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Dynamic PSA-based Multi-unit Accident Scenario Modelling Approach

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1. Introduction

PSA (Probabilistic Safety Assessment) is an element for evaluating the safety of nuclear power plant (NPP) and is essential for periodic safety review of operating NPP and licensing of new NPP. PSA assumes specific scenarios and analyzes safety for representative scenarios. It also uses conservative assumptions for complex cases.

Recently, research is being performed to evaluate realistic risk assessments considering dynamic accident scenarios. This is expected to help understand the differences between the current traditional PSA and PSA reflecting dynamic characteristics.

Many dynamic PSA studies use the dynamic event tree method [1, 2, 3, 4, 5]. They perform success criteria analysis using safety analysis codes, for various cases such as considering differences in the number of trains in the safety system. However, this method cannot simulate real situations because it is based on given event trees.

This study uses a method to stochastically model the operation/failure/timing of component and operators regardless of event trees. This method can create scenarios by modeling the operation of NPP component/operators in a realistic manner.

For the generated scenario, a safety analysis using a T/H code like MAAP5 [6] is performed to determine whether core damage (CD) occurs or not. This is repeated N times to evaluate CCDP (Conditional Core Damage Probability, CCDP = F/N, F = number of times CD occurs), which can be compared with the CCDP of traditional PSA.

This article describes the dynamic scenario modeling approach in Session 2, the DynaScen framework, a software for dynamic PSA developed in this study, in Session 3, the test results in Session 4, and the conclusion in Session 5.

2. Dynamic Scenario Modelling Approach

The approach of this study is to stochastically determine the state of each component/operator. For example, a component in standby state starts or fails to start when required. Once started, it continues to operate or fails to run at time Tr. All of these processes are stochastically determined using the failure probability for each component.

In the case of the operator, the operator's action time can be stochastically determined from the distribution of action times. (In the traditional PSA, the operator failure probability is calculated by considering the average action time and available time. In this study, the operator action time is stochastically sampled from the action time distribution, and the operator failure/success is determined through safety analysis for the sampled scenario.)

The method used in this paper consists of three models: component, trigger, and shared component. Those are described below.

2.1 Component Model

2.1.1 General Component Model

Failure time can be estimated for component such as pumps or valves:

- Fail to start or fails on demand
    - Generate a random number r from Uniform distribution (0, 1)
    - if r < Ps then it fails to start at T = 0, else it starts, where Ps is the failure probability for start
- Fail to run
    - Generate a random number r from Uniform distribution (0, 1)
    - Tr = r / λr , where Tr is the failure time and λr is the failure rate

2.1.2 Action Time Distribution Model

Operator action time or offsite power recovery time can be estimated using the probability density versus time:

- X and Y axis represent time and CDF
- A value is sampled from CDF
    - Generate a random number r from Uniform distribution (0, 1)
    - Find Ta corresponding to Y = r, where Ta is the action time or recovery time

Fig. 1 shows an example of the Cumulative distribution function (CDF).

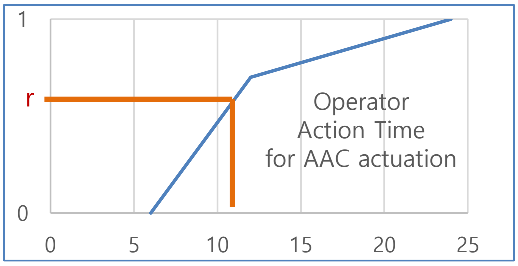

Fig. 1. Example of action time distribution model

2.2 Trigger Model

The trigger model is used to check the conditions of other components or triggers. If a specific condition is met, a trigger is generated to perform other necessary actions. For example, if both EDGs fail, the plant will be in SBO state. It will start an action to run AAC.

- SBO condition : EDG-A = Fail AND EDG-B = Fail

Table 1 shows various ways to handle triggers.

Table 1. Various trigger type

Type	Description & Examples
AND	When all input triggers are satisfied (use the latest condition). Both EDGs Fail (SBO Condition): - EDG-A = Fail - EDG-B = Fail
PR	If any of the input Triggers are satisfied (use a fastest condition). If either one of the two AFW-TDPs succeeds (secondary SG cooling success)" - AFW-TDP-A = Run - AFW-TDP-B = Run
MORE	If the time of the first trigger is later than the time of the second trigger (use the second trigger condition). Offsite power recovery time is later than the time when both EDG/AAC: - OffsitePower = On - tEDG/AAC-Fail = On
GIVEN	Both triggers are satisfied (use the second Trigger condition). AFW-TDP is in a running state, and all EDG/AAC/MACST fail, so MACST-PLPP is attempted in long term.: - tAFW-TDP-Run = On - tSBO-MDG-Fail = On

2.3 Shared Component Model

AAC or MACST component is shared across multiple units. Therefore, these component will be connected to the unit that requested them first. The shared component model is used to model the distribution of shared components within a site.

For example, U1 and U2 share one AAC. It will connect AAC to the first unit that requests AAC, and then process AAC distribution as fail for units that request AAC thereafter.

3. DynaScen Framework

DynaScen is a software for dynamic PSA developed in this study. Its overall framework is shown in Fig. 2.

Step A) stochastic scenario modeling

Create one scenario following the stochastic approach described in session 2. Repeat this N times to create N scenarios.

Step B) MAAP5 calculation for each scenario

For each scenario, perform MAAP5 calculations to determine whether CD occurs or not. If CD occurs F times, CCDP can be estimated as F/N. The number of MAAP5 calculations N requires about 10 to 100 x 1/CCDP to estimate approximate CCDP.

When CCDP is greater than 0.01, CCDP can be calculated relatively accurately with a small number of MAAP5 calculations. When CCDP is low, the number of samples N must be large to obtain meaningful accuracy. When the number of samples is large (for example, when MAAP5 needs to be calculated more than 10,000 times), it may take too much time to run the MAAP5 code.

To cope with these cases, the following several methods can be used:

- B1) Evaluate PCT (peak cladding temperature) by executing MAAP5 code and check whether CD occurs.
- B2) If it is certain that CD will occur after reviewing the scenario, MAAP5 calculation is not performed. MAAP5 calculation is performed only when it is not certain.
- B3) Create a Meta Model using Deep Learning and use it instead of MAAP5
- B4) Perform MAAP5 calculations for many scenarios to sufficiently cover the various states of all components and store them in a database. Afterwards, determine CD or not by finding a similar case.

Step C) Comparison with Traditional PSA

- C1) Compare the results of the dynamic scenario method and the traditional PSA method (The dynamic scenario method is the results of Step A and Step B)
- C2) Incorporate dynamic features in traditional PSA. The dynamic scenario modeling method stochastically determines the state of components. By reflecting the state of these components in the traditional PSA model, we can determine whether CD occurs or not.

4. Example Calculations

The Step B interface that determines CD using MAAP5 code run is under development, so it will be performed in future study. In this paper, we present the test results for Step A and Step C.

4.1 Description of Example Model

The loss of offsite power (LOOP) event for the entire site is selected as an example model. The example model includes the systems considered in the PSA scenario to cope with LOOP event. The major safety systems are modeled required after LOOP such as power-related systems (offsite power, EDG, AAC DG), secondary SG cooling (AFW-TDP, AFW-MDP), LOCA possibility (PSV Stuck Open, RCP Seal LOCA), feed & bleed operation related (SDS), safety injection related (SIS, CS), MACST (TSC, 1MW DG, 3MW DG, PLPP). Systems such as CCWS and LP SIS that have little impact on major scenarios in case of LOOP are excluded from the model.

4.2 Test Results

4.2.1 Comparison of DynaScen and Traditional PSA

At first, we verified whether the results generated by DynaScen in the absence of a trigger are the same as the traditional PSA results. This corresponds to the traditional PSA if DynaScen models all components as starting initially without a trigger. If triggers are considered, the results are different from the traditional PSA because the operating times of the components change dynamically. Table 2 shows the comparison of DynaScen and the traditional PSA results.

- If triggers are not considered, DynaScen should produce the same CCDP results as the Traditional PSA (This is corresponding to the typical Monte Carlo approach to calculate the top event probability, as in FTeMC [7]).
- When triggers are considered, the dynamic characteristics for timing will be reflected, so different results are produced for each scenario compared to the traditional PSA.

4.2.2 DyanScen with Incorporation of Dynamic features into the traditional PSA

By incorporating DynaScen's dynamic scenario into the traditional PSA, sensitivity analyses are performed for various cases. Only the timing effects are reflected in the traditional PSA and the success criteria are used as they are assumed in the traditional PSA. Even if only the dynamic timing effects are reflected in the traditional PSA without linking it to the MAAP5 analysis, it still provide considerable insights.

It is tested the applicability of DynaScen in cases where multiple units share AAC and MACST (3MW MDG, 1MW MDG, PLPP):

- Sensitivity analyses are done for 1 unit, 2 units, and 4 units
- Comparison are performed both without and with MACST
- Base case is the site LOOP
- Delayed recovery of offsite power is a case for external disasters such as forest fires

A) Case for sharing AAC in multiple units without MACST

The impact of sharing AAC in multiple units without MACST is evaluated. The results is shown in Table 3.

- In the case of late recovery of offsite power, the CCDP is much larger than that of the base case.
- For 2 Units/1 AAC, CCDP is slightly larger than for 1 Unit/1 AAC
- For 4 Units/1 AAC, CCDP is slightly larger than for 2 Units/1 AAC
- CCDP for 4 Units/2 AAC are similar with that for 2 Units/1 AAC
- Please note that the difference between units exists due to the randomness of the Monte Carlo method.

B) Case for sharing AAC/MACST in multiple units with MACST

The impact of sharing AAC/MACST in multiple units with MACST is evaluated. The results is shown in Table 4.

- When MACST is installed, CCDP is significantly lower than when MACST is not installed.
- Even in the case of late recovery of offsite power supply, MACST equipment can be used to deal with it, so CCDP appear similarly with the base case.

4.3 Reasons for differences between DynaScen and Traditional PSA

The main reasons for differences between DynaScen and Traditional PSA are:

- Since PSA assumes a specified order and timing, it does not reflect the actual dynamic characteristics. In many cases, the dynamic scenario proceeds differently than the traditional PSA model.
- In the traditional PSA, safety analysis is performed for representative and conservative accident scenarios, so it does not reflect dynamically changing accident scenarios. Safety analysis for each case is required to properly reflect dynamic characteristics.

Several examples of the differences are given in Table 5.

5. Conclusions

In this study, we developed a method to stochastically simulate the state of each component. This method basically has the following characteristics.

- The state of each component is stochastically determined in a manner similar to the actual component, such as failure status, failure time, and operating time, and the relationship between components can be dynamically evaluated.
- It will evaluate whether CD occurs or not for each scenario using the following two methods.
  - Approach 1) For each scenario, the results of safety analysis using MAAP5 or meta model are used.
  - Approach 2) The scenarios generated by DynaScen can be directly applied to existing PSA without additional safety analysis. This alone can significantly reflect dynamic characteristics.

The new dynamic scenario approach has the following features:

- It can solve the limitations caused by the static characteristics of the existing traditional PSA in complex multi-unit accident scenarios.
- It can support more realistic analysis and evaluation of multi-unit risk.
- It can help to more accurately identify key vulnerabilities at multi-unit nuclear power plant sites, thereby contributing to the development of measures to improve multi-unit safety.

In the future, we plan to perform the following research:

- Research is conducted to link MAAP5 or Meta Model calculations for each case.
- We analyze the causes of differences from traditional PSAs for various multi-unit accident scenarios. By reviewing these results, we derive ways to apply them to the traditional PSA.

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Table 2. Comparison of results for DynaScen and the traditional PSA

Scenario	Traditional PSA	DynaScen w/o Trigger	Ratio	DynaScen w/ Trigger	Ratio
ET-LOOP-3!	2.04E-03	2.04E-03	1	2.04E-03	1
ET-SBO-R-06!	2.00E-02	1.99E-02	1	1.62E-02	0.81
ET-SBO-R-13!	4.30E-03	4.29E-03	1	3.05E-03	0.71
ET-SBO-R-15!	3.27E-03	3.26E-03	1	3.04E-02	9.3
ET-SBO-R-17!	2.61E-02	2.62E-02	1	2.50E-03	0.1
ET-SBO-R-18!	1.45E-02	1.45E-02	1	9.45E-03	0.65
ET-SBO-R-19!	1.94E-02	1.93E-02	0.99	1.88E-02	0.97
ET-SBO-R-20!	9.34E-02	9.35E-02	1	9.37E-02	1
ET-SBO-S-06!	8.97E-03	8.99E-03	1	8.22E-03	0.92
ET-SBO-S-13!	2.26E-03	2.24E-03	0.99	1.87E-03	0.83
ET-SBO-S-18!	1.07E-02	1.06E-02	0.99	1.07E-02	1
ET-SBO-S-19!	4.07E-03	4.08E-03	1	4.05E-03	1
ET-SBO-S-20!	1.96E-02	1.96E-02	1	1.97E-02	1.01
ET-TSLOCA-3!	4.08E-03	4.08E-03	1	3.95E-03	0.97
Other sequences	1.73E-03	1.73E-03	1	1.66E-03	0.96
TOP-SBO	2.34E-01	2.34E-01	1	2.26E-01	0.97

Table 3. Impact of sharing AAC in multiple units without MACST

Case	Site LOOP (Base case)	Late recovery of offsite power
1 Unit	U1=1.92e-5	U1=1.55e-4
2 Units / 1 AAC	U1=2.12e-5, U2=2.21e-5	U1=1.63e-4, U2=1.55e-4
4 Units / 1 AAC	U1=2.38e-5, U2=2.35e-5 U3=2.40e-5, U4=2.44e-5	U1=1.69e-4, U2=1.66e-4 U3=1.73e-4, U4=1.81e-4
4 Units / 2 AAC	U1=2.30e-5, U2=2.24e-5 U3=2.17e-5, U4=2.25-5	U1=1.58e-4, U2=1.55e-4 U3=1.58e-4,U4=1.67e-4

Table 4. Impact of sharing AAC/MACST in multiple units with MACST

Case	Site LOOP (Base case)	Late recovery of offsite power
1 Unit	U1=2.1e-6	U1=2.2e-6
2 Units / 1 AAC	U1=1.9e-6, U2=2.1e-6	U1=1.7e-6, U2=2.1e-6
4 Units / 1 AAC	U1=2.0e-6, U2=2.3e-6 U3=2.0e-6, U4=1.3e-6	U1=2.3e-6, U2=1.9e-6 U3=2.7e-6, U4=2.0e-6
4 Units / 2 AAC	U1=2.0e-6, U2=2.3e-6 U3=2.0e-6, U4=1.3e-6	U1=2.0e-6, U2=1.9e-6 U3=2.7e-6, U4=2.1e-6

Table 5. Differences in Traditional PSA and Dynamic Approach

Models	Traditional PSA	Dynamic Approach
Scenario order and timing	Specified sequence and timing (e.g. EDG failure, AAC startup failure, failure to restore off-site power within 6 hours)	Dynamic timing (e.g. EDG/AAC failure timing is random. Power recovery before their failure time (e.g. 17 hours, not pre-defined 6 hr))
Operating period of safety system	Safety analysis assumes mostly start failure of safety systems	Safety analysis based on given scenarios (failure to start, failure after N hours of operation, etc.)
RCP Seal Failure Time	Assumed to occur in the first 30 minutes	Occurs randomly after the SBO
PSV Stuck Open	Assuming core damage due to limited time	Realistically model AC power restoration and SIS system availability
Shared system	The model is complex and requires assumptions such as priorities.	A simple and practical model based on the time of occurrence

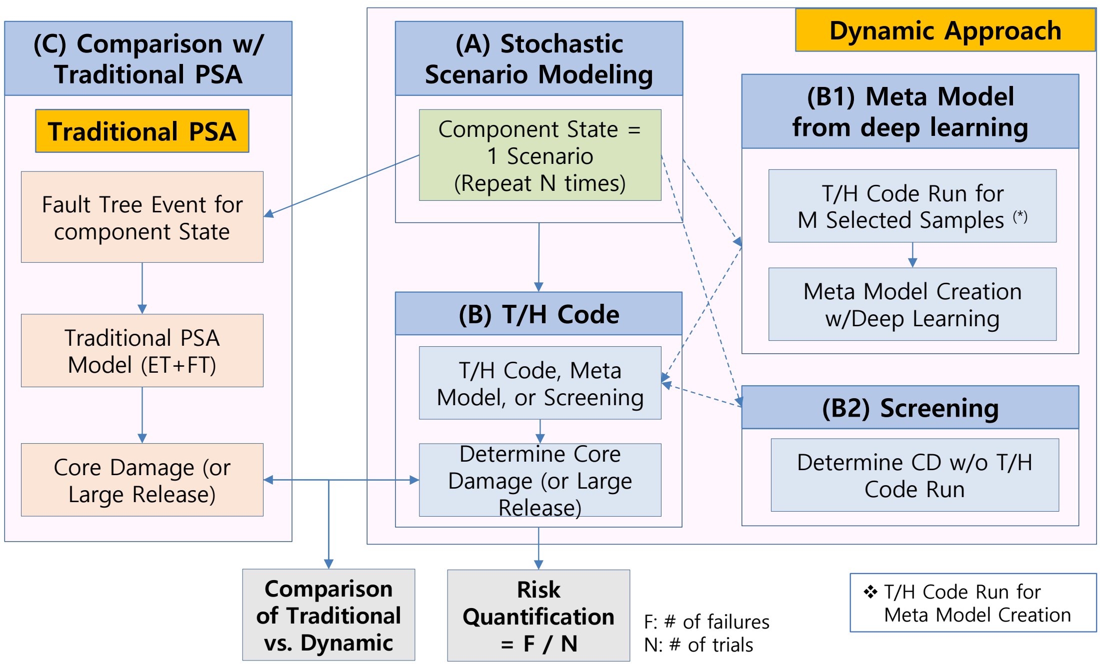

Fig. 2. DynaScen Framework for dynamic PSA-based scenario modeling approach