Application of EMRALD for Simulation-Based Estimation of Station Blackout Sequence Frequencies in a Nuclear Power Plant

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ABSTRACT

This study investigates the use of event modeling risk assessment using linked diagrams (EMRALD), a dynamic probabilistic safety assessment (PSA) tool developed by the Idaho National Laboratory to analyze complex accident sequences triggered by a loss of offsite power (LOOP) in nuclear power plants. Unlike traditional PSA methods based on event tree and fault tree, EMRALD enables intuitive modeling of time-dependent system behaviors and component interactions, making it well suited for evaluating all the accident sequences. The analysis was conducted in two stages. First, a previously published station blackout (SBO) scenario was reconstructed using EMRALD to verify its computational reliability. The results were validated through comparison with both a convolution-based model and Monte Carlo simulations, confirming EMRALD's ability to accurately estimate conditional core damage probabilities (CCDP) and associated risk sequences. Second, a comprehensive LOOP scenario was developed, incorporating multiple power supply and heat removal components such as emergency diesel generators (EDGs), alternative AC diesel generator, motor driven auxiliary feedwater pumps, and turbine driven auxiliary feedwater pumps along with their common cause failure probabilities. EMRALD dynamically simulated these systems and estimated CCDP based on Monte Carlo simulation. The simulation results identified power supply system failures as key contributors to core damage. Mechanical pump failures showed relatively low impact, and SBO-R (EDGs fail to run) sequences appeared more frequently than SBO-S (EDGs fail to start).
This modeling approach demonstrates EMRALD’s applicability for analyzing time-sensitive, interdependent accident sequences under LOOP conditions.

Keywords: Probabilistic safety assessment, Event modeling risk assessment using linked diagrams, Time-dependent, Loss of offsite power, Station blackout

I. Introduction

Probabilistic safety assessment (PSA) has long provided valuable insights into reactor operation and design by quantitatively evaluating nuclear reactor risk, identifying critical events significantly impacting reactor safety, and analyzing components that significantly contribute to such risks. Among numerous PSA studies conducted to date, station blackout (SBO) has consistently been identified as a significant contributor affecting reactor safety. SBO is recognized as a specific scenario of a loss of offsite power (LOOP) event, characterized by the complete failure of emergency diesel generators (EDGs).

Under SBO conditions, nuclear power plants typically rely on alternative AC diesel generators (AAC DGs) to ensure secondary heat removal. Specifically, AAC DGs drive motor driven auxiliary feedwater pumps (MDPs) or provide direct current power to turbine driven auxiliary feedwater pumps (TDPs) to provide feedwater and remove heat effectively, maintaining reactor core cooling. However, the reliability and availability of these components involve inherent uncertainties, as operational failures or reduced performance levels remain possible under specific conditions. Such uncertainties require explicit evaluation and consideration within PSA frameworks.

This study utilizes a dynamic probabilistic modeling tool, event modeling risk assessment using linked diagrams (EMRALD), to systematically analyze diverse scenarios associated with LOOP-induced SBO events. EMRALD addresses limitations inherent in conventional PSA methodologies by effectively capturing time-dependent behaviors, state transitions, and interactions among plant components. The purpose of this research is to analyze and compare SBO event sequences that emerge from LOOP scenarios, using EMRALD to evaluate how these complex time dependent sequences develop and diverge under varying conditions. This research also clarifies the calculational accuracy of EMRALD and demonstrates its utility in implementing complex sequences intuitively and clearly.

II. Analytical Framework and Modeling approach

I1.A. Introduction to EMRALD

EMRALD is a dynamic PSA tool developed by Idaho national laboratory to facilitate the analysis of time-dependent complex scenarios. Unlike traditional PSA tools that rely primarily on event trees (ET) and fault trees (FT), EMRALD is structured around state changes and designed to represent how systems evolve over time. Prescott et al [1] express EMRALD as a dynamic PSA tool that bridges the gap between traditional modeling practices and dynamic simulation by offering an intuitive graphical interface and simplified external coupling capabilities.

In EMRALD, models are typically built using a plant-level diagram, logic or subsystem diagrams representing the configuration of systems, and component-level diagrams that define individual component states and transitions. These diagrams can interact through state changes, and the success or failure of multiple diagrams can form logic trees like FT, where certain conditions trigger some events. This modular structure enables users to express the same plant features in multiple ways, encouraging creativity and flexibility in modeling.

Such flexibility, however, means that the complexity of the model and the accuracy of the analysis result depend significantly on the user's modeling skill and familiarity with EMRALD. The tool provides opportunities for simplification or enhancement based on user’s choices, which gives EMRALD a higher degree of user influence than traditional PSA tools. For highly skilled users, this translates into the ability to assess intricate, time-dependent scenarios that would be difficult to model using conventional approaches much easier.

EMRALD also helps users create Monte Carlo simulations more easily and intuitively, making it simpler for others to follow the timeline and changes in scenario conditions. Additionally, it clearly shows which components fail and lead to core damage, making it easier to identify cutsets and its fractions.

Recognizing these strengths, EMRALD was selected in this study as the primary tool for analyzing complex LOOP sequences.

II.B. SBO sequences

SBO refers to the loss of all AC power sources necessary to cool the reactor core. It is typically a subset of a LOOP event in which all EDGs also fail to operate. When SBO occurs, the nuclear power plant (NPP) attempts to remove decay heat by utilizing alternative AC power sources such as the AAC DG, or by operating components that require no external power, such as the TDPs. If heat removal is successfully maintained until offsite power is recovered, the NPP remains safe. However, if heat removal fails before power recovers, the event progresses toward core damage.

The progression of SBO depends on the availability and reliability of these backup systems, the timing of failures, the interactions between systems, and the status of batteries, which provide time margin to TDPs. As these systems interact, various accident sequences may develop depending on which components succeed or fail and when these events occur. Such variability affects the available margin for offsite power recovery and can significantly influence the overall reliability of the NPP. Two types of SBO scenarios are typically considered: SBO-S and SBO-R, depending on whether all EDGs fail to start or at least one EDG fails to run.

Previous study, Kim [2], introduced a convolution approach as a method for analyzing complex time-dependent scenarios. The study specifically focused on SBO-S scenario, which is adopted in the present work to verify the computational accuracy of EMRALD. The scenario was evaluated with all three methods, and the results were found to be almost the same. The parameters used in calculation are from [2] which are noted in Ma et al. [3]

III. Analysis of LOOP

III.A. Scenario Development and Implementation in EMRALD

In Sections II.B, the special case of LOOP, known as the SBO-S scenarios, was analyzed to validate the computational accuracy of EMRALD. Building on that foundation, this section expands the analysis by leveraging EMRALD's capabilities to model and simulate a more complex and realistic sequence of events.

Comprehensive LOOP scenarios were constructed, incorporating the important system interactions that may follow LOOP. The model includes two EDGs, one AAC DG, two MDPs, and two TDPs. For all duplicated components, the possibility of

CCFs was also included, with failure probabilities sourced from [3] and Ma et al. [4] The offsite power recovery time is assumed to follow a lognormal distribution, with distribution parameters sourced from Johnson et al. [5]

When LOOP event occurs, all the components except AAC DG are assumed to be initiated. After both EDGs fail, the AAC DG starts to run, and if it also fails and the battery depletion time elapses, the TDPs are modeled to fail due to a lack of DC power support.

The heat removal system is considered to have failed if either of the following conditions is met: (1) both MDPs and TDPs fail, or (2) both AAC DG and TDPs fail. In the first condition, failure is assumed regardless of EDG or AAC DG availability. If the heat removal system fails and offsite power is not recovered before the time margin T_C, the scenario results in core damage. The failure in the second case occurs when the MDPs shut down due to loss of power supply resulting from the failure of both the EDGs and the AAC DG. Figure 1 provides a rough overview of the modeled LOOP scenario. In the actual modeling, possible failure combinations of each component were considered, fail to start or run, and for two same components, CCFs are also modeled. However, in the case of the LOOP scenario, expressing every sequence through an ET would result in an excessive number of combinations. Therefore, Figure 1 presents a simplified form that reflects only the failure status of each component, focusing on the essential logic.

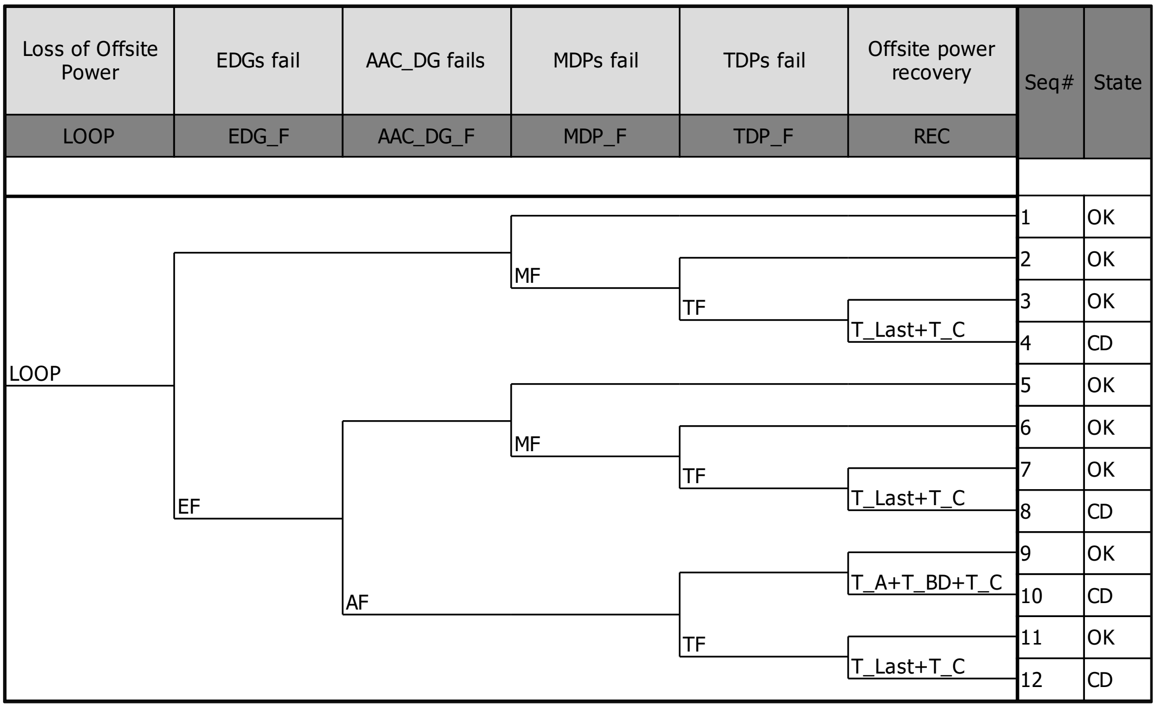

Figure 1: Rough LOOP scenario overview

III.B. Comparative Analysis of LOOP sequences

As described in Section III.A, a detailed analysis of LOOP scenarios was conducted. The accuracy of the simulation results was assessed by comparing outputs from EMRALD and Monte Carlo approaches.

Given that the calculated core damage probability is extremely small, on the order of 3E-6, some differences in the numerical results are to be expected. These differences can be mitigated by significantly increasing the number of simulation runs.

Figure 2 summarizes the CCDP results from both EMRALD and Monte Carlo simulations under the LOOP scenario. The results include cases where core damage occurs due to AAC DG and TDPs failures, as well as cases resulting from MDPs and TDPs failures. In most sequences leading to core damage, the dominant contributors were the failure of both EDGs followed by AAC DG failure and subsequent battery depletion causing the TDPs to fail, resulting in a loss of secondary heat removal. For the notations, the first letter indicates the component that fails: 'A' for the AAC DG, 'M' for the MDPs, and 'T' for the TDPs. The subsequent letters describe the failure mode: 'S' denotes failure to start, 'R' denotes failure to run, 'SR' indicates that one unit fails to start and the other fails to run, 'RR' and 'SS' indicate that both units fail to run or start, respectively. 'CR' and 'CS' represent common cause failures leading to both units failing to run or start. Additionally, 'BD', used only for TDPs, signifies that both units fail due to battery depletion. Also, the symbol '-S' means that those sequences are SBO-S, the others are SBO-R.

EMRALD conducted approximately 1E+9 simulation trials, while the Monte Carlo simulation involved about 5E+9 times. Due to the extremely low probability of some sequences, many rare scenarios were scarcely observed, and gaps were noted between the two simulation methods.

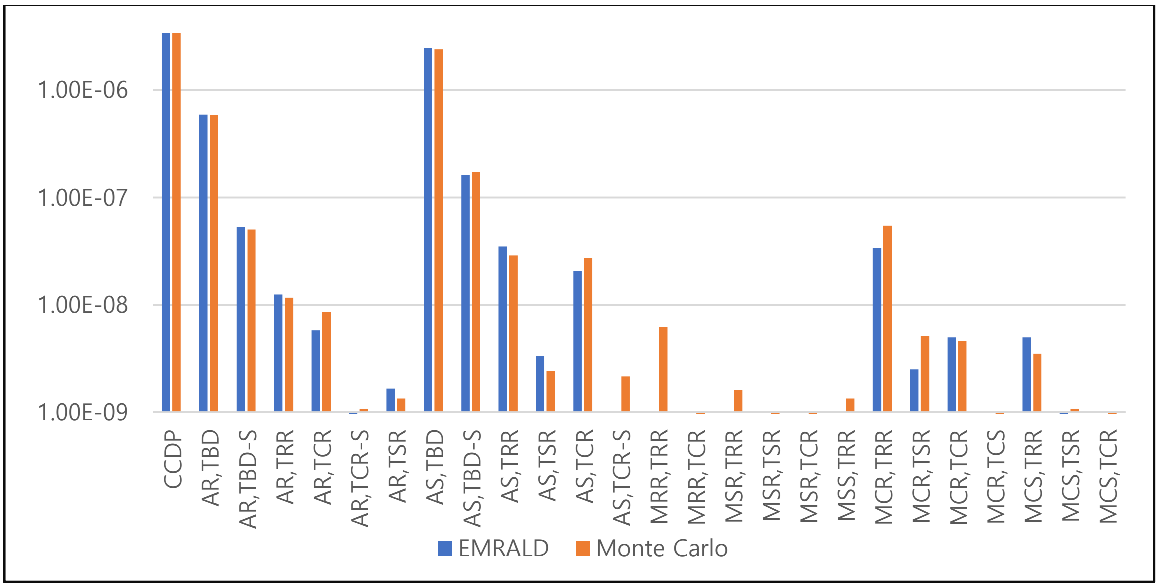

Figure 2: Analysis of LOOP Scenario with 2 methods

IV. Discussions

Based on the simulation results presented, the comparison between EMRALD and Monte Carlo simulations confirms that EMRALD is useful in handling complex scenarios. The LOOP scenarios modeled in this study involve numerous time-based parameters, making it challenging to analyze through ET and FT analysis. Nevertheless, EMRALD successfully estimated the overall CCDP and the probabilities of various cut sets leading to core damage in a single simulation framework.

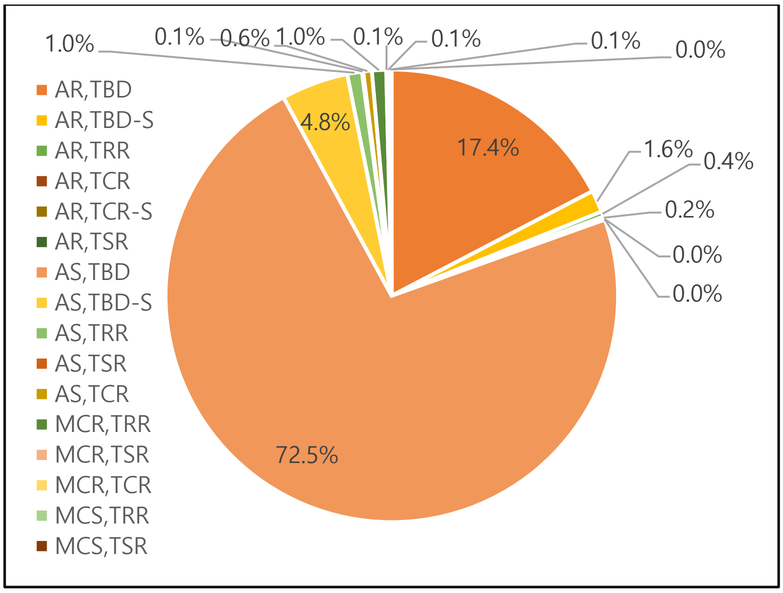

Figure 3: Fractional comparison of total CCDP sequences

When analyzing the progression of the accident from LOOP to SBO, it becomes clear that SBO-R scenarios are more dominant than SBO-S scenarios. This suggests that, when analyzing SBO as one of the major severe accident scenarios in nuclear reactors, evaluating SBO-R is particularly important. Given that SBO-R sequences involve many time-dependent elements, precise modeling is essential for reliable analysis.

The findings suggest that reinforcing the reliability of EDGs and AAC DG and extending battery life for TDP operation can significantly improve safety.

EMRALD's dynamic modeling capability allows intuitive exploration of complex sequences. This supports its usefulness in both design evaluation and emergency planning. Although EMRALD required much more time to compute the scenario sequences than the Monte Carlo simulation, it was faster to build the same model using EMRALD

V. Conclusions'

This study utilized EMRALD, a dynamic probabilistic safety assessment (PSA) tool, to evaluate complex accident sequences following a loss of offsite power (LOOP) in nuclear power plants. The research was structured in two phases: first, validating EMRALD's computational reliability by replicating an SBO-S scenario previously analyzed using a convolution approach; and second, expanding the model to include a full LOOP scenario with multiple time-dependent variables and component interactions.

By comparing the results of EMRALD simulations with Monte Carlo simulations, the study confirmed the tool's capability to calculate CCDP and sequence probabilities with high accuracy. The results highlighted that failures of DGs and following battery depletion of TDPs are dominant contributors to core damage. Additionally, the analysis revealed that SBO-R scenarios are more dominant than SBO-S, emphasizing the importance of precise modeling for those cases.

Through this modeling, EMRALD proved effective in capturing time-dependent dynamics and component dependencies without relying on extensive mathematical formulations.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Trade, Industry and Energy (MOTIE) of Republic of Korea [grant number RS-2024-00398867].

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