Developing an Operator Decision Matrix for Multi-Failure Accident Sequences Using VCU's GPWR Simulator

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Background

In the case of a transient event, nuclear reactor operators can face complex scenarios where multiple simultaneous system or component failures can occur, requiring them to diagnose plant conditions and implement proper recovery actions. VCU's Generic Pressurized Water Reactor (GPWR) simulator (Figure 1) enables students to simulate these cases to observe and better understand how to safely drive the reactor to a safe end state. However, these multi-failure cases can be challenging for the operator to take the optimal corrective actions under time pressure, potentially limiting effective training and situational awareness. To reduce cognitive load and improve operator response to complex low-probability events, a systematic, logic-based decisional matrix was developed using the GPWR simulator as a testbed.

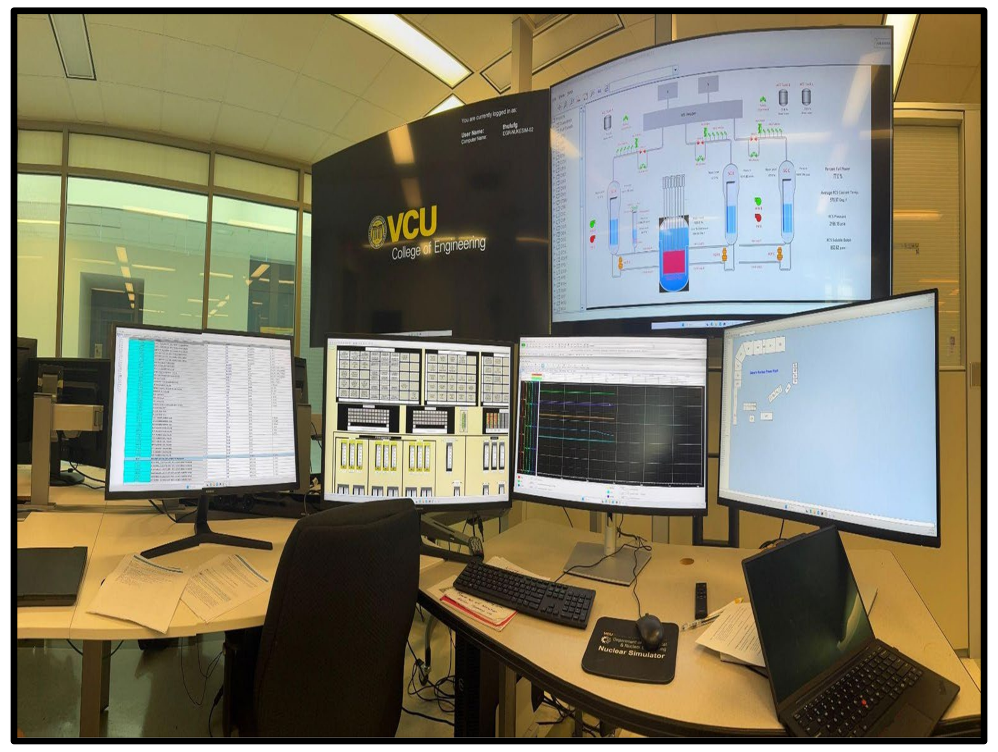

Figure 1. Photo of VCU's GPWR simulator.

The decision matrix maps multiple concurrent failure scenarios simulated using the GPWR software to recommended operator actions. To promote realistic and precise operator intervention, the recommended actions were gathered from the collection of operating procedures from the GPWR software documentation. The prototype was designed with the intention of integration with a machine learning model in development, and VCU's GPWR software itself.

Decision Matrix Logic

Using probability risk assessment (PRA) concepts as a basis for its logic and overall structure, the scenarios that were simulated and implemented into the decision matrix combine an initiating event (e.g., loss of coolant accident, loss of instrument air, loss of offsite power, etc.) with failures of mitigating systems (e.g., coolant injection systems, containment sprays, diesel generators, etc.). Each scenario was simulated to observe the reactor's response both with and without operator intervention, focusing on if an automatic reactor trip occurred and what control room annunciators lit up. If one annunciator panel was lit, the appropriate annunciator panel procedure (APP) was placed in that cell to be referenced in the GPWR documentation, alongside the relevant page number. If multiple panels were lit, each APP was placed in that cell in order of severity, following the severity analysis philosophy outlined in Figure 2.

In the case of a reactor trip, a step-by-step emergency operating procedure (EOP) flowchart called EOP-PATH-1 guides the operator through diagnosing the key problem and stabilizing the system. Once reaching the point of the flowchart where the plant's conditions is diagnosed, the document identifies an explicit EOP to follow that guides the operator to recover systems or implement alternative cooling. With this, PATH-1 and the corresponding emergency operating procedure identified was placed in the cell for each simulated scenario in the decision matrix that resulted in a reactor trip.

This decisional matrix can be quickly referenced for rapid diagnosis and to determine the severity of multi-failure accidents.

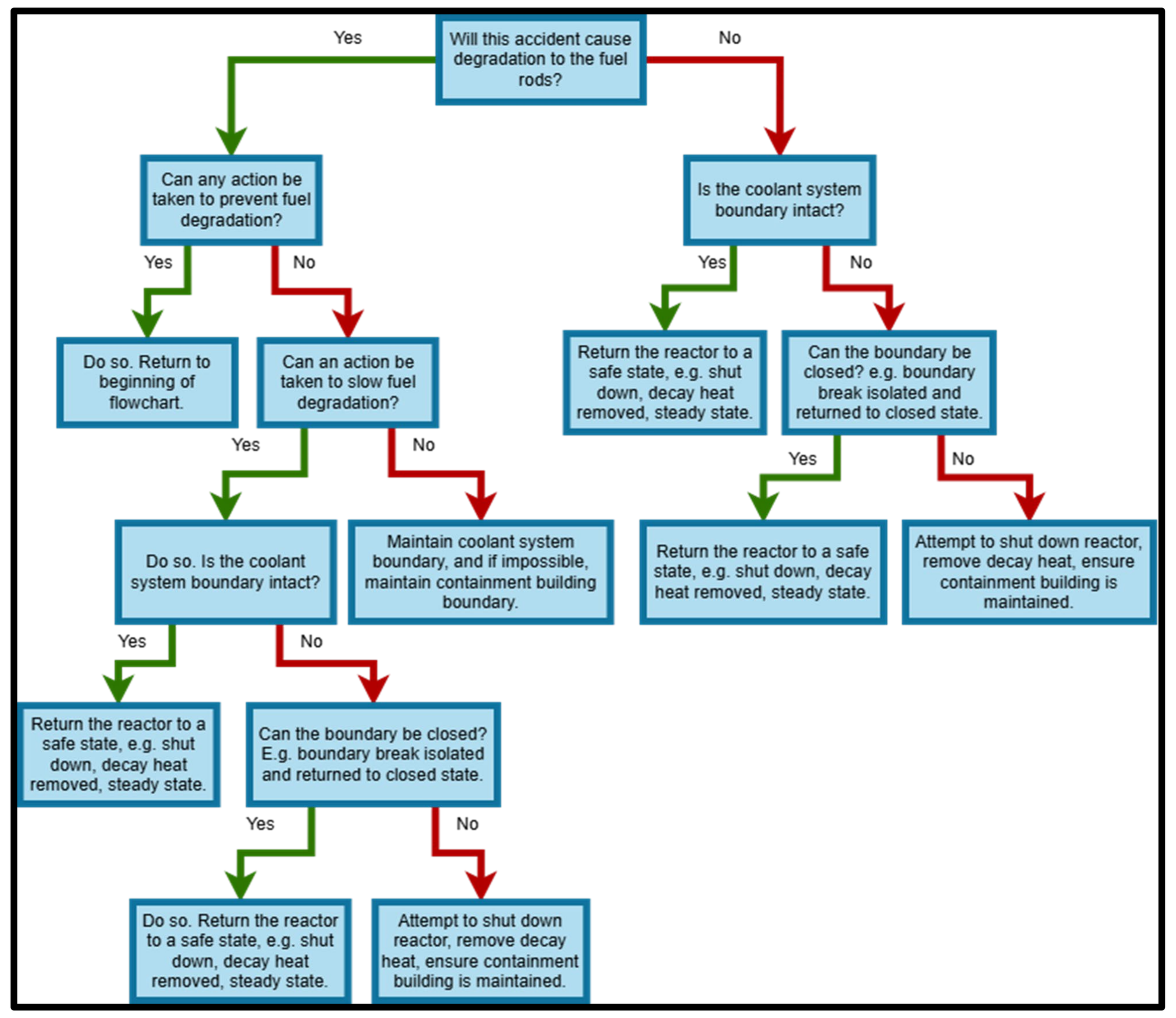

Figure 2. APP order of severity ranking logic.

Machine Learning Model

A machine learning model framework was developed to integrate the decision matrix logic and the corresponding trend data extracted from the GPWR multi-failure accident scenario simulations. The model is trained on simulator-generated data such as reactor pressure, temperature, and other time-dependent variables to actively identify unusual outliers based on the signals and sensor data in real-time during GPWR operation. During real time analysis, the model will compare the reactor's parameters with the model's trained expectations for steady-state behavior. Any deviation from the expectation would engage the decision matrix to analyze the state of plant's conditions and identify the potential failures to then direct the operator to the necessary operating procedures.

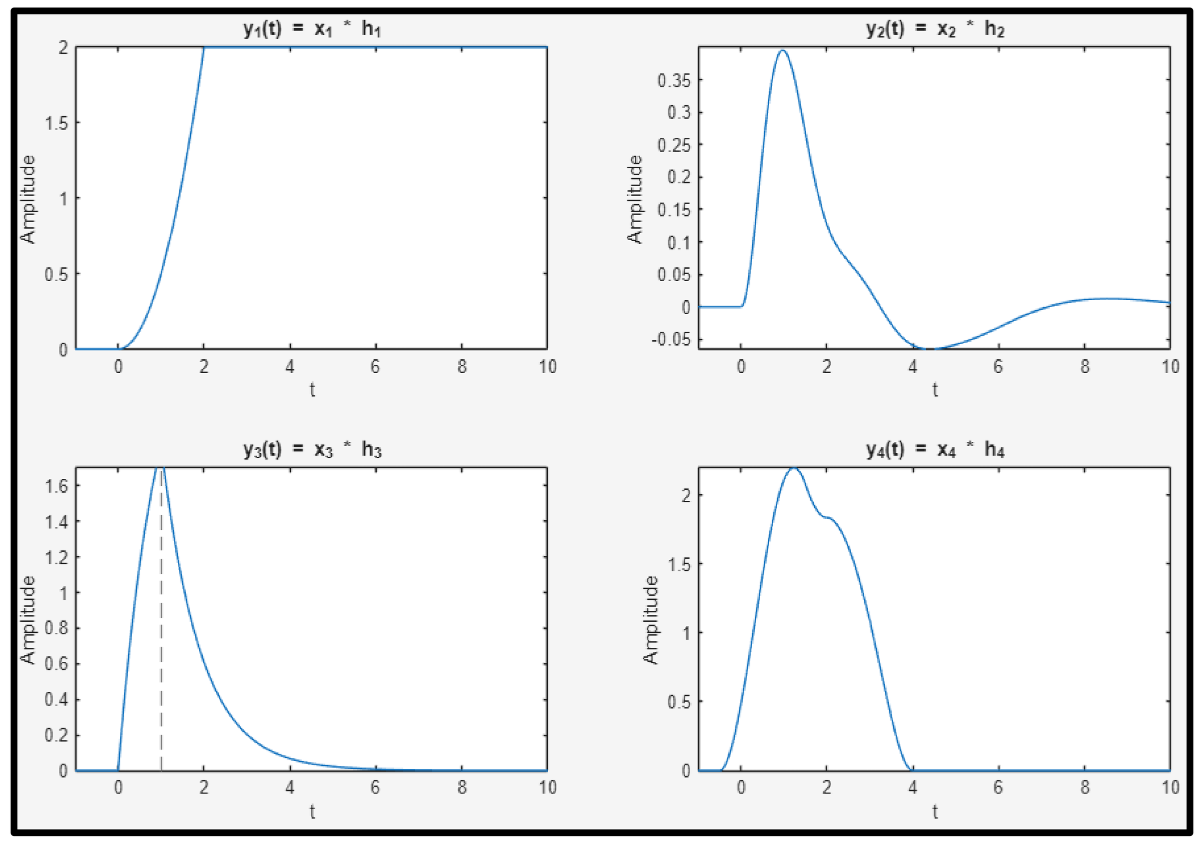

Figure 3. Machine Learning Convolution Processing Plots.

The systematic workflow employed for this model is a signal processing pipeline that will serve as the foundation for the model. The pipeline starts with raw simulator csv data, processing and cleaning the data, then "engineer features" that can be used for classification and anomaly detection. A MATLAB-based convolution and fast Fourier transforms (FFT) processing framework was developed to analyze time-series reactor signals, with the ability to add and remove columns based on the case data being dealt with (Example plots from the script shown in Figure 3). The FFT script works to speed up the convolution script. Convolution in the time down applies a filter to the signal, while FFT analyzes and speeds up that filtering. FFT are great for varying time-series data because they are specifically designed for computer algorithms. The purpose of this is feature engineering, where meaningful patterns can be extracted from transient behavior by analyzing the time-series data for vertical edges, horizontal edges, as well as the amplitude relative to the time-axis (x-axis). With feature engineering, the model gains the ability to pivot what "features" are focused on. The processed signals will be used as inputs to supervised learning model, likely a Random Forest Classifier for its simplicity and ease. The model will be trained on both normal operation and simulated failure scenarios using the 80/20 rule, 80% training data, 20% test data, to ensure the model does not become over or underfit.

Conclusions and Next Steps

Using PRA concepts as an organizational guideline, a logic-based decisional matrix was developed to guide GPWR simulator operators through complex multi-failure events. The model accurately maps these scenarios to their corresponding plant condition diagnosis and its respective operating procedure, guiding the operator through mitigating the accident to a safe end state. Integration of the decision matrix logic and operating procedure documentation with the machine learning model will enable a clean and automated guide for operators, reducing risks of improper operator intervention and promoting best practices for training purposes. Our next steps include:

- Using convolution as a precursor to convolutional neural networks (CNN), integrating CNN for automated feature extraction from the simulator-generated data, eliminating the need for manual "feature engineering."
- Integration of the machine learning pipeline with the GPWR user interface for live, in-situ feedback.

References

1. IAEA, Accident Management Programmes for Nuclear Power Plants. (2019).
2. PATH-1. GPWR Nuclear Plant Operating Manual (Vol. 3, Pt. 4, 24th ed.). GSE Power Systems.
3. Course Notes. Meinnweiser, Greg. 2026. Probabilistic Risk Assessment. Canvas Learning Management System.

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