Developing An Operator Decision Matrix for Multi-Failure Accident Sequence Using VCU's Generalized Pressurized Water Reactor Simulator

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INTRODUCTION

The safe operation of nuclear power plants (NPPs) depends critically on operators' ability to accurately diagnose and respond to abnormal and accident conditions in real time. A central objective of the nuclear industry is the protection of the public from radiation exposure, which is achieved through multiple engineered barriers designed to prevent the release of fission products [1]. Despite the presence of both passive and active safety systems, nuclear reactors remain vulnerable to operational accidents when mitigation actions are delayed, misinformed, or improperly executed [2]. Accident scenarios involving multiple simultaneous components or system failures are particularly challenging, as they generate complex, rapidly evolving plant conditions that require timely and well-informed operator decision-making.

Pressurized Water Reactors (PWRs) are among the most widely deployed reactor types and are characterized by tightly coupled thermal-hydraulic and neutronic behaviors. Operator training and safety analysis for these systems frequently rely on high-fidelity reactor simulators to reproduce realistic transient and accident conditions. At Virginia Commonwealth University (VCU), the Generalized Pressurized Water Reactor (GPWR) simulator, as shown in Figure 1, provides a triple-loop PWR environment capable of modeling a broad range of operational transients and accident scenarios.

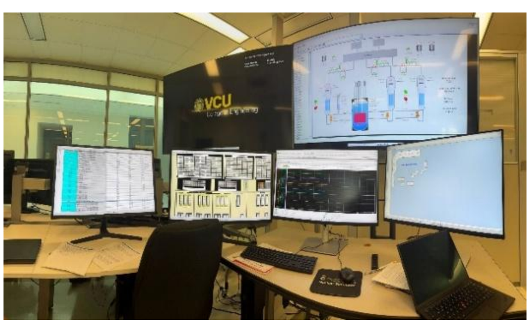

Fig. 1. The VCU's GPWR simulator.

While the simulator accurately represents reactor physics and system interactions, its effective use requires substantial prior knowledge of PWR systems, safety logic, and accident management procedures. For student and novice operators, the lack of structure and real-time guidance during complex accident scenarios can limit the simulator's effectiveness as a training and education tool.

On the other hand, probabilistic risk assessment (PRA) and event-tree-based methodologies have long been used to analyze accident progression and guide mitigation strategies in NPPs. The U.S. Nuclear Regulatory Commission (NRC) has applied PRA frameworks to assess reactor accident consequences and inform operator response strategies for NPPs [3]. More recently, research efforts have explored decision-making paradigms and data-driven approaches to improve accident detection and response. For example, Yang et al. [4] demonstrated a functional modeling and reasoning approach for emergency action planning during nuclear reactor accidents, emphasizing early anomaly detection and optimized response strategies. Cheng et al. [5] investigated neural-network-based decision-making methods for small modular reactors, showing that automated approaches can successfully manage normal and accident scenarios under specific conditions. While these studies highlight the potential of advanced computational techniques, many existing approaches focus on accident classification or automated control rather than providing explicit, operator-oriented guidance that supports human decision-making during multi-failure events.

This project addresses these limitations by developing a deterministic operator decision matrix framework for multi-failure accident scenarios in a triple-loop PWR simulator. This framework integrates PRA-based accident logic with simulator-derived plant state variables to generate structured operator guidance aimed at preserving the barriers to fission product release, as emphasized in defense-in-depth safety philosophy [6]. Accident outcomes are evaluated based on their ability to prevent or delay fuel degradation, maintain coolant system boundary integrity, and return the reactor to a safe or stable end state, consistent with international accident management guidance [7]. The decision matrix is designed for direct integration into the GPWR simulator, which enables real-time instructional support during training exercises while providing a foundation for future integration with machine-learning-based accident identification methods.

By combining deterministic safety principles with data extracted from high-fidelity simulator simulations, this research contributes a transparent and interpretable decision-making support framework for complex PWR accident management. The proposed approach emphasizes human-centered design, reproducibility, and extensibility, making it suitable for educational environments and for continued development toward hybrid decision systems that augment, rather than replace, operator judgement.

METHODOLOGY

This study focuses on the development of a deterministic operator decision matrix for managing multi-failure accident scenarios within a triple-loop PWR simulator. The proposed framework integrates PRA principles, simulator-derived reactor state variables, and deterministic outcome evaluation logic to generate structured, operator-oriented guidance aimed at achieving the safest attainable reactor end state. The safety philosophy underlying this framework is consistent with established nuclear accident management guidance [6, 7]. All accident scenarios, system responses, and data used in this study were generated using the GPWR simulator at VCU.

Reactor Simulator and Accident Scenarios

The VCU GPWR simulator is an industry-grade, triple-loop PWR simulator capable of modeling detailed thermal-hydraulic and neutronic behavior under both normal operation and accident conditions. The simulator reproduces reactor core kinetics, primary and secondary coolant system dynamics, steam generator behavior, pressurizer response, and safety system activation, providing a realistic representation of PWR accident progression, consistent with reactor safety analysis methodologies designated by the U.S. NRC [3]. The simulator also supports the implementation of component level failure such as pump trips, valve malfunctions, control rod failures, and coolant boundary ruptures, which enable the necessary of the study for complex multi-failure interactions.

In this work, accident scenarios were selected based on the twelve initiating event categories commonly taught in probabilistic risk assessment curricula and used in reactor accident consequence analysis [3]. These include General Plant Transients (GPT), Anticipated Transient Without SCRAM (ATWS), Reactor Vessel Failure (RVF), Loss of Offsite Power (LOOP), Station Blackout (SBO), Loss of DC Power (LOSSDC), Small-, Medium-, and Large-Break Loss of Coolant Accidents (SLOCA, MLOCA, LLOCA), Steam Generator Tube Rupture (SGTR), Main Feedline Break (MFLB), and Main Streamline Break (MSLB). These initiating events collectively represent a wide spectrum of plant challenges, including reactivity excursions, inventory loss, heat removal degradation, and electrical power loss. Both single-failure and multi-failure variants of the scenarios were simulated to evaluate interactions between concurrent system degradations, as show in Figure 2.

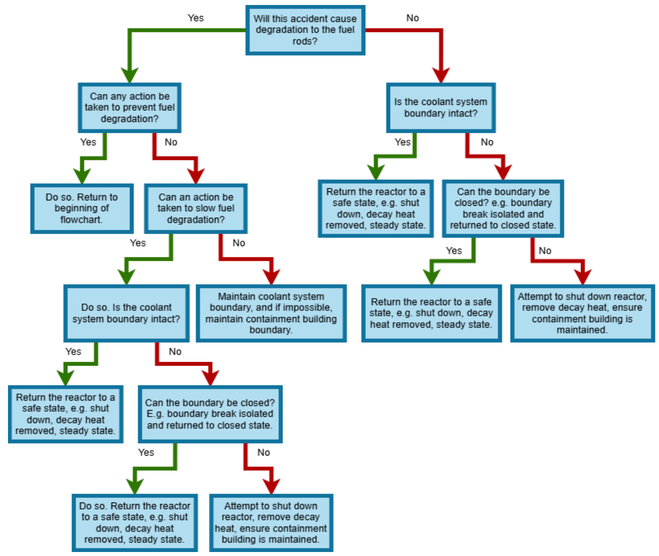

Fig.2. Accident scenario outcome evaluation.

Reactor State Variables and Data Extraction

The reactor state variables used to construct and evaluate the decision matrix were extracted directly from the GPWR simulator's data acquisition system. These variables represent key thermal-hydraulic, neutronic, and system-status indicators that operators routinely rely on for accident diagnosis and mitigation [3]. Thermal-hydraulic variables include reactor coolant system pressure, hot-leg and cold-leg temperatures, pressurizer pressure and level, steam generator pressure and level, reactor pressure vessel water level, and primary and secondary mass flow rates. Neutronic indicators include reactor power, neutron flux distribution, and reactivity feedback signals. Component and system-status indicators include pump operation states, valve position, control rod insertion signals, and safety system actuation flags.

Simulator outputs were recorded as time-dependent datasets for each accident scenario and intervention case. In addition to raw sensor signals, derived features such as rates of change in pressure, temperature, and coolant inventory were analyzed to capture transient behavior associated with accident progression. These datasets for the basis for identifying accident signatures, evaluating decision outcomes, and enabling future integration with data-driven accident identification methods, consistent with prior reactor accident analysis and decision-support approaches [3, 4].

Integration with Machine Learning Techniques

Although the operating decision matrix itself is deterministic, the framework is designed to interface with machine-learning-based accident identification methods. Supervised machine learning techniques are being used to associate simulator-generated reactor state data with specific initiating events and failure modes, following approaches explored in recent nuclear decision-making research [4, 5]. The role of machine learning in this work is limited to accident scenario identification, while the decision matrix remains responsible for determining the recommended operator actions.

Machine learning models are trained using labeled GPWR simulation data, with labels corresponding to the initiating event category and accident progression outcome. Preprocessing steps include data cleaning, normalization, and alignment of time-series signals to ensure consistency across simulations. Once trained, the machine learning model can classify observed reactor behavior and direct the operator to the appropriate branch of the decision matrix. This hybrid approach preserves deterministic safety logic while leveraging data-driven pattern recognition to improve situational awareness [5].

RESULTS AND DISCUSSION

At present, the primary outcome of this work is the development of a structured, deterministic operator decision matrix framework intended to support student training and guided operator decision-making during multi-failure accident scenarios within the GPWR simulator. The framework itself, together with the associated fault and event trees corresponding to twelve PRA-based initiating event categories, constitutes the principal design artifact produced to date. Collectively, these elements define how accident conditions are classified, how reactor safety priorities are established, and how observable plant states are mapped to recommended operator actions. Quantitative performance metrics and formal validation results are not presented in this paper, as format testing and evaluation are currently ongoing.

A key emphasis of the framework is its application to student training on the GPWR simulator. Earlier project milestones focused on simulator familiarization and development of system-level understanding prior to introducing the decision matrix. Within this training context, the matrix is intended to function as a structured instructional aid rather than an automated control system. By organizing operator actions according to PRA logic and defense-in-depth principles, the framework reinforces correct safety priorities and promotes systematic reasoning during accident response exercises. This approach is particularly relevant for students and novice operators, who may otherwise struggle to identify appropriate mitigation strategies during complex, rapidly evolving multi-failure scenarios.

The identification and systematic organization of reactor state variables also represent an important outcome of this work. Key thermal-hydraulic, neutronic, and system-status indicators were selected from the GPWR simulator to support effective accident diagnosis and decision-making. These variables form the informational backbone of the decision matrix and correspond to signals that operators routinely monitor during accident conditions. In summary, the decision matrix is designed to guide student operators through accident response by organizing actions according to PRA logic and established accident management priorities.

In parallel with the deterministic decision matrix, a machine-learning component is under active development to support accident scenario identification. At present, the machine learning component is limited to data ingestion, preprocessing, labeling, and preliminary model structure definition using GPWR simulator data exported in CSV format. The intended role of the machine-learning component is to assist with scenario recognition and to guide users to the appropriate decision-matrix pathway, while preserving deterministic logic for action selection. This hybrid framework reflects a deliberate design choice to maintain interpretability and alignment with established accident management principles.

FUTURE WORK

Several current implementation limitations should be acknowledged. The decision matrix has not yet been validated through controlled simulator studies or human-in-the-loop evaluations, and its effectiveness relative to existing training approaches remains to be assessed. In addition, the framework is currently tailored to the GPWR simulator architecture and available signal set, which may limit direct transferability without modification. Future work will focus on completing the decision matrix algorithm, training and validating the machine-learning classifier, integrating the framework into the GPWR front-end software, and conducting faculty-guided walkthroughs to evaluate usability and instructional value in a formal educational setting.

REFERENCES

1. Centers for Disease Control and Prevention, “Guidelines for ALARA – As Low As Reasonably Achievable,” Radiation and Your Health, Feb. 26 (2024)
2. A. CHET, “Nuclear Mitigation Measures at the Department of Energy's Hanford Nuclear Site,” Geology and Human healthy (2012)
3. U.S. NRC, Modeling Potential Reactor accident Consequences, U.S. NRC, NUREG/BR-0359 (2012).
4. J. YANG et al., “A novel approach for emergency action planning based on functional modeling and reasoning,” Process Safety and Environmental Protection, 203, 107874 (2025).
5. S. CHENG et al., “A multi-objective decision-making method for small modular reactor operation based on A3C algorithm,” Progress in Nuclear Energy, 176, 105405 (2024).