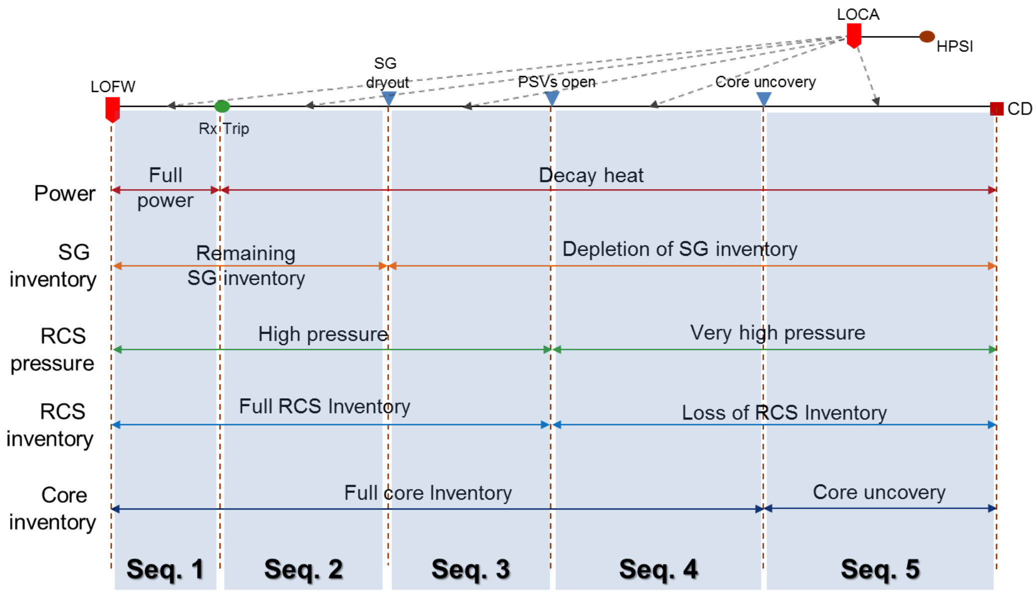

Fig. 2 Categorization of second accident timing [6]

After LOCA occurs, the plant condition which needs an F&B operation can be categorized. First, the RCS pressure will not decrease below shutoff head of high pressure safety injection pump (HPSIP) until core damage, so safety injection system (SIS) cannot inject coolant after LOCA occurs in this case. In this first plant condition, the pressurizer safety valve (PSV) would be opened or not according to RCS pressure. Second, the SIS can inject coolant temporary before core damage, and PSVs are opened after SIS stops to inject coolant. Third, the SIS can inject coolant temporary before core damage, but PSVs are not opened after SIS stops to inject coolant. Forth, SIS can inject coolant continuously until core damage, but insufficient amount of heat removal by F&B transient, the core would be damaged. Starting point of all sequences to core damage is TLOFW occurrence. End point of all sequences to core damage is core damage timing [6].

The first sequence group (Sequence 1) includes the sequences when LOCA occurs before reactor trip and after a TLOFW accident occurs. Plant condition of Sequence 1-1 is no safety injection due to high RCS pressure until core damage. The indicators in Sequence 1-1 are Rx trip, SG dryout, PSV opening, and core uncovery. Plant condition of Sequence 1-2 is SIS can inject coolant temporary and PSVs are opened after SIS stops to inject. The indicators in Sequence 1-2 are Rx trip, SG dryout, SI start, SI stop, PSV opening, and core uncovery. Plant condition of Sequence 1-3 is SIS can inject coolant temporary and PSVs are not opened after SIS stops to inject. The indicators in Sequence 1-3 are Rx trip, SG dryout, SI start, SI stop, and core uncovery. Plant condition of Sequence 1-4 is SIS can inject coolant continuously. The indicators in Sequence 1-4 are Rx trip, SG dryout, SI start, and core uncovery. The second sequence group (Sequence 2) includes the sequences when LOCA occurs before SG dryout and after Rx trip. 4 plant conditions of Sequence 2 after LOCA occurs are same as Sequence 1. The indicators in Sequence 2-1 are SG dryout, PSV opening, and core uncovery. The indicators in Sequence 2-2 are SG dryout, SI start, SI stop, PSV opening, and core uncovery. The indicators in Sequence 2-3 are SG dryout, SI start, SI stop, and core uncovery. The indicators in Sequence 2-4 are SG dryout, SI start, and core uncovery. The third sequence group (Sequence 3) includes the sequences when LOCA occurs before the PSVs first open and after SG dryout. 4 plant conditions of Sequence 3 after LOCA occurs are also same as Sequence 1 and 2. The indicators in Sequence 3-1 are PSV opening, and core uncovery. The indicators in Sequence 3-2 are SI start, SI stop, PSV opening, and core uncovery. The indicators in Sequence 3-3 are SI start, SI stop, and core uncovery. The indicators in Sequence 3-4 are SI start, and core uncovery. The fourth sequence group (Sequence 4) includes the sequences when LOCA occurs before core uncovery and after the PSVs first open. The plant conditions after LOCA occurs can be divided 3 types. Plant condition of Sequence 4-1 is no safety injection due to high RCS pressure until core damage. The indicator in Sequence 4-1 is core uncovery. Plant condition of Sequence 4-2 is SIS can inject coolant temporary. The indicators in Sequence 4-2 are SI start, SI stop, and core uncovery. Plant condition of Sequence 4-3 is SIS can inject coolant continuously. The indicators in Sequence

4-3 are SI start and core uncovery. The fifth sequence group (Sequence 5) includes the sequences when LOCA occurs before core damage and after core uncovery. 3 plant conditions of Sequence 5 after LOCA occurs are same as Sequence 4. There is no other indicator in case of Sequence 5-1. The indicators in Sequence 5-2 are SI start, and SI stop. The indicator in Sequence 5-3 is SI start [6].

After identification of indicators in all sub-sequence groups, the permutation of indicators is performed to obtain all sequences. There are 1115 permutation groups. After then, the impossible sequences should be eliminated. There are rules to eliminate impossible sequences. The termination of safety injection should be followed after the starting of safety injection. PSVs cannot be opened after the occurrence of LOCA and before the beginning of safety injection, or during safety injection. After the reactor is tripped, the other indicators are followed in cases of Sequence 1. The steam generators dried out before termination of safety injection in case of Sequence group 1 and 2 since the RCS pressure will increase after loss of heat removal by secondary side. As shown in Fig. 3, the timing of SIS injection termination is always later then the timing of stream generators dry out. Based on this rule, 16 sequences can be eliminated. Finally, there are 95 sequences in sequence tree model. Fig. 4 shows Sequence group 3, respectively. All sequences in Fig. 4 are that core is damaged due to failure of an F&B operation [6].

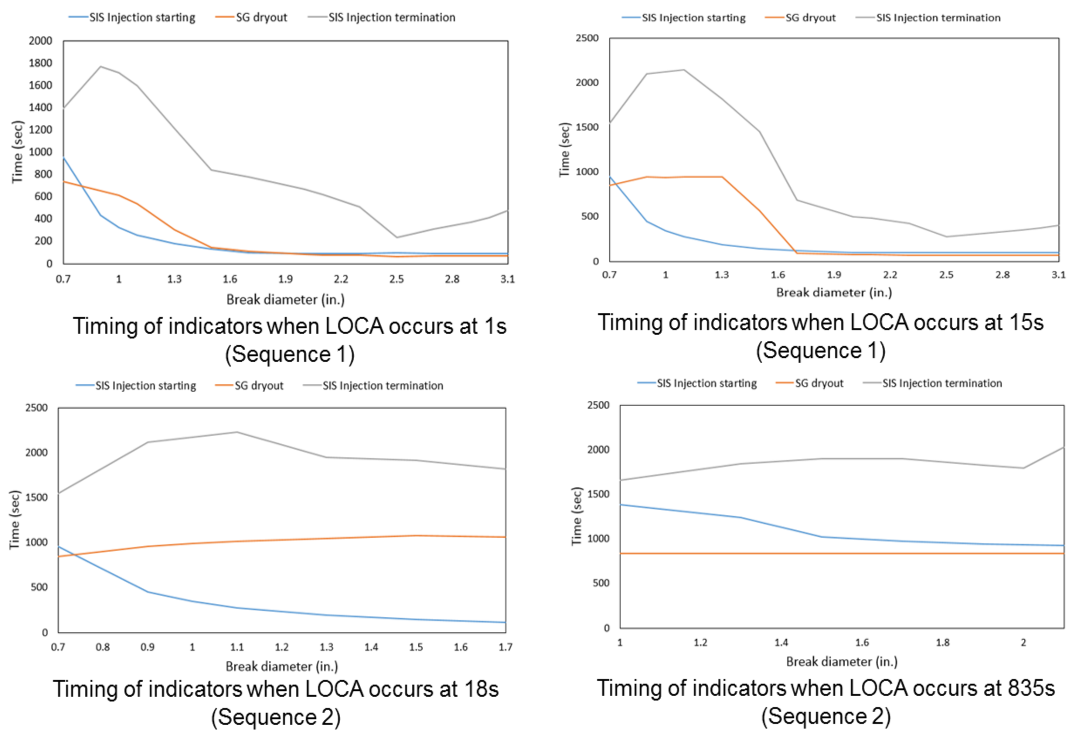

Fig. 3. Timings of SIS injection starting, SG dryout, SIS injection termination according to break size and break timing

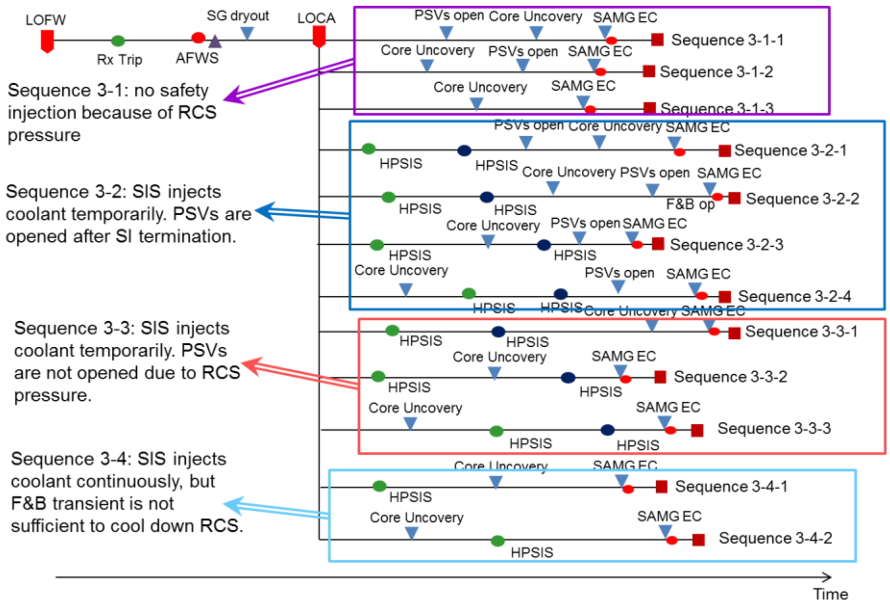

Fig. 4 Sequence 3 of sequence tree model for sequences to core damage due to failure of an F&B operation under TLOFW accident with LOCA [6]

As the sequence tree model can reflect the plant dynamics that arise from the interaction of different accident timings with the plant condition, and also from the interactions between operator action, mitigation systems, and the indicators for operation, the model can be used to develop a dynamic event tree model [3, 4, 5].

III. Sampling Analysis

Relationships between plant components, operator action, and plant condition can be illustrated as shown in Fig. 5 [8]. Each mitigation action affects the plant condition and the next mitigation action, as do accident type and timing. Following an accident, the reactor trips and the auxiliary feedwater system (AFWS) fails. Any time a break occurs, pressure will drop according to the break size and timing; after the break, if pressure is low and the amount of SI is sufficient, the plant becomes safe to shut down. But if pressure is high, operators need to open the SDS valves. In the end, the success of an F&B operation is determined by whether the core is damaged or not. Break size, break timing, and SIS availability are selected as variables. In addition, RCP trip timing is selected as a variable since the continued operation of the RCPs adds significant energy to the primary system.

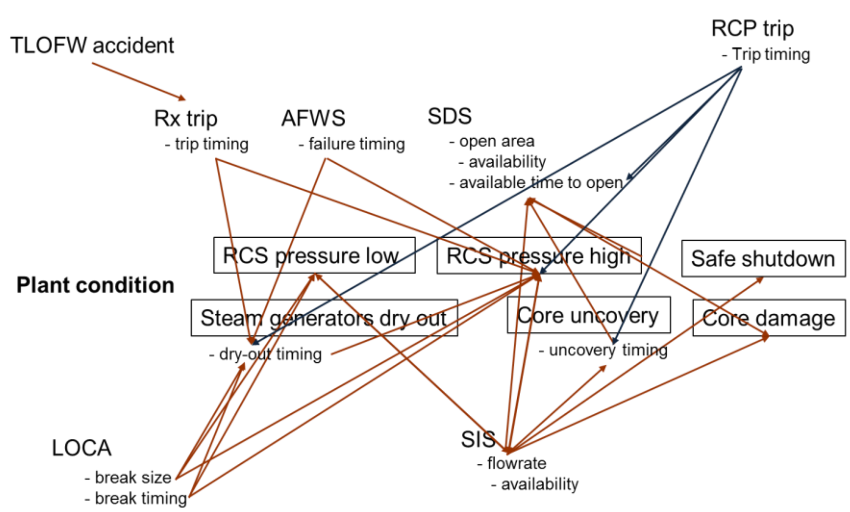

Fig. 5. Relationships between plant components, operator action, and plant condition in a TLOFW accident with LOCA [8]

MARS code is used to sampling analysis with an OPR1000 as the example plant model as shown in Fig. 6 [9]. MOSAIQUE were used to generate 500 sampling cases' inputs. The sampling method is Latin hypercube sampling in MOSAIQUE. Break size and break timing are assumed to have uniform distribution due to lack of information. The range of break timing is 0 s - 3934 s (severe accident management guide line entry timing in a reference TLOFW accident). The range of break size is 0 in - 3.5 in. If 3.5 in. break occurs at 3934 s and 1 HPSIP available condition, the plant condition is cooled down without an F&B operation by operators. Reactor is tripped when the process parameter reaches the set point of reactor protection system. RCPs are tripped when the subcooled margin becomes less than 15℃. To identify the transitions of the sequence according to SIS availability, 2 conditions of SIS availability have the same 500 sampling cases: 1 HPSIP available, 2 HPSIPs available.

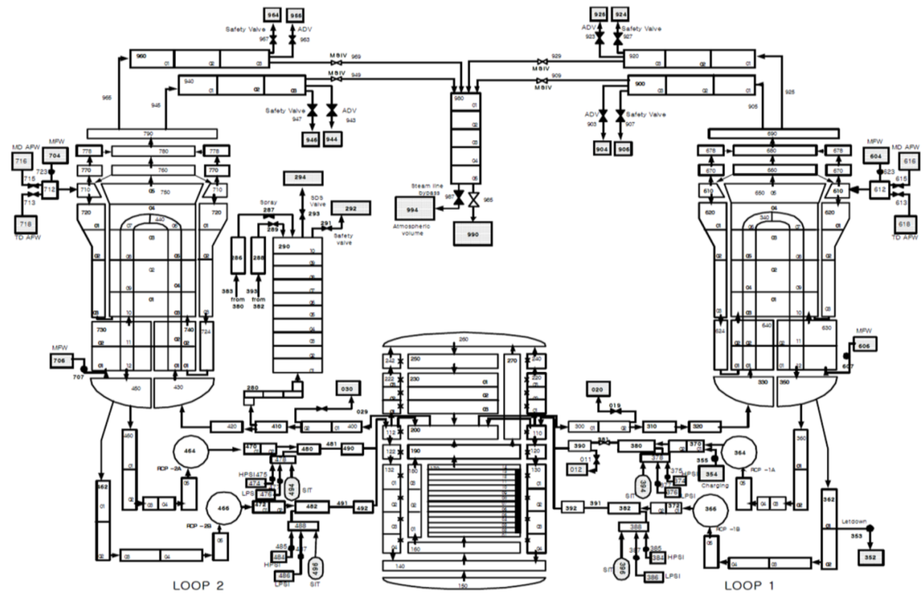

Fig. 6. Nodalization diagram of the MARS model for examples of the OPR1000 [9].

From the sampling analysis, 19 types of sequences were observed. The 4 types of sequences are observed where safety injection is not possible due to high RCS pressure until core damage. Sequences of core damage where PSVs are not opened until core damage are 5 types of sequences. In these cases, operators cannot initiate F&B operation until core damage when the conventional emergency operating procedure of OPR1000 is used. In the previous study, Kim et al. developed advanced operation procedure to cover all possible scenarios for an F&B operation and systematically inform its urgency. Using advanced operation procedure, operators can initiate the F&B operation under all possible sequences under TLOFW accident with LOCA.

The temperature margin distribution can be calculated according to component availability. The temperature margin is the difference between core damage criterion (1477 K) and max. PCT of each cases. This temperature margin is estimated according to availability of components as shown in Table I. If the component availability can be monitored [10], temperature margin can be used with operation procedure.

TABLE I. Temperature margin according to component availability

Percentile	1 SDS valve & 1 HPSIP	1 SDS valve & 2 HPSIPs	2 SDS valves & 1 HPSIP	2 SDS valves & 2 HPSIPs
Min	-131.9	-79.8	6.8	24.7
5%	87.89	136.8	228.8	218.3
10%	186.98	267.34	372.4	361.6
25% (Q1)	244.7	326.35	428.5	473.2
50% (Median)	280.1	374	474.5	477.5
75% (Q3)	298.4	410.95	480.7	482.4
90%	323.94	426	486.2	486.3
95%	349.13	442.09	488.4	488.9

Max	461	474.55	492.0	494.6

IV. Discussion

The analysis of combined accident conditions is necessary even though their probability is extremely low because they can bring huge impact. Especially, even if events extremely unlikely occurs such as design extension conditions, plant might have a chance to safe cool down using safety features and proper operator actions. If operators will check the long-term sub-criticality, heat removal function and emergency power, the plant will be safe under design extension conditions. In a viewpoint of operator action or system function related to heat removal function, sequence tree model is very useful to identify the accident sequences under combined accident.

In this study, target operation was an F&B operation. The target accident scenario was LOCA after TLOFW accident. Sequence tree model for another combined accident can be developed to identify plant condition which is necessary the specific safety function easily. For example, when the small LOCA occurs first, and then TLOFW accident occurs, the F&B operation might be needed. When the detailed sequence of small break LOCA is identified, the second accident timing can be categorized as similar as LOCA after TLOFW accident. After small LOCA occurs, the timing of failure of main feedwater system and auxiliary feedwater system is dominant factor for core damage sequences. Core will not be necessary the F&B operation if the sufficient SI flowrate is injected by SIS. If the main feedwater system and auxiliary feedwater is failed after SITs inject, the F&B operation is not necessary because RCS pressure decreases and HPSIP can inject the sufficient coolant. Meanwhile, if the main feedwater system and auxiliary feedwater is failed before SITs inject, the F&B operation might be necessary.

If new safety components for heat removal is applied, the proper condition to use new safety component can be identified using sequence tree model. Kim et al. suggests integrated passive safety system (IPSS) and this component can be used under a station black out (SBO) combined with LOCA [9, 11]. If the sequence tree model for SBO combined with LOCA is developed, the plant conditions which need IPSS can be easy to identify. From reference [12], the hybrid safety injection tank system can be used the SBO and combined accident related to SBO. For use of hybrid safety injection tank system properly, the sequence tree model is very useful to identify the plant condition which is necessary the hybrid safety injection tank system under combined accident.

V. CONCLUSIONS

Cooling the RCS after a scram is one of the most important safety functions for preventing core damage. To support the operator in deciding whether to initiate an F&B operation under various reactor conditions, plant conditions requiring the initiation of an F&B operation were identified. Sequence tree modeling was suggested to identify the plant conditions which require systematic safety action to prevent core damage under a combined accident. Using the sequence tree model, all possible scenarios necessitating a specific safety action to prevent core damage can be identified Accident sequences under a combined accident were analyzed considering the relationship between the available heat removal mechanisms and plant condition. Indicators were used to recognize the availability of the heat removal mechanisms and the plant condition with flow charts.

For a TLOFW accident with LOCA, second accident timings were categorized as 5 types according to plant condition. Indicators were selected as branch point using the flow chart and tables, and a corresponding sequence tree model was developed. After LOCA occurs, the plant condition which needs an F&B operation can be also categorized. Sub group of sequence represents the plant condition after LOCA occurs. In each sub group of sequence, the indicators are identified. After identification of indicators in all sub-sequence groups, the permutation of indicators is performed to obtain all sequences. After then, the impossible sequences should be eliminated. 1115 permutation group were identified. After rules for elimination of impossible sequences are applied, 95 sequences in sequence tree model and the sequences.

Sequence tree model for another combined accident can be developed to identify plant condition which is necessary the specific safety function easily. Moreover, if new safety components for heat removal is applied, the proper condition to use new safety component can be identified using sequence tree model.

ACKNOWLEDGMENTS

This research was supported by the KUSTAR-KAIST Institute, Korea, under the R&D program supervised by KAIST.

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