# Development of Complex External Event Scenarios Using Dynamic Event Trees in DICE

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**Abstract:** External event probabilistic safety assessment (PSA) evaluates the impact of external events through hazard and vulnerability analyses, followed by system analysis. Traditional external event PSA may be conservative as it does not account for changes in previously passed branches due to external events. This study attempts to realistically reflect multiple external event impacts using Dynamic Event Tree (DET) methods. DET unfolds scenarios in real-time, allowing scenario transitions, thus reducing conservatism.

We used DICE (Dynamic Integration Consequence Evaluation), developed by Kyung Hee University, as a tool for the DET method. Since the original DICE could not incorporate the effects of external events, we developed an external event module that can be flexibly integrated with DICE. Additionally, we modified the DICE source code to dynamically adjust the component failure rates when external events occur. Using the developed module and modified DICE, scenario transitions due to external events were confirmed. This demonstrated that DET methods can reduce conservatism in nuclear power plant risk analysis.

**Keywords:** Probabilistic Safety Assessment, Dynamic Event Tree Method, External Event

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## 1. INTRODUCTION

Recent rapid climate changes have led to various natural disasters such as earthquakes, tsunamis, and hurricanes. These natural disasters can impact the safety of nuclear power plants, which is why Probabilistic Safety Assessment (PSA) for external events is conducted as part of nuclear power plant safety evaluations. Previous studies have mainly focused on single external event PSA, which assess the impact of individual events. However, the 2011 Fukushima Daiichi nuclear disaster in Japan highlighted the need for multi-external event PSA. In this incident, an earthquake caused a loss of off-site power, leading to the operation of emergency diesel generators. Unfortunately, the subsequent tsunami inundated these generators, cutting off power to the plant and resulting in core meltdown. This incident underscored the necessity of considering the combined effects of multiple external events rather than assessing the impact of single events alone.

External event PSA ultimately involves event tree analysis similar to internal event PSA for evaluating the safety of nuclear power plants. In the past, we have employed Dynamic Event Tree (DET) methods to discover previously unrecognized scenarios and to conduct realistic analyses that reduce overly conservative assumptions. This is because DET methods do not predefine accident scenarios. Instead, they perform real-time thermal-hydraulic analysis of the plant, taking into account scenario changes due to equipment failures or human errors.

Therefore, by using DET methods to reflect the effects of multiple external events, we aim to conduct realistic accident analyses that are less conservative than traditional external event PSA. For this purpose, we conducted research using the DET method tool, DICE, along with an additional developed external event module.

## 2. Previous Research

### 2.1. External Event PSA

External event PSA is a method for probabilistically assessing the damage to nuclear power plants, and it is divided into single external event PSA and multi-external event PSA. Single external event PSA evaluates only the impact of the initial external event, while multi-external event PSA considers additional external events that occur following the initial event. In this study, we aim to explain both PSA methods based on seismic PSA.

Seismic PSA consists of three major analyses. First, the Probabilistic Seismic Hazard Analysis (PSHA) assesses the frequency of ground acceleration due to earthquakes. Second, the Seismic Fragility Analysis (SFA) evaluates the probability of damage to structures and equipment. Third, system analysis evaluates the reliability of accident mitigation functions using event tree and fault tree methods and ultimately calculates the Core Damage Frequency (CDF) of the nuclear power plant. System analysis occurs in two stages. First, the primary seismic event tree analysis defines the damage state of the nuclear power plant caused by the earthquake. Second, based on the defined damage state, the secondary seismic event tree analysis evaluates the integrity of accident mitigation functions to determine the occurrence of core damage. The secondary seismic event tree analysis proceeds similarly to the event tree analysis of internal event PSA, excluding mitigation functions lost due to the earthquake or reflecting the results of the primary seismic event tree in the fault tree of the secondary seismic event tree [1].

Multi-external event PSA requires additional computational models and changes in system analysis methods to reflect the impact of subsequent external events after the initial event. For example, a multi-external event PSA for earthquakes incorporates the probability of aftershocks into the analysis model and adjusts the primary and secondary seismic event tree analyses to account for additional damage caused by aftershocks. The primary seismic event tree analysis defines complex damage states due to aftershocks, and the secondary seismic event tree analysis includes additional events in the fault tree based on the timing and ground acceleration of aftershocks to reflect their effects [2].

### 2.2. Dynamic Event Tree Methods

Unlike traditional event tree analysis, DET methods do not follow predetermined accident scenarios. Instead, they generate and analyze scenarios in real-time based on the thermal-hydraulic state of the system, equipment failures, and human errors. This approach allows for the discovery of previously unrecognized scenarios and more realistic accident analysis [3].

To perform accident analysis using DET methods, analytical tools are required, and various tools are available worldwide. Examples include PyCATSHOO (France), ADS-IDAC (USA and so on), SCAIS (Spain), and MCDET (Germany) [4].

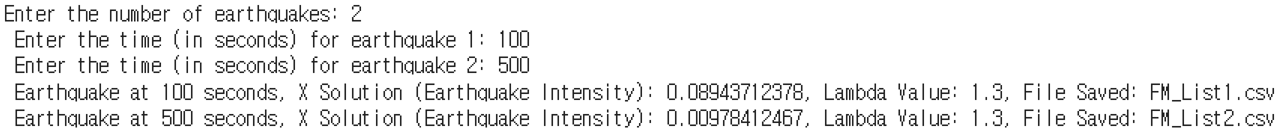
DICE is composed of several modules: a physical module that handles the thermal-hydraulic analysis of the power plant model, a diagnostic module that oversees equipment operation and branching rules based on automatic or manual actions during the simulation, a reliability module that determines the occurrence of branching and calculates branching probabilities based on the outputs from the diagnostic module, and a scheduler that manages information exchange between these modules [5]. This modular structure makes DICE highly flexible, enabling the easy integration of new modules or the modification of existing ones.

Therefore, in this study, we used DICE and added an external event module while modifying the reliability module to reflect the impact of external events.

## 3. Research and Development

### 3.1. External Event Module

To incorporate the effects of external events into DICE, a module for hazard and fragility analysis of external events is required. Therefore, in this study, an external event module was developed to perform the analysis of external events. The external event module was developed as a separate component from DICE and uses external event hazard data to determine the occurrence, timing, and hazard level of external events. The hazard values are derived using a random comparison with an arbitrary hazard curve. Subsequently, the determined hazard values and fragility data are used to generate new reliability data based on the existing reliability data of the DICE reliability module.



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Enter the number of earthquakes: 2
 Enter the time (in seconds) for earthquake 1: 100
 Enter the time (in seconds) for earthquake 2: 500
 Earthquake at 100 seconds, X Solution (Earthquake Intensity): 0.08943712378, Lambda Value: 1.3, File Saved: FM_List1.csv
 Earthquake at 500 seconds, X Solution (Earthquake Intensity): 0.00978412467, Lambda Value: 1.3, File Saved: FM_List2.csv
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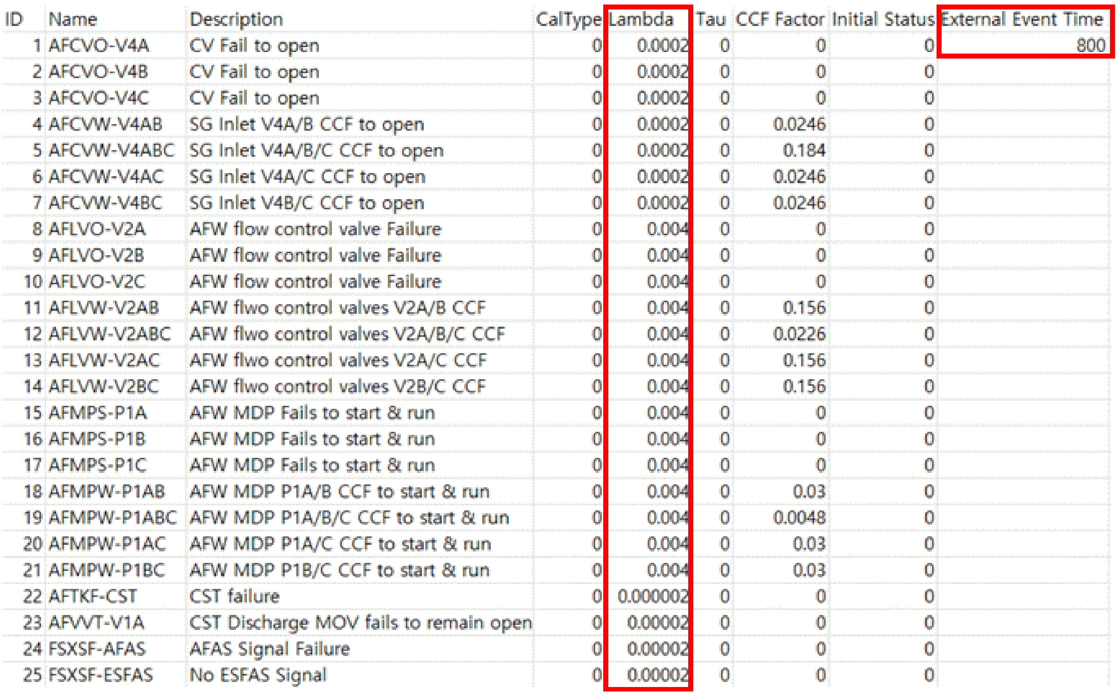
Figure 1. Simulation Results through the External Event Module



| ID | Name | Description | CalType | Lambda | Tau | CCF Factor | Initial Status | External Event Time |
|---|---|---|---|---|---|---|---|---|
| 1 | AFCVO-V4A | CV Fail to open | 0 | 0.0002 | 0 | 0 | 0 | 800 |
| 2 | AFCVO-V4B | CV Fail to open | 0 | 0.0002 | 0 | 0 | 0 | |
| 3 | AFCVO-V4C | CV Fail to open | 0 | 0.0002 | 0 | 0 | 0 | |
| 4 | AFCVW-V4AB | SG Inlet V4A/B CCF to open | 0 | 0.0002 | 0 | 0.0246 | 0 | |
| 5 | AFCVW-V4ABC | SG Inlet V4A/B/C CCF to open | 0 | 0.0002 | 0 | 0.184 | 0 | |
| 6 | AFCVW-V4AC | SG Inlet V4A/C CCF to open | 0 | 0.0002 | 0 | 0.0246 | 0 | |
| 7 | AFCVW-V4BC | SG Inlet V4B/C CCF to open | 0 | 0.0002 | 0 | 0.0246 | 0 | |
| 8 | AFLVO-V2A | AFW flow control valve Failure | 0 | 0.004 | 0 | 0 | 0 | |
| 9 | AFLVO-V2B | AFW flow control valve Failure | 0 | 0.004 | 0 | 0 | 0 | |
| 10 | AFLVO-V2C | AFW flow control valve Failure | 0 | 0.004 | 0 | 0 | 0 | |
| 11 | AFLVW-V2AB | AFW flwo control valves V2A/B CCF | 0 | 0.004 | 0 | 0.156 | 0 | |
| 12 | AFLVW-V2ABC | AFW flwo control valves V2A/B/C CCF | 0 | 0.004 | 0 | 0.0226 | 0 | |
| 13 | AFLVW-V2AC | AFW flwo control valves V2A/C CCF | 0 | 0.004 | 0 | 0.156 | 0 | |
| 14 | AFLVW-V2BC | AFW flwo control valves V2B/C CCF | 0 | 0.004 | 0 | 0.156 | 0 | |
| 15 | AFMPS-P1A | AFW MDP Fails to start & run | 0 | 0.004 | 0 | 0 | 0 | |
| 16 | AFMPS-P1B | AFW MDP Fails to start & run | 0 | 0.004 | 0 | 0 | 0 | |
| 17 | AFMPS-P1C | AFW MDP Fails to start & run | 0 | 0.004 | 0 | 0 | 0 | |
| 18 | AFMPW-P1AB | AFW MDP P1A/B CCF to start & run | 0 | 0.004 | 0 | 0.03 | 0 | |
| 19 | AFMPW-P1ABC | AFW MDP P1A/B/C CCF to start & run | 0 | 0.004 | 0 | 0.0048 | 0 | |
| 20 | AFMPW-P1AC | AFW MDP P1A/C CCF to start & run | 0 | 0.004 | 0 | 0.03 | 0 | |
| 21 | AFMPW-P1BC | AFW MDP P1B/C CCF to start & run | 0 | 0.004 | 0 | 0.03 | 0 | |
| 22 | AFTKF-CST | CST failure | 0 | 0.000002 | 0 | 0 | 0 | |
| 23 | AFVVT-V1A | CST Discharge MOV fails to remain open | 0 | 0.00002 | 0 | 0 | 0 | |
| 24 | FSXSF-AFAS | AFAS Signal Failure | 0 | 0.00002 | 0 | 0 | 0 | |
| 25 | FSXSF-ESFAS | No ESFAS Signal | 0 | 0.00002 | 0 | 0 | 0 | |

Figure 2. Example of Newly Generated Reliability Data

### 3.2. Modification of DICE Source Code

The DICE source code was modified to reflect the effects of external events using the reliability data generated by the external event module. First, the data loading method of the reliability module was adjusted to accommodate multiple sets of reliability data generated by the external event module. Next, an algorithm was added to determine the timing of equipment failures based on the new reliability data. Previously, DICE used a single set of reliability data generated before the simulation to determine equipment failure times. Specifically, it categorized equipment failure modes into startup failure and operational failure, distinguishing only between pre-simulation failures and failures during the simulation. However, changes in failure rates due to external events occurring at specific times can lead to startup failures and alter operational failure times. Therefore, it was necessary to incorporate the effects of the newly generated reliability data.

For example, as shown in Figure 3, assuming external events occur at times t1 and t2, DICE initially calculates the equipment failure time using the original reliability data. If the calculated failure time is before t1, the equipment fails without the influence of external events. However, if the calculated failure time is after t1, the failure time must be re-evaluated using the new reliability data generated by the external event, necessitating a recalculation with the new data.

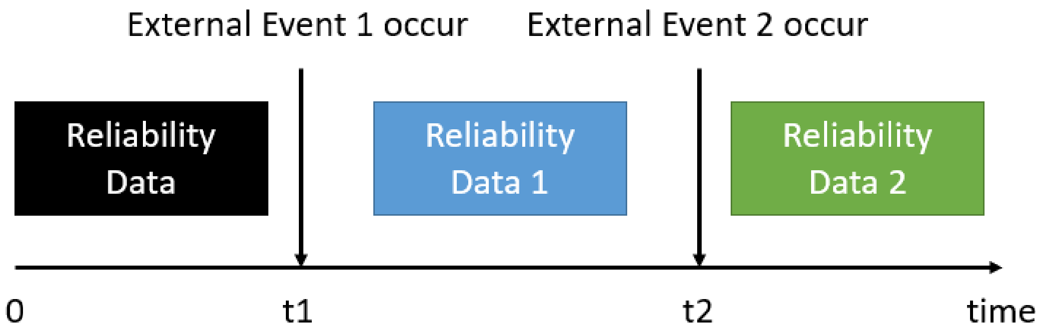


Figure 3. Structure for Determining Equipment Failure Timing When External Events Occur

## 4. CASE STUDY

In this study, we developed an external event module and modified the DICE source code to conduct realistic analyses that reduce the conservatism of traditional external event PSA. To validate this approach, a case study was conducted using a hypothetical Westinghouse 3-Loop model during a Small Loss-of-Coolant Accident (SLOCA) scenario involving aftershocks. The study assumed a 2-inch (5.08 cm) break in the cold leg and considered the failure of the High-Pressure Safety Injection (HPSI) system due to aftershocks.

The frequency and magnitude of aftershocks were defined using a modified version of the earthquake hazard curve shown in Eq. 1.

$$y = 8 \times 10^{-6} x^{-2.601} \tag{1}$$

where y represents the annual exceedance probability and x represents the peak ground acceleration (PGA). For aftershocks, an arbitrary weighting factor was applied to lower ground accelerations on the hazard curve to account for their decreased intensity but increased probability of occurrence.

For the fragility curve, the baseline failure rates of the components were modified by applying an arbitrary weighting factor whenever seismic events exceeding a certain magnitude occurred. This approach allowed us to simulate a situation where the failure rates gradually increase with each aftershock.

In the traditional external event PSA, a conservative assumption was made that all HPSI systems fail at the occurrence of the main earthquake, meaning the HPSI was assumed to be inoperative from the beginning. In contrast, using the DET method, we compared scenarios where the HPSI systems were operational until the aftershock occurred, which then increased the failure rate of the HPSI systems, leading to their failure.

Using the DET method allows for scenarios where the HPSI systems, triggered by HPSI signals, are operational but fail at the point of the aftershock, demonstrating scenario transitions at non-branch points. Figure 4 illustrates these scenario transitions. In traditional ET, scenarios develop by deciding the success/failure at branching points, but with DICE, scenarios are developed not only by determining branches based on the number of operational safety systems at branch points but also by showing changes in scenarios at non-branch points due to the occurrence of external events. This enables a more realistic analysis, reducing the conservatism inherent in traditional external event PSA.

Figure 5 shows the results of the case study. Scenario I5 represents the conservative assumption where all HPSI systems fail due to the main earthquake. Scenarios I1, I2, I3, and I4 depict situations where, initially, all three HPSI systems are operational but fail at the time of the aftershock, with 0, 1, 2, or 3 HPSI systems failing, respectively. The similar results for I1 and I2 are due to the inability to inject through the broken cold leg, which limits the effectiveness of the HPSI.

This case study confirms the ability to model scenario transitions using the DET method and demonstrates that more realistic Peak Cladding Temperature (PCT) values can be obtained compared to traditional external event PSA results.

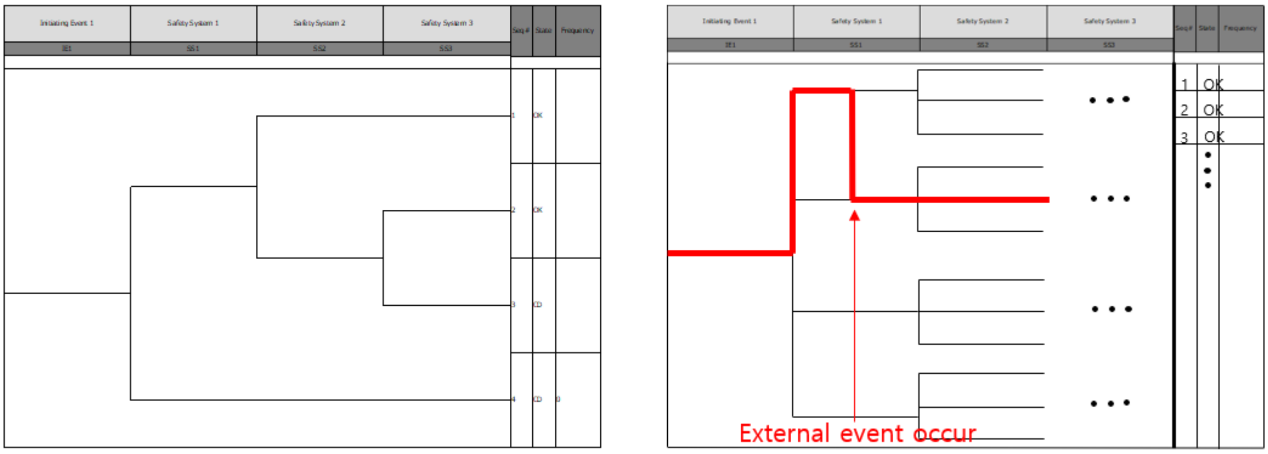


Figure 4. ET depicting scenario transitions using DICE compared to traditional ET

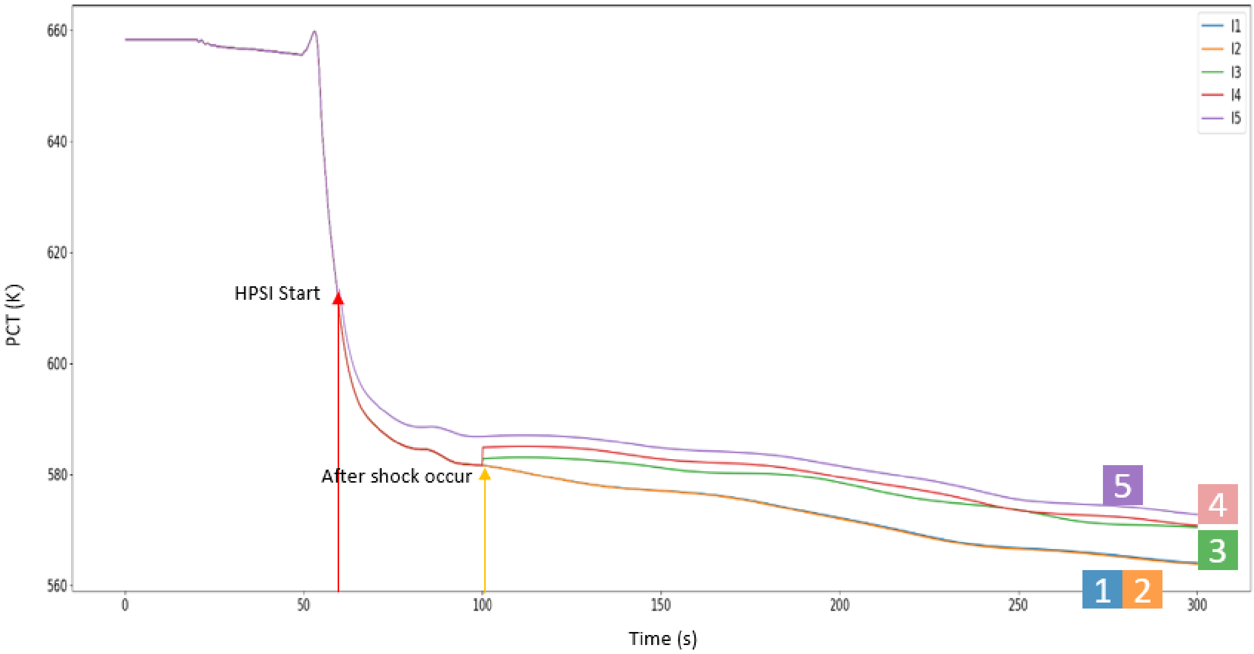


Figure 5. Changes in PCT during SLOCA scenarios based on the case study

## 5. Conclusions

We developed an external event module and modified the DICE source code, confirming that it is possible to perform realistic analyses that reduce the conservatism of traditional external event PSA. A case study was conducted based on a scenario involving aftershocks during a SLOCA in a hypothetical Westinghouse 3-Loop model. The study compared the traditional conservative assumptions with the DET method.

The results showed that the DET method allows for scenario transitions, enabling more realistic analyses. Unlike the results of traditional external event PSA, more realistic PCT values were derived. This indicates that the DET method allows for a more realistic assessment of nuclear power plant safety.

This confirms help the DET method to enable a more realistic evaluation of nuclear power plant safety. Future research will aim to extend the application of scenario transitions not only to changes in the failure states of equipment due to external events but also to changes in the damage state of the nuclear power plant. This will enable even more realistic evaluations of nuclear power plant safety.

## Acknowledgements

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