Dynamic Safety Assessment of Operator Action Timing in TLOFW Scenarios

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1. Introduction

Total Loss of Feedwater (TLOFW) is considered one of the most risk-significant transients in pressurized water reactors, as the loss of the secondary heat sink causes rapid pressurization of the primary system and core heat-up, which can ultimately lead to core damage (CD) if mitigation is delayed. In probabilistic safety assessment (PSA), TLOFW has been evaluated through predefined event/fault tree (ET/FT) scenarios such as feed-and-bleed (F&B) and auxiliary feedwater system (AFW) recovery.

While the static models provide traceable numerical risk metrics, they inevitably exclude many low-probability yet physically possible scenarios due to the limited consideration of different execution orders between ET headings. PSA expects that, by conservatively constructing a few representative scenarios, other conditions can be enveloped within the conservative assumptions [1].

However, small variations in action time or system state change between representative scenarios can violate the assumptions, leaving behind potential risk. Moreover, fixed success criteria embedded in ET/FT models obscure time-dependency that arises from interactions between systems and operators, thereby concealing critical factors that influence accident progression. As a result, uncensored risk may remain unidentified in the analysis.

To overcome these limitations, many studies have proposed dynamic PSA. The dynamic approaches consider the time-dependency or system states and generate scenario branches whenever operator actions or system states change, thereby revealing risks that could not be censored in PSA [2]. However, as a simulation-based approach, dynamic PSA faces challenges of massive computational resources due to the exponential growth in the number of scenarios when discretizing variables such as operator action timing and system states. To address this challenge, adaptive sampling methods have been introduced, which selectively explore the scenario space by focusing computational resources on the region of interest. Adaptive sampling methods include support vector machines, kriging, and deep learning-based searching algorithm for informative limit surface/states/scenarios (Deep-SAILS) [3].

In this study, TLOFW dynamic scenarios are analyzed with optimized simulations by applying Deep-SAILS. However, as the dimension increases, directly plotting high-dimensional results becomes challenging for visualizing the limit surface. To address this challenge, this study adopts the dynamic risk assessment through automatic accident sequence generation using optimized simulations for nuclear power plants (DRAGON) [4].

2. Methodology

2.1. Deep-SAILS

To practically investigate uncensored risk, this study adopts Deep-SAILS [3]. Deep-SAILS is a deep neural network-based limit surface/states searching algorithm. First, the algorithm generates scenarios with the discretized scenario configuration parameters and trains a metamodel with extreme scenarios to predict scenario consequences. Extreme scenarios represent scenarios configured by the possible maximum or minimum values of the scenario configuration parameters. Second, the algorithm samples only the scenarios predicted to lie in the limit surface. The limit surface represents the boundary that separates success scenarios from CD scenarios. Third, the algorithm iteratively retrains the metamodel using thermal-hydraulic simulation results from only the sampled scenarios until the stopping condition is satisfied. Figure 1 shows the flowchart of Deep-SAILS.

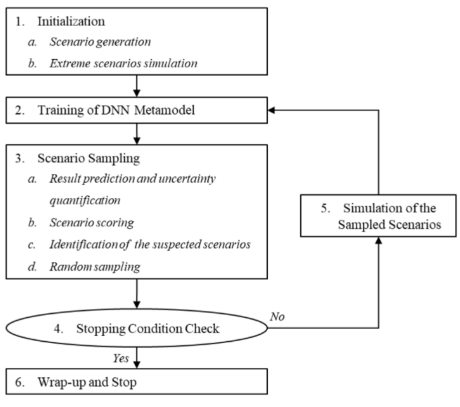

Fig. 1. Flowchart of Deep-SAILS.

2.2. DRAGON

To visualize the results of high-dimension in a practical form for analysis, this study adopts DRAGON [4]. The algorithm applies the alpha shape method to Deep-SAILS simulation results and construct the success boxes with candidate points in the scenario space to extract branching points. When the user specifies the desired number of candidate points, the algorithm identifies the optimal points that maximize the coverage of success scenarios in the scenario space. The algorithm automatically generates dynamic sequences with the optimal points and represents them in the form of a dynamic event tree (DET). Figure 2 shows the flowchart of the algorithm. In this study, DRAGON is used to project the limit surface into a DET, enabling a clear analysis of how combinations of operator action times influence accident consequences.

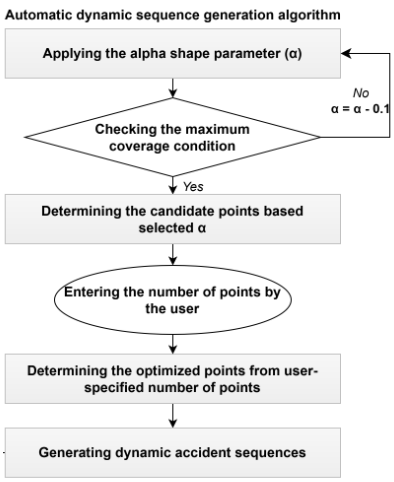

Fig. 2. DET generation algorithm of DRAGON.

3. Case study

3.1. Scenario description

To evaluate the impact of operator action initiation times on accident consequences in TLOFW mitigation, four actions were selected: high pressure safety injection (HPSI), pressurizer power-operated relief valve (PORV) opening, HPSI recirculation, and AFW recovery. Figure 3 shows the TLOFW scenarios analyzed in this study. While other scenario parameters do not follow a fixed order, HPSI recirculation can be initiated only if both HPSI injection and PORV opening have succeeded.

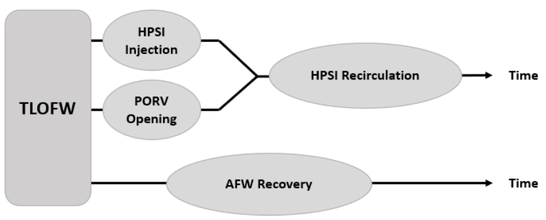

Fig. 3. Description of TLOFW scenario

Table 1 shows the discretized values of each parameter. The uncertain domains were derived by analyzing the results of a preliminary Deep-SAILS simulation, in which rough discretization was applied across the mission time for all parameters. Each parameter does not represent the absolute time elapsed since the initiation of the accident, but rather the delay time measured from the moment when the conditions for initiating that action are satisfied.

Table I: Uncertain domains and discretization of scenario configuring parameters under TLOFW.

Parameter	Unit	Uncertain domain	Discretization
PORV open delay	hr	(0, 1.5)	16 (0, 0.1, 0.2, 0.3, … 1.3, 1.4, 1.5)
HPSI injection delay	hr	(0, 1.5)	16 (0, 0.1, 0.2, 0.3, … 1.3, 1.4, 1.5)
HPSI recirculation delay	hr	(0, 6)	21 (0, 0.3, 0.6, 0.9, … 5.4, 5.7, 6.0)
AFW recovery time	hr	(0, 6)	61 (0, 0.1, 0.2, 0.3, … 5.8, 5.9, 6.0)

3.2. Simulation optimization

Figure 4 shows the result of a Deep-SAILS execution plotted in two dimensions with recirculation delay time and AFW recovery time fixed. In the graph, the points marked with black crosses and numbers indicate the locations and corresponding peak cladding temperature (PCT) calculated by the thermal-hydraulic system code, while the DNN predictions are represented by color shading. As the PCT approaches the failure criterion of 1478 K, the color becomes white, and this region corresponds to the limit surface. The distribution of the physically simulated scenarios shows that only the scenarios around the limit surface were successfully sampled. As a result of the Deep-SAILS execution, 19,670 out of 327,936 scenarios were simulated, meaning that the limit surface was successfully identified with only 6% of the total scenarios.

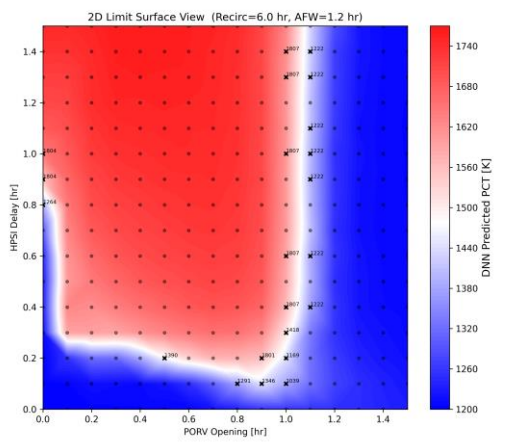

Fig. 4. Deep-SAILS result when HPSI recirculation delay is 6hr and AFW recovery time is 1.2hr.

3.3. DET generation

Figure 5 shows the DET generated by DRAGON. There is no fixed order among the DET headings.

Rather, they represent the delay time ranges of each operator action. To prevent the DET from becoming excessively complex, the number of branching points in this study was set to six. As the number of branching points decreases, the DET becomes simpler. However, the maximum number of success scenarios that can be included within the success box of the scenario space also decreases. The algorithm searches a combination of six candidate points from the candidate points identified by the alpha-shape method, in order to maximize the inclusion of success scenarios. As a result, 72,279 out of the total 94,667 success scenarios in the scenario space were included in the DET, achieving a coverage of 76%. The results in Figure 4 are included in sequences 6, 7, 11, 13, and 15 of the DET.

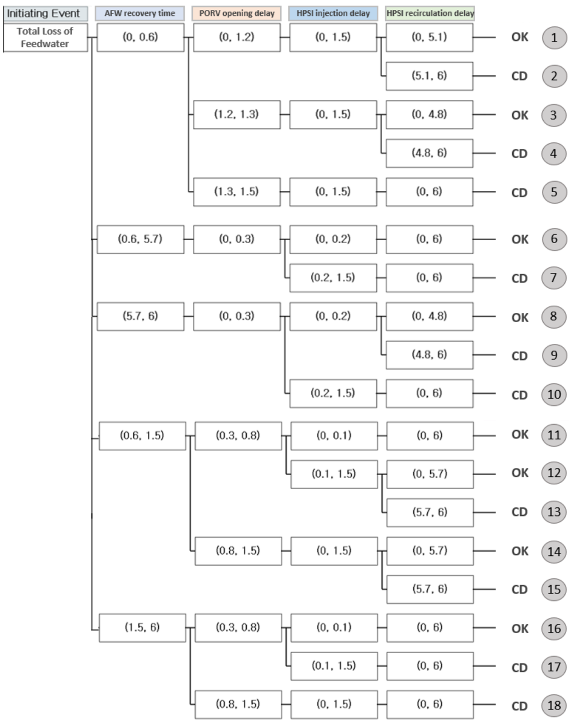

Fig. 5. DET generated by DRAGON.

4. Results and discussion

In PSA, conservative assumptions have been used to propose success criteria for the initiation times of operator actions in TLOFW accidents. For pressurizer PORV opening and HPSI injection, both operator actions are required to be initiated within 35 minutes after the accident [5]. For HPSI recirculation, although no specific initiation time is proposed, it is suggested that it should be initiated immediately once the refueling water tank is depleted. In PSA, no success criterion was proposed for AFW recovery in TLOFW accidents.

Using the DET in Figure 5, this study suggests success criteria that depend on the interaction between AFW recovery and the other operator actions. Note that DET headings do not have fixed order. Each heading denotes the delay time range for the corresponding action. When AFW recovery occurs early, within 0 to 0.6 hours, nearly all scenarios terminate in OK regardless of the precise timings of the other actions. The few CD branches in this window are associated with markedly late complementary actions, such as recirculation beyond 4.8 hours or a very late PORV opening, indicating that early recovery of AFW largely stabilizes the plant and that maintaining recirculation at or before roughly 5 hours preserves additional margin.

As AFW recovery moves into the 0.7 ~ 1.5 hours range, the consequences become dependent on the delay time of the other actions. Unless AFW is quickly recovered to provide secondary-side cooling and lower the primary side pressure below the operating condition of HPSI, PORV opening is required for HPSI injection to occur. However, if the PORV is opened early before AFW recovery lowers the primary side pressure and the initiation of HPSI injection is delayed, loss of primary coolant through the PORV can cause core uncovery and a sharp rise in PCT. A comparison between sequence 7 and sequences 11–15 in the DET confirms that when PORV opening delay is very short while HPSI injection is delayed, the range of scenarios leading to CD is broader than in cases where the PORV opening delay is longer.

For larger delays, when AFW recovery time is later than 1.6 hours, the safe region narrows substantially but does not vanish. The DET still contains OK sequences 6, 8, and 16 when PORV opening and HPSI injection occurred very early and if AFW recovery is very late (more than 5.7 hours), successful recirculation delay is bounded to 4.8 hours. Outside these combinations, branches trend to terminate in CD, indicating rapidly diminishing mitigation potential as AFW recovery is pushed further beyond 1.6 hr.

To keep the DET readable the number of branching points was limited, yielding a coverage of 76% of all OK scenarios. Consequently, the remaining 24% of OK scenarios are conservatively treated as CD in the DET. The dynamic criteria above should therefore be interpreted as conservative results.

PSA regards AFW recovery as a continuously required action in TLOFW scenarios. PSA treats AFW recovery as an action that is always required in TLOFW scenarios. This study not only introduces a success criterion for AFW recovery, but also proposes revised success criteria for F&B that change under the assumption that AFW recovery may succeed at different times. In PSA, the success criterion for F&B was proposed as initiation within 35 minutes after the accident. However, according to several DET sequences such as sequence 14, it can be concluded that F&B may be delayed up to three hours without leading to core damage, unless HPSI recirculation is excessively delayed. In conclusion, it was found that among the scenarios conservatively classified as CD in static PSA, there were many scenarios that could actually prevent core damage, even though the dynamic approach used in this study also included some conservative assumptions.

5. Conclusion

This study applies Deep-SAILS and DRAGON to a dynamic TLOFW scenario in which the timing of four operator actions is discretized. This study aims to reveal the scope of previously uncensored risk and to provide guidance on the acceptable time for operator actions that have a decisive impact on accident consequences. Rather than assigning probabilities, the focus is on searching the limit surface in the time coordinates of four operator actions and identifying acceptable operator action timings to mitigate the TLOFW accident and express the result as a DET for sequence-level analysis.

The result shows that the AFW recovery time exhibits different dependencies on the other three operator actions across specific intervals. Early AFW recovery yields broadly safe outcomes with relatively flexible requirements on the other actions. When AFW is moderately delayed, CD can still be prevented provided that PORV opens very early and either HPSI injection is not delayed beyond a certain threshold or recirculation is not initiated too late. With large AFW delay, only narrow combinations of very prompt PORV/HPSI and bounded recirculation remain viable. This refers to scenarios in which CD can be prevented solely by primary-side cooling through F&B, even without AFW recovery.

Although conservative assumptions were applied to the dynamic approach used in this study, it was concluded that several scenarios classified as CD in PSA could in fact be recovered before core damage occurred according to the analysis results of this study. Through this study, it was confirmed that uncensored risk not examined in PSA can be identified through a dynamic approach. Therefore, this study suggests that dynamic analysis should be considered for reactor types such as SMRs with an extremely low core damage frequency.

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