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Streamlined Simulation Using Scenario Weighting Method for Simulation and Storage Management

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1. Introduction

Safety assessment for nuclear power plants (NPPs) is critical to ensuring public safety by systematically identifying potential hazards and mitigating associated risks [1]. The Fukushima accident underscored how failures in complex, interdependent NPP systems can escalate into severe nuclear incidents, causing prolonged environmental contamination and substantial ecological damage [2]. Consequently, high accuracy safety assessment methodologies are essential for accurately evaluating potential accident scenarios and developing effective safety enhancement strategies.

Dynamic safety assessment, unlike static safety assessment, incorporates the temporal evolution of system states, providing more accurate analyses by reflecting real-time operational variations. However, dynamic safety assessments involving extensive scenario simulations using thermal-hydraulic (TH) system codes demand substantial computational resources [3]. Balancing simulation accuracy, computational efficiency, and time management remains challenging.

To overcome the significant computational burden associated with dynamic safety assessments, we propose the Optimized and Accelerated Simulation using Intermediate State Storage (OASIS) method. OASIS improves computational efficiency by storing intermediate states from prior simulations and identifying overlaps in subsequent scenarios, enabling simulations to resume efficiently from relevant points rather than from initial conditions.

Current study apply the OASIS framework in a Station Blackout (SBO) scenario, evaluating its effectiveness through comparative analysis of simulation runtime and storage management. Results demonstrate OASIS's potential as a practical approach for enhancing computational efficiency in large-scale dynamic safety assessments.

2. Method

A key feature of TH codes is its "Restart" function, enabling simulations to resume efficiently from saved states rather than initial conditions. This significantly reduces computational time, allowing comprehensive exploration of accident scenarios with optimized resource use. The proposed framework utilizes this "Restart" function to streamline simulation execution, minimize redundant computations, and enhance overall efficiency. Figure 1 illustrates the flowchart of the framework.

3.1 Branch Point Creation

In this phase, branch points are systematically

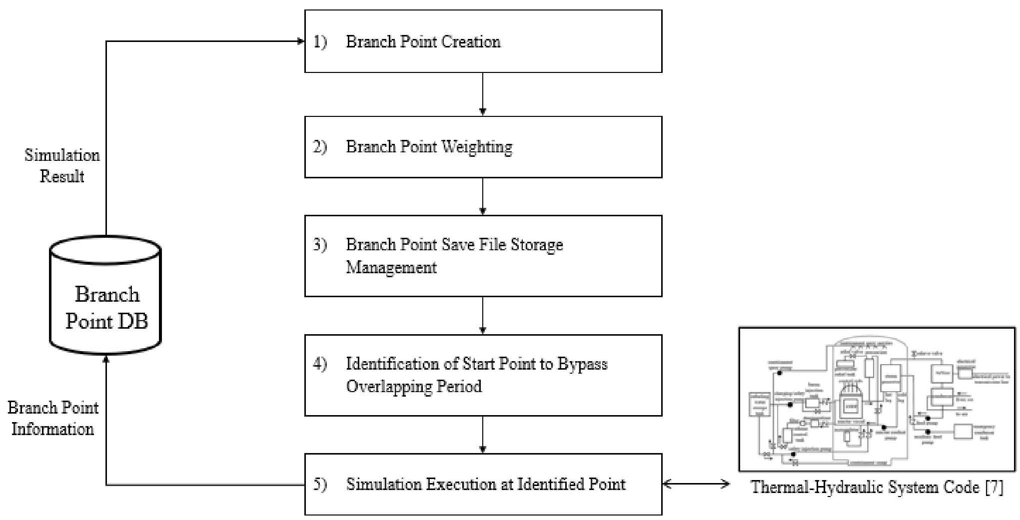

Fig 1. Flowchart of Optimizied and Accelerated Simulation using Intermidiate Storage

identified and designated at specific moments involving changes in component states, human operations, or delay times. Branch points are established at component initiation, the commencement of human operations, and adjustments in component delay times. A structured nomenclature is used to document these points, representing scenarios through bracketed divisions. Simultaneous operations, such as AC and DC power and auxiliary feedwater system operations, are represented using nested bracket structures like [[Operational record of AC, DC Power], [Operational record of auxiliary feedwater]]. Each scenario follows the format [[#, #, #, -1], …], where numerical values of interger (≥ 0) indicate operation completion times, and -1 denotes inactive components or operations potentially activated later.

3.2 Branch Point Weighting

In this phase, weights are allocated to previously identified branch points according to Eq. (1), where T represents the elapsed simulation time at the branch point, and B denotes the number of branches extending beyond it:

$$Branch\ Point\ Weight = T \times B \qquad (1)$$

The weight quantifies potential computational time savings and determines storage priority. For instance, a branch point with a longer elapsed simulation time and a greater number of subsequent branches receives a higher weight, thus higher storage priority.

3.3 Branch Point Save File Storage Management

In this phase, storage management is performed by ranking branch points in descending order based on their assigned weights. Save files corresponding to the lowest-weight branch points are removed to optimize storage space while preserving essential simulation data.

3.4 Identification of Start Point to Bypass Overlapping Period

In this phase, previously stored branch point save files are utilized to determine the most efficient simulation starting point for the current scenario. The system identifies and selects the save file that minimizes unnecessary computations, designating its corresponding branch point as the simulation's initial state.

3.5 Simulation Execution at Identified Point

In this phase, the simulation begins from the identified starting point using the relevant save file determined in the previous step. As the simulation proceeds, additional branch points and their associated outcomes are systematically documented within the database. These updated records subsequently inform the application of the algorithm to future scenarios, promoting efficient simulation execution and enhancing data-driven analyses.

3. Case Study

The case study evaluates the effectiveness of the proposed framework using a Station Blackout (SBO) scenario, based on the Korean-designed OPR1000 pressurized water reactor with an approximate capacity of 1,000 MWe.

The TH system code employed in this analysis was MAAP 5.05, a computational software developed specifically to simulate thermal-hydraulic phenomena and to evaluate potential accident scenarios in nuclear power plants (NPPs) [4]. MAAP 5.05 is primarily oriented toward severe accident analyses, providing quantitative predictions of system behavior under a wide variety of accident conditions. Its capabilities contribute significantly to improving risk assessments and facilitating risk-informed decision-making in the operation and management of NPPs.

In this case study, Deep-SAILS, an adaptive sampling algorithm, was coupled with the OASIS framework. Deep-SAILS was developed specifically for nuclear power plant (NPP) risk assessment and aims to efficiently and precisely identify the Limit Surface (LS), which separates successful scenarios from failure scenarios [5]. To overcome the substantial computational demands typical of static probabilistic safety assessment, Deep-SAILS incorporates a Deep Neural Network (DNN) Metamodel enhanced by Monte Carlo Dropout techniques.

This analysis specifically investigates the operational roles and effectiveness of Alternative AC-Diesel Generator (AAC-DG) and Mobile Diesel Generator (MDG) systems, employed as emergency backup power solutions to restore AC power under SBO conditions. Table 1 summarizes the key scenario parameters and their discretized operational conditions.

Table I: Problem Description

Parameter(Axis)		Operating Condition	Resolution (HR)
1	**First Delay Time** (EDG & TDP Run for the first 4HR)	**0~12HR** after Initial Event LOOP	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 **(13)**
2	**AAC-DG & MDP Run Time**	**0~12HR** after First Delay Time	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 **(13)**
3	**Second Delay Time**	**0~12HR** after AAC-DG & MDP Fail to start or run	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 **(13)**
4	**MDG & MDP Run Time**	**0~12HR** after Second Delay Time	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 **(13)**

Operational scenarios for AAC-DG and MDG are modeled with discretized activation delays ranging from 0 to 12 hours, reflecting realistic time constraints encountered during emergency responses. During the initial 4-hour delay period, critical safety systems, such as the Emergency Diesel Generator (EDG) and Turbine Driven Pump (TDP), remain operational, ensuring continued cooling of the reactor core and residual heat removal in scenarios where primary safety systems are compromised or unavailable [6].

Upon completion of the initial delay, AAC-DG and MDG operate for a period ranging from 0 to 12 hours.

Following AAC-DG and MDP failure, MDG and MDP are subsequently activated after a second delay, also varying from 0 to 12 hours. After this second delay, MDG and MDP operate again for a duration between 0 to 12 hours. Time parameters are discretized into hourly intervals, resulting in the discrete set: {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12} hours.

Storage capacity is un-limitation and limited to 5 GB. When conducting the case study by coupling OASIS with Deep-SAILS without imposing storage capacity constraints, approximately 8.4 GB of storage was required. Consequently, the storage limit was set to approximately 60% of this value, or 5 GB. The Deep-SAILS and OASIS methods were applied across the scenarios, and results were generated using MAAP 5.05.

Scenarios terminate either when Peak Cladding Temperature (PCT) surpasses 1255 K [7] or when simulation time reaches 12 hours. The failure criterion in this study is based on the PCT threshold. Scenarios exceeding 1255 K are classified as Core Damage (CD), while those remaining below this limit after 12 hours are classified as OK.

In the current case study, a total of 28,561 scenarios were analyzed. By employing Deep-SAILS coupled with OASIS, the required number of scenarios to be simulated decreased significantly. Specifically, when no limitation was imposed on database storage capacity, the number of scenarios reduced to 2,027, representing an efficiency ratio of approximately 7.097%. Meanwhile, under a restricted database storage condition of 5 GB, the scenario count was reduced to 2,131, yielding an efficiency ratio of approximately 7.461%. The difference of around 0.26% between these two efficiency ratios is presumed to originate from minor uncertainties inherent in the thermal-hydraulic calculations performed by MAAP 5.05, as well as intrinsic uncertainties associated with the Deep-SAILS algorithm itself.

Furthermore, the total MAAP simulation time with OASIS for the scenario without storage capacity limitations was approximately 8,639.66 hours equivalent to about 8 hours and 51 minutes per scenario batch, whereas the corresponding simulation under a storage capacity constraint of 5 GB required approximately 9 hours and 6 minutes per batch. Consequently, the computational efficiency achieved by OASIS, initially calculated as a 63.51% reduction for the unlimited storage scenario, slightly decreased to approximately 62.43% under the 5 GB storage restriction.

Table 2 presents a detailed comparison of the computational efficiencies obtained with OASIS for scenarios both with unlimited storage capacity and with a constrained storage capacity of 5 GB.

Despite reducing the required storage capacity by approximately 40% (from roughly 8.4 GB to 5 GB), the resulting difference in total simulation time per scenario set was only around 15 minutes. This corresponds to an overall efficiency difference of merely 1.08%. This result clearly indicates that the implementation of OASIS can effectively mitigate limitations associated with restricted storage capacity. Additionally, by utilizing the "Restart" functionality of the thermal-hydraulic (TH) system code, OASIS notably reduces the significant computational burden typically encountered in dynamic safety assessments of nuclear power plants. These findings demonstrate the capability of the integrated OASIS–Deep-SAILS framework to maintain high computational efficiency while effectively managing storage constraints, thus offering significant advantages for practical safety assessment applications.

Table II: Comparison of OASIS Computational Efficiency under Unrestricted and 5 GB Storage Capacity Conditions

	Unrestricted Case	5GB Storage Capacity
Efficiency	63.51%	62.43%

4. Conclusion and Future work

To address computational burden in large-scale scenario simulations, this study proposed a framework incorporating intermediate state management. In case study, by combining Deep-SAILS for adaptive sampling near the Limit Surface (LS) with the Restart functionality of the TH system code, redundant computations were significantly reduced. Consequently, critical scenarios were efficiently prioritized, and unnecessary repetition of full-scale simulations was effectively avoided.

Operational scenarios for AAC-DG and MDG were modeled with discretized activation delays (0–12 hours), reflecting realistic emergency response constraints. By coupling Deep-SAILS with OASIS, significant computational efficiencies were achieved: scenarios analyzed reduced from 28,561 to 2,027 (7.097%) without storage constraints, and to 2,131 (7.461%) under a 5 GB storage limit. Despite a 40% reduction in storage capacity, the resulting computational efficiency decreased only marginally (by 1.08%), underscoring the robustness of the integrated framework. Additionally, using the "Restart" functionality within the TH system code substantially mitigated computational load, emphasizing the practical effectiveness of the OASIS and Deep-SAILS integration for dynamic nuclear safety assessments.

Future research should further extend the applicability of the proposed framework, particularly by enhancing the scope and relevance of safety assessments across various operational scenarios. This includes applying the framework to newly integrated safety components and systems, such as passive safety systems, whose effectiveness in severe accident scenarios warrants further investigation. While the present case study conducted simulations up to a timeframe of 12 hours, subsequent studies should consider extending simulation durations to align with realistic component mission times such as 24 or 72 hours. This extension would provide deeper insights into system reliability and effectiveness under prolonged emergency conditions, enabling more comprehensive evaluations of nuclear plant safety.

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