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# Development of DICE(Dynamic Integrated Consequence Evaluation) for Procedure Coverability Studies: Conceptual Design Phase

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## 1. Introduction

The efforts to acquire insights and reflect lessons-learned into accident scenarios through Probabilistic Safety Assessment (PSA) have been steadily evolving. In dealing with the results of PSA, quantitative outcomes can be used to determine the overall safety of a nuclear facility, but it should be noted that the qualitative check-up of the critical sequences, equipment and operator actions and dependency that the accident scenario describes is more significant for decision-making. In order to effectively achieve this goal, the PSA model needs to be structured to best estimate the reality as much as possible. In this respect, the PSA model currently in common use can be said to be improved.

In addition to the general features of PSA, dynamic PSA is able to allow the diversity of 'condition' to be reflected during the process of calculating the model, thus provide the insight that the existing PSA cannot capture. For more than 20 years, research and development of dynamic PSA have been carried out worldwide, and their analysis and the summary have recently been carried out. [1, 2] In Korea, the researches on accident sequence precursor can be found as an application of dynamic PSA, [3, 4] but it has not been common in practice. One of the reasons may be because there is no dedicated tool to perform dynamic PSA despite the fact that there are world-class safety analysis codes and PSA codes in Korea.

In this study, we are proceeding with conceptual design to develop dynamic PSA tool named Dynamic Integrated Consequence Evaluation (DICE). In this paper, we will introduce the basic structure of DICE and the key element technologies, and describe the expected applications.

## 2. Method of Development

### *2.1 Classification in Techniques*

Figure 1 shows the over-arching classifications which are applicable for the dynamic PSA referred from literatures. [1, 5] In Figure 1, the methodologies to support the dynamic PSA are mainly into two categories: continuous and discrete time approaches. DICE is working on the basis of the discrete time method, particularly Discrete Dynamic Event Tree (DDET). The DDET is the simulation-based framework that integrates models to generate event trees dynamically and automatically.

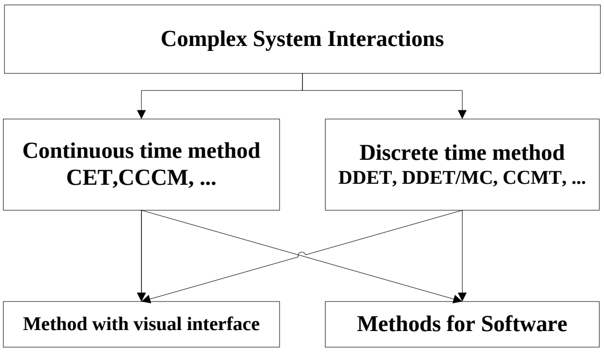


Fig 1. Classification of Dynamic PSA Methodologies

As the methods for software in DICE, dynamic fault tree, Monte Carlo simulation, and other techniques are expected to be implemented while the visual interface is under a needs organizing phase.

### *2.2 Module Structure of DICE*

The main module to support the structure of DDET has been already presented in Figure 2 in the previous study. [3, 6]

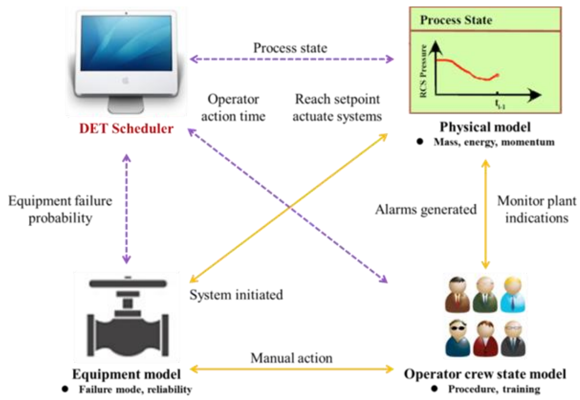


Fig 2. Schematic diagram of DDET and dynamic interactions in NPPs

The DDET integrates the plant physical model, operator crew model, and equipment model depending on the dynamic interactions under an accident situation. The DDET conducts the new generation of branch points and analyzes potential accident sequences by using the scheduler. The scheduler has the function that is responsible for sharing and exchanging information between the models while reflecting dynamic interactions under an accident situation. Each model will be briefly described as follows, on the basis of the results of conceptual design for DICE:

*2.2.1 Scheduler*

It functions new generation and analysis for the branch of potential accident sequences. The scheduler performs the acquisition/distribution of information for each module or model at the specified time interval. In addition, it sets up the truncation criteria for determining the interruption of analysis and assigns the boundary condition of thermal-hydraulic analysis. The schematic diagram of the DICE schedule is shown in Figure 3.

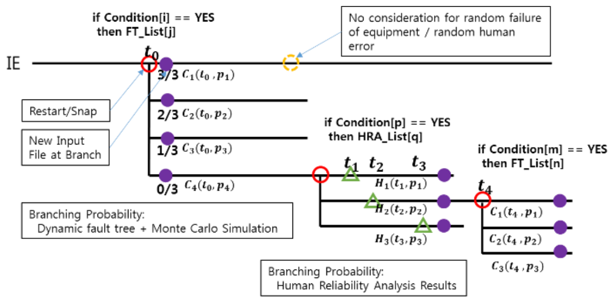


Fig 3. Execution Process of DICE

The DICE scheduler run a plant physical model for a time step, dt, using initial information such as initiating event and initial component status. When the plant variable met a special condition, the scheduler makes the calculation log which has the plant variables such as temperature, pressure, component status and etc. until that time. At the same time the scheduler makes necessary branches as required. These branches were built using the information from an equipment model and an operator crew model. The equipment model offers the information of the success/fail to run of required functionality combining equipment status. On other hand, the operator crew model offers the information for the success/fail of operator action in the specific time interval. Each branch has the probability to go into the sequence. Multiplying these probabilities which appeared in a sequence, finally can provide quantitative outcomes of each scenario.

After branching, the scheduler assigns a mission to the plant physical model using the calculation log and the modified input file, which reflecting the updated information from equipment/operator crew model. The red circles which shown at Figure 3 stand for the calculation log, the purple circles mean the modified input files. At the phase of the conceptual design for DICE, the complex situation such as random failure of equipment and the random human error was not considered.

The DICE scheduler is implemented to operate in a distributed environment because of the requirement to run a large number of physical models.

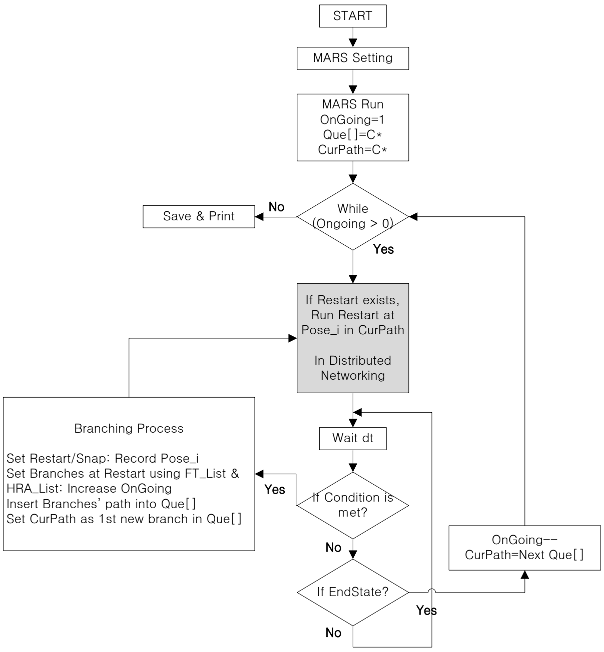


Fig 4. Flowchart of DICE

Figure 4 shows the algorithm of the DICE scheduler working as follow;

1) Run the plant physical model, such as MARS-KS (Korean regulatory safety analysis code) using initial setting such as initiating event, initial input file, branch condition and so on.
2) If the plant variables do not meet the branching condition, keep going calculation. Otherwise;
    a. Save the calculation log until that time which includes the plant variables such as temperature, pressure, component status and so on, and
    b. Set the branches and generate the modified input file using the information from equipment/operator crew model.
3) Perform the calculation for 1$^{st}$ sequence of the new branches for every time step using the log and the input file from the step 2.
4) Repeat the step 2-3 until the plant variables meet the end state conditions.
5) When the plant variable met the end state;
    a. Reports the result and save,
    b. Back to the previous branching point, and perform the calculation for the next sequence.

*2.2.2 Plant Physical Model*

This study will focus on the performing dynamic PSA for design basis accidents by selecting the MARS-KS as a calculation engine for sequences. This choice is closely related with the case studies after the development of DICE explained in Chapter 3.

Basically the plant physical model takes the thermal-hydraulic analysis in accident situation of nuclear system by reflecting the interaction between the other modules in DICE. In order for the flexibility of connecting other physical models, a kind of the translator between DICE and the physical model is implemented such that other models can be replaced with appropriate translator into DICE. Therefore the analysis is not limited to a specific plant type.

The thermal-hydraulic analysis for accident sequence is carried out in the form of restarting the thermal-hydraulic analysis code at branching point, reflecting the conditions and the branch determined by scheduler. For this purpose, DICE will use the restart function of MARS-KS, but the restart function is a unique nature of the particular code. For consistent analysis with other models, all variables not included in the restart file at branching point should be stored and be used at the restart.

The thermal-hydraulic model should consider the method to reflect the variables' modification when branching is occurred. Two methods will be compared together:

1) Reflect variables' information to the input file which used at restarting. In this case, the input file should be constructed to contain all possibilities of branching such that success/failure or partly success can be reflected by simple adjustment of variables.
2) Directly modify the variables loaded in memory at branching point, before restarting. In this case, the thermal-hydraulic model should be hard-coded merged in DICE.

*2.2.3 Operator Crew Model*

This model calculates the changing probabilities to a proper sequence when the plant operating conditions were changed by operator's action. Also it offers the information of operating conditions to plant physical model. The operator actions can divided as follow:

1) Recovery after the abnormal situation triggered by a plant physical model
2) Preemptive action before abnormal situation

The operator's action are represented as H branching point at Figure 3. The probability at the branching point by operator's action is the success probability of the diagnosis and execution, $P_{H_i}(Success|t_{i-1}\sim t_i)$ during available time.

Detailed methodologies to compute these probabilities are under reviewing; TACOM [7] in calculate the performance time, K-HRA [8] or HCR/ORE (Human Cognitive Reliability/Operator Reliability Experiment) in calculating the success probability.

*2.2.4 Equipment Model*

It has the function of providing the reliability of automatic and manual operation of equipment. The equipment model calculates the change probabilities to proper operate mode and provides the operating information such as component status to plant physical model. For instance, assume the Loss Of Coolant Accident (LOCA) scenario. The primary pressure will decrease and the safety system injects borated water to cold legs at certain time line. This situation can be represented in the first branching point, C, in Figure 3. Each branch stands for the cases how many redundant safe injection works. The fail to inject borated water can be occurred by failure of components or no generation of signals. In this study, the signal failure is considered only all or none for the simplification.

The probabilities to go into each sequence can be obtained from a system fault tree by modifying the success criteria of the top event. The summation of all branch probabilities at the branching point should be one. In reality, an infinite number of complex combinations of component status may be able to be made to determine success/fail of the system function. However, this study will take simplified fault trees at least which is enough to co-work with the plant physical model. The quantification of the fault tree can be performed by conventional analytic engines or Monte Carlo simulation. In further study, a dynamic fault tree method will be introduced to apply in-depth dynamic features.

## 3. Expected Applications

We will discuss the coverability (i.e. condition of being coverable or being able to cover) of the operating procedures as an example of application of DICE. In this study, the coverability of procedures stands for the scope of success path of accident scenarios that the procedures can manage or mitigate. In other words, this is the answer for the question: 'Is it possible to reach any undesired end state at the end of procedure execution?' It should be 'no,' which means 'perfect' coverability. A similar one can be found in previous study [9]. In this study, a Medium-break Loss of Coolant Accident (MLOCA) was reviewed using the DDET technique. Several hundred of ADS-TRACE simulations were carried out with variation in fracture size and operator model, resulting in the following dynamic event trees.

Conditional Core Damage Probability (CCDP) and Core Damage Frequency (CDF) calculations were performed according to fracture sizes. It was confirmed that dividing the fracture size of MLOCA produces a model that can better show quantification results. The CDF analysis by selecting only the specific fracture size was sometimes even not conservative. It can be confirmed that this study provides opportunity to complement the limitations of conventional PSA. Therefore, the first application of DICE will be the coverability check of emergency operation procedures in Nuclear Power Plants (NPPs). It should be noted that a hypothetical plant and its procedures are targeted. The scope of the procedure should be ascertain even if the randomness of the hardware failure and human errors affects situation. Time-dependent stochastic simulation was not easy, so the current deterministic methods with sensitivity study is worth being reviewed.

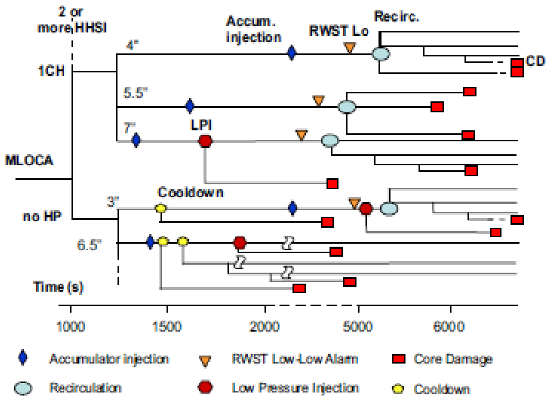


Fig 5. Dynamic event tree of ADS-TRACE simulator

The present procedure is designed based on conservative assumptions and accumulated latest knowledge so it is not likely for any missing scenarios to be present. Under this situation, this tool can contribute on either way regardless of observations: if it identifies any missing scenarios or not.

## 4. Conclusions

In this paper, we described the outcomes of the conceptual design related to the development of DICE, a dynamic PSA support tool, and presented the expected applications using it.

Based on the DDET method, we have broadened the expected utilization by securing the versatility or flexibility for each major module. For example, the plant physical model can be combined with any other safety analysis codes, and the equipment model allows various methods related to the quantification of system reliability, for instance, conventional fault tree, dynamic fault tree, reliability block diagram, and so on, to be linked. In the case of the operator crew model, the alternatives for execution time and success probability are dynamically linked. The scheduler itself was designed to be a distributed computation suitable for large capacity calculations using resources to be automatically connected to the network.

For readers' information, this study is supposed to continue for three years. By 2020, the prototype tool development and case study will be completed. After that, improvement work will be done upon additional requirements.

## ACKNOWLEDGEMENT

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