Development of the Dynamic Event Tree Tool (DICE-MULTI) for SMR Multi-Module Simulation

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ABSTRACT

Small Modular Reactors represent a significant advancement in nuclear technology, featuring multiple reactor modules within a shared facility. However, pending technical challenges and the lack of safety evaluation standards for SMRs necessitate the development of new assessment methodologies. To address this, DICE-MULTI, an extension of the Dynamic Event Tree tool DICE, was developed to enable simulations of multiple physical models. DICE-MULTI supports safety assessment of SMRs through DET analysis, contributing to the establishment of future safety review standards. Key advancements in DICE-MULTI include the synchronization of time steps across multiple physical models. This feature resolves discrepancies in simulation times caused by differing operational states, such as transient conditions in one model and steady-state conditions in another. Time step synchronization ensures accurate representation of real-time interactions between physical models, including the effects of potential shared components like an Emergency Cooling Tank. Additionally, DICE-MULTI introduces a third physical model dedicated to calculating shared component parameters, referred to as "common variables," in real time. This physical model dynamically computes and distributes these variables to the respective physical models, ensuring precise simulation of interdependencies. To verify its functionality, DICE-MULTI was tested using simplified models. The results demonstrated its capability to effectively handle multi-module simulations. These developments position DICE-MULTI as an available tool for the safety assessment of SMRs, offering enhanced accuracy in modeling complex interactions within multi-module systems.

Keywords: Small Modular Reactor, Dynamic Event Tree, Multi-Module Simulation

I. INTRODUCTION

Small Modular Reactors (SMRs) are next-generation nuclear systems that pursue enhanced safety, economic feasibility, and operational flexibility, based on a fundamentally different design philosophy compared to conventional large-scale reactors. Each module is constructed as a compact and independent unit, and the system is designed with inter-module operability and scalability in mind, making it distinct from traditional nuclear power plants. Such structural characteristics lead to a complex operational environment in which multiple reactor modules operate within a single facility and share common systems.

Due to the nature of SMRs, a systematic and precise safety analysis is required to address various scenarios arising from dynamic inter-module interactions and the use of shared systems (e.g., cooling systems, power supply systems). While conventional Probabilistic Safety Assessment (PSA) techniques provide quantitative evaluation of various accident scenarios, they face limitations in accurately reflecting complex dynamic interactions, time-dependent state changes, and inter-system linkages [1].

Particularly in multi-module environments, the limitations of static analysis inherent in existing PSA methodologies become more pronounced. Multi-module systems present significant challenges in accurately modeling inter-module interactions, dynamic behavior of shared systems, and time-dependent operational state changes, forcing reliance on conservative assumptions. For example, traditional multi-unit PSA typically assumes that each unit is always operating at full power or conservatively treats shared system failures as simultaneously affecting all modules [2]. Such conservative treatment risks oversimplifying the actual dynamic characteristics of the system, potentially leading to overestimation of safety margins or masking important safety phenomena.

Static PSA, composed of Boolean logic-based event tree and fault tree analyses, has inherent limitations in adequately considering time-dependent interactions or sequential events [3]. These problems make it difficult for static models to realistically represent the staged propagation processes of how shared system failures affect other modules in multi-module facilities.

In response to these challenges, Dynamic Event Tree (DET) analysis and Dynamic Fault Tree (DFT) methodologies have emerged as representative approaches capable of realistically simulating the evolution of uncertainties over time. Unlike static event tree analysis, which examines predefined accident scenarios, DET dynamically branches scenarios based on system state changes during the simulation. This enables more accurate representation of complex interactions and time-dependent system behaviors as accidents progress [4]. Meanwhile, DFT extends static fault tree analysis by introducing a temporal dimension, allowing modeling of spare management, order-dependent failures, and functional dependencies. While static fault trees only consider whether components fail, DFT analyzes when failures occur and how the failure sequence impacts the system, providing more realistic reliability assessments [5]. In multi-module environments, DET effectively overcomes the limitations of static PSA by accurately reflecting inter-module interactions, the dynamic response of shared systems, and time-dependent operator actions without resorting to conservative assumptions. One of the leading tools implementing the DET methodology is DICE, which enables dynamic simulations that incorporate diverse uncertainties.

However, the original DICE is structured to perform simulations at the level of a single system or module, limiting its applicability to scenarios involving inter-module interactions or shared system effects in multi-module environments like SMRs. Therefore, this study developed DICE-MULTI, an extended analysis tool based on DICE, capable of handling multiple physical models simultaneously. The tool implements time synchronization among physical models operating in different states and dynamically calculates and updates shared variables (e.g., flow rate, temperature) across modules.

DICE-MULTI aims to provide a realistic simulation framework for the dynamic behavior of SMR multi-module systems, ultimately contributing to the establishment of a reliable basis for safety assessment and regulatory standards.

II. Functions and Implementation Structure of DICE-MULTI

The original DICE is a dynamic probabilistic safety assessment tool based on the Dynamic Event Tree (DET) methodology, designed to simulate scenario branching over time by incorporating system behavior and uncertainty. It consists of a thermal-hydraulic physical module, a diagnosis and reliability module that determines responses based on system states, and a scheduler that controls simulation flow and scenario branching. Its architecture is primarily tailored for accident scenario analysis within a single reactor module.

However, SMR systems inherently involve multiple reactor modules operating within a shared facility, interacting through common systems and physical couplings. In such systems, the limitations of DICE’s single-module design become apparent. For instance, a cooling anomaly in one module may impact the thermal conditions of a shared Emergency Cooling Tank (ECT), which in turn affects the thermal-hydraulic response of another module. Such interdependencies are difficult or even impossible to realistically capture with the original DICE structure.

To meet the analytical demands of multi-module systems, this study introduces DICE-MULTI, an extended version of DICE designed to enable concurrent simulations of multiple physical models. Each physical module in DICE-MULTI operates independently but pauses at regular computation intervals referred to as progress steps to exchange state information with other modules. During these exchanges, shared variables (e.g., ECT flowrate and temperature) are dynamically calculated based on the outputs of each module. The scheduler manages the timing of these exchanges, coordinates the order of information propagation, and ensures system-wide consistency in variable updates.

A key feature of DICE-MULTI is its ability to preserve time synchronization even when modules are operating under different transient conditions. This allows for accurate modeling of inter-module thermal and hydraulic interactions. Furthermore, DICE-MULTI supports heterogeneous configurations in which each module may have different design parameters, operational modes, or accident progressions offering a more realistic and versatile simulation environment than conventional parallel analysis approaches.

By retaining the core architecture of DICE while introducing multi-module integration, shared parameter synchronization, and coordinated scheduling capabilities, DICE-MULTI provides a robust analytical platform suitable for evaluating the complex behavior of i-SMR systems. Moreover, its flexible architecture can be extended to multi-physics applications, such as P2X systems and hydrogen-coupled energy networks, making it a promising tool for future energy system safety assessments [6].

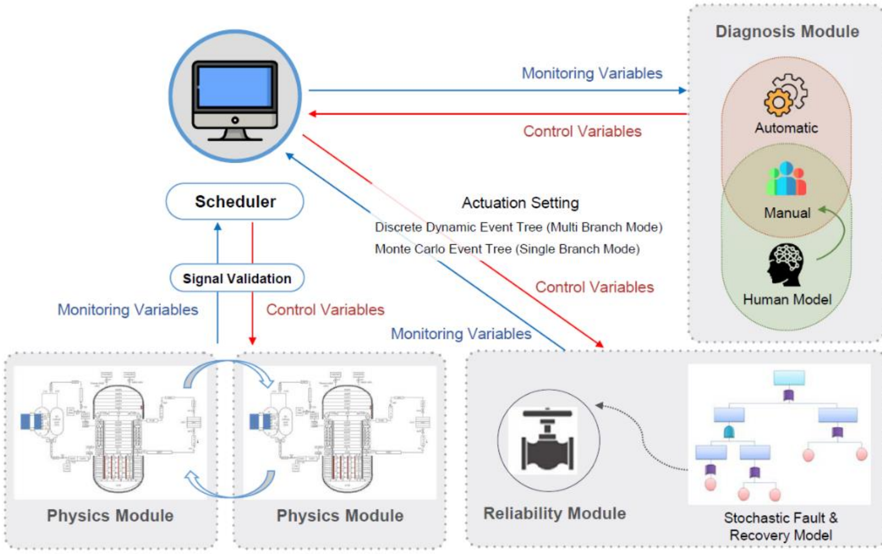

FIGURE 1. Schematic Architecture of DICE-MULTI

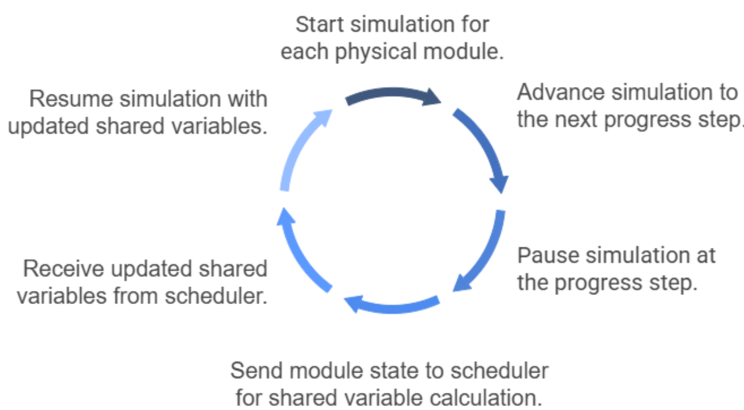

FIGURE 2. Flowchart of Shared Variable Exchange Process in DICE-MULTI

III. Case Study: Application of DICE-MULTI to a Multi-Module LOFW Accident Scenario

To evaluate the multi-module interaction capabilities of DICE-MULTI and assess the influence of dynamically coupled shared system variables on the overall system behavior, a case study was conducted using a simplified model of a SMR. This study focused on a Loss of Feedwater (LOFW) accident scenario and compared the thermal behavior of the ECT under three different simulation conditions. The shared variables liquid temperature, gas temperature, and pressure in the ECT were configured to be dynamically exchanged between physical modules at each progress step.

The first scenario served as a reference case in which both modules remained in normal operation without any initiating event. In the second scenario, a LOFW event was introduced in only one of the two modules at 500 seconds, while the other module continued in a steady state condition. In the third scenario, both modules experienced LOFW events simultaneously at the same point in time, allowing for the observation of compounded thermal loads on the shared ECT. All simulations were run up to 1000 seconds, and the liquid temperature of the ECT was used as the key indicator for comparing inter-module effects.

In the first scenario, the ECT liquid temperature remained stable throughout the simulation, confirming that the shared variable exchange and synchronization mechanisms operated consistently under non-accident conditions. In the second scenario, despite only one module undergoing the LOFW event, a noticeable increase in ECT temperature was also observed in the unaffected module. This result demonstrates the ability of DICE-MULTI to accurately capture inter-module thermal interactions mediated through shared resources. In the third scenario, when both modules experienced the LOFW accident simultaneously, the temperature increase in the ECT was significantly larger, indicating that shared system behavior becomes more pronounced and nonlinear when subjected to concurrent stress.

These results confirm that DICE-MULTI provides a realistic simulation framework capable of representing dynamic interactions and shared system feedbacks in multi-module environments. In particular, the observation that modules not directly affected by an accident can still experience thermal impacts through shared systems highlights a critical limitation of traditional single-module or static analysis methods. Thus, incorporating such interdependencies is essential for accurate safety assessment of multi-module reactor systems**.**

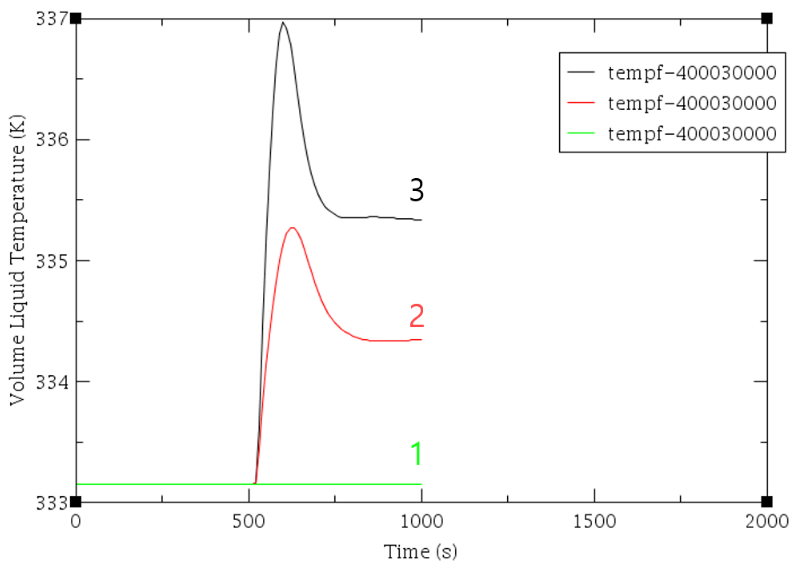

FIGURE 3. Transient Evolution of Temperature in the ECT Under Different Module Accident Scenarios

IV. Conclusion

In this study, DICE-MULTI was developed as an extension of the original DICE tool to enable more realistic simulation of dynamic interactions in multi-module SMR systems. In systems such as SMRs, where multiple reactor modules are interconnected through shared systems, conventional single-module analysis or static PSA methods fall short in capturing time-dependent behaviors and inter-module coupling effects. To address this analytical gap, the proposed DICE-MULTI framework allows simultaneous operation of multiple physical models with integrated time synchronization and shared variable exchange.

A case study was conducted using a conceptual accident scenario in which the ECT was treated as a shared component. Simulations were performed under three conditions: no accident, a LOFW accident in one module, and LOFW accidents in both modules. The results showed that even when the accident occurred in only one module, thermal effects were propagated through the shared ECT to the unaffected module, altering its state. In the case of simultaneous accidents in both modules, the thermal load on the shared ECT was compounded, leading to significantly higher temperature increases. These results highlight dynamic characteristics that cannot be captured by single-module simulations and demonstrate DICE-MULTI's capability to realistically reflect inter-module effects in multi-reactor environments.

DICE-MULTI expands the analytical scope of the original DICE tool by incorporating time-synchronized simulations, dynamic shared variable handling, and orchestrated scheduling among modules. It also presents the potential for simulation-based safety assessments that avoid the need for conservative assumptions required in static PSA, offering a more realistic evaluation of system behavior.

However, this study was limited to a simplified conceptual SMR model and a single type of accident scenario. Future work should involve applying the framework to detailed reactor designs and incorporating additional shared system variables such as electrical and control systems. Furthermore, integration of operator response models and probabilistic input distributions will allow the tool to evolve into a more comprehensive and practical platform for multi-module safety assessment**.**

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REFERENCES

[1] Multi-unit Probabilistic Safety Assessment Regulatory Framework Development Research Project, Nuclear Safety and Security Commission, Republic of Korea (2023).
[2] Technical Approach to Probabilistic Safety Assessment for Multiple Reactor Units, Safety Reports Series No. 110, International Atomic Energy Agency, Vienna, Austria (2023).
[3] Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, Safety Standards Series No. SSG-3, International Atomic Energy Agency, Vienna, Austria (2010).
[4] Dynamic Probabilistic Safety Assessment Studies for Advanced Reactors, Idaho National Laboratory, INL/EXT-15-36726, Idaho Falls, Idaho, United States (2015).
[5] M. Cepin and B. Mavko, A dynamic fault tree, Reliability Engineering & System Safety, vol. 75, no. 3, pp. 239–252, Elsevier, Oxford, United Kingdom (2002).
[6] D. G. F. Final PhD Thesis, "Flexibility in Multi Energy Systems: Co-simulation Approaches for P2X Resource Integration," TU Delft Research Portal, Delft, Netherlands (2023).