

Development of a Flexible Operation Evaluation Program for Establishing Reactor Core Control Strategy and Preliminary PCI Analysis

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1. Introduction

In the field of Small Modular Reactors (SMRs), research on Low Enriched Uranium Plus (LEU+) and Accident Tolerant Fuel (ATF) has been actively conducted to reduce the generation of spent nuclear fuel. Accordingly, there is a growing need to quantitatively evaluate the load-following performance of SMR cores utilizing LEU+/ATF. To perform such evaluations, it is essential to establish detailed core loading models, control rod control strategies, and specific evaluation scenarios in advance.

While a basic program for this purpose was developed in a previous study[1], this research extends it by newly implementing features to compare various control strategies and to monitor the primary indicators associated with Pellet-Cladding Interaction (PCI), which directly affects fuel integrity, thereby establishing a foundation to perform practical PCI assessments through integration with a specialized fuel design code. Furthermore, a preliminary scenario for evaluating load-following performance was established, and the validity of the developed program features was verified through its application.

2. Program Features

The program developed in the previous study operates on the Windows OS. It utilizes the MASTER code[2] to perform calculations on a step-by-step basis and visualizes the results for each step, thereby enabling the preliminary evaluation of tracking and monitoring parameters.

2.1 Local Data Derivation for Fuel Rod Nodes and Preliminary PCI Analysis

During load-following operations, PCI is a primary factor that threatens cladding integrity. Therefore, to prevent fuel damage caused by PCI, it is essential to identify and track the key inducing factors in real-time prior to direct thermo-mechanical damage assessment.

In particular, the rapid local power changes occurring at the control rod driving positions are considered a primary indicator suggesting the potential for PCI occurrence. This program tracks the local power changes derived from the core analysis code at the fuel rod and assembly levels, providing key data to preliminarily

assess PCI risk through visual implementation. The upper panel of Fig. 1 visualizes the local power changes for each fuel rod node at a specific time point, while the lower panel graphs the trend of power changes for a specific fuel rod node over operating time.

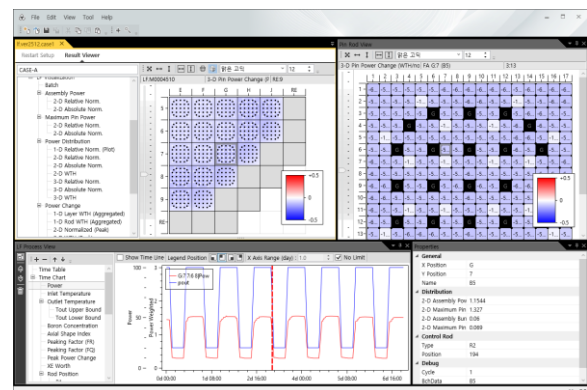


Fig. 1. Program interface visualizing the local power changes and the trend graphs of power changes for fuel rod nodes at a specific axial position within the fuel assembly.

2.2 Control Strategy Comparison

Establishing a Control Strategy that determines the timing of control rod insertion and withdrawal during load-following operations is a decisive factor in securing core stability. Particularly, when the concept of Soluble Boron-free Operation is applied, the power distribution and Axial Shape Index (ASI) behavior of the core respond sensitively to the control rod driving logic.

Based on this, the present program implements a feature to simultaneously simulate multiple scenarios applying different control algorithms and quantitatively compare their results. Specifically, it can comparatively analyze the cumulative control rod driving distance and local power changes across different control strategies. Furthermore, it can be utilized to evaluate performance differences between distinct core Loading Patterns.

2.3 Fuel Rod Data Sorting and Table Generation for Integration with Fuel Design Codes

Previously, local power change was mentioned as a key indicator for identifying fuel rods that require integrity evaluation. However, to efficiently screen vulnerable fuel rods experiencing significant variations among the vast number of fuel rods within the core,

systematic sorting and classification are essential. Accordingly, this program includes a feature that sorts fuel rod node data based on local power change and other key parameters, outputting it in a tabular format. Fig. 2 visualizes an example of a data list sorted by local power change for all fuel rod nodes at a specific time point.

In particular, local power change serves as a predictive screening indicator for anticipating PCI risk. To perform an actual thermo-mechanical PCI damage assessment, integration with a specialized fuel design code is indispensable. In the future, this program plans to support a feature that groups high-risk fuel rods screened through the sorting function and automatically generates input files for the fuel design code based on this data. Furthermore, an extended integration feature will be added to directly execute the design code for each fuel rod and import the detailed evaluation results back into the program.

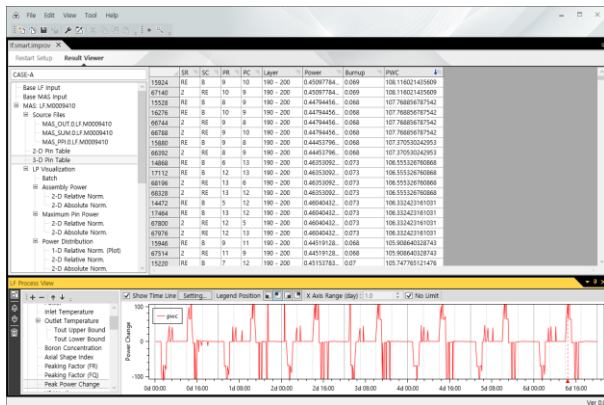


Fig. 2. Example of a data list for all fuel rod nodes sorted by local power change.

3. Application and Verification

This section presents the results of verifying the functions of the developed program by applying a preliminary evaluation scenario for soluble boron load-following operation targeting the SMART reactor.

3.1 Application to Preliminary Evaluation Scenario

In this study, a preliminary evaluation scenario for a 100-20-100 pattern soluble boron load-following operation was established targeting the SMART reactor. Over a simulation period of one-week, the verification of the developed program and the evaluation of core integrity were performed by tracking compliance with the ASI limits and local power changes. This scenario simulates daily load-following operation, and the following operating conditions were applied according to the relevant load-following regulatory requirements.

- The scenario duration was set to 7 days.
- The power change rate was set to 40% per hour, resulting in an 80% change over 2 hours.

- A 100-20-100 daily power variation operation was performed and repeated 7 times.
- The daily cycle consisted of: 100% power operation from 0:00 to 2:00, an 80% power decrease from 2:00 to 4:00, maintaining a minimum power of 20% for 8 hours from 4:00 to 12:00, an 80% power increase from 12:00 to 14:00, and 100% power operation from 14:00 to 24:00.
- Requirements related to unplanned power change operations and frequency-following operations were not applied.

In this preliminary evaluation, two different control strategies were comparatively analyzed. Specifically, the control dead-bands for the coolant outlet temperature (T_{out}) according to the core power were set to $\pm 3^{\circ}\text{C}$ (Case A) and $\pm 2^{\circ}\text{C}$ (Case B), respectively. Excluding the outlet temperature dead-band, the remaining simulation conditions were identically applied to both cases to perform real-time simultaneous calculations. The controlled remaining conditions include the input data for the MASTER core analysis code and the basic control algorithms for control rods and boron concentration. The specific control mechanism was adapted from the control strategy algorithm of a previous study[3].

The driving logic of the applied basic control strategy is as follows. First, when the coolant outlet temperature deviates from the set dead-band, reactivity is controlled by preferentially driving the R3 bank among the control rod banks (R1, R2, R3). In this case, if the R3 bank descends beyond a specific insertion depth, the R2 bank is designed to overlap and drive together. Second, when the ASI value deviates from the limit range, the axial power distribution is controlled by preferentially adjusting the control rod position. If the additional driving margin of the control rods is insufficient, excess reactivity is controlled through boration and dilution.

3.2 Evaluation Results

Utilizing the visualization features built into the program, ASI, cumulative control rod driving distance, and representative local power changes for each case were output as graphs, and the results were comparatively analyzed.

The simulation results showed that in Case B ($\pm 2^{\circ}\text{C}$), which has a relatively narrow coolant outlet temperature control dead-band, the cumulative control rod driving distance gradually increased to a greater extent, whereas the representative local power changes over time tended to remain lower compared to Case A ($\pm 3^{\circ}\text{C}$). This indicates that while Case A, which sets a wider outlet temperature limit range, has the advantage of reducing the cumulative driving distance by decreasing the total frequency of control rod operation, it induces greater local power changes within the core as the adjustment range per single control rod drive increases.

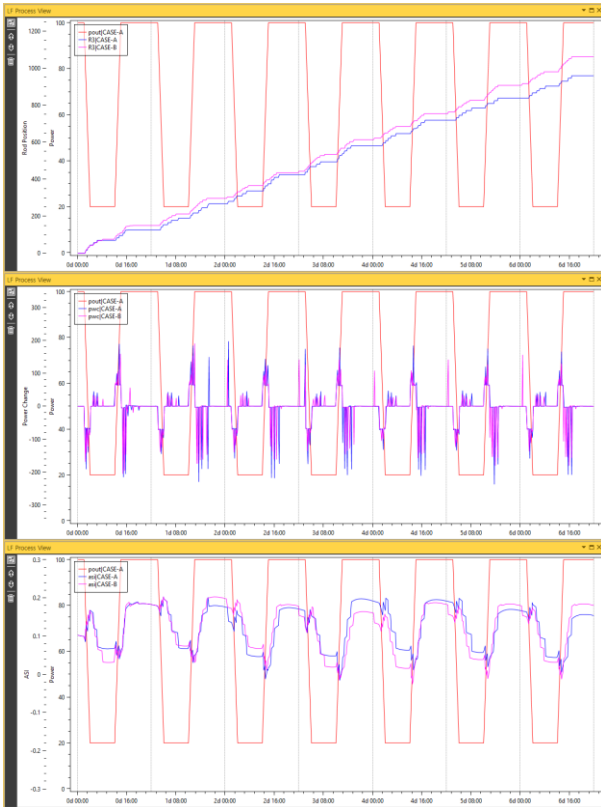


Fig. 3. Comparison results of control strategies over a one-week period, showing the graphs of cumulative control rod driving distance, peak local power change, and ASI, respectively.

Furthermore, the specific fuel rod node where the largest local power change occurred (maximum change value: -237 WTH) during the execution of this scenario was identified, and the trend of power changes over the entire time period for that node was analyzed in detail. The identifier of the corresponding fuel rod node was named 'G:5 10:9 17', which signifies the 17th axial node (130-140 cm section from the bottom) of the fuel rod arranged at the 10:9 coordinates within the fuel assembly located at the G:5 coordinates of the core loading model. Fig. 4 shows the trends of local power and local power changes of the corresponding node over time.

Notably, despite the total reactor power returning to its initial state after the load-following operation cycle ended, the local power of the corresponding node showed an irreversible change, not fully recovering to its initial value. This change is analyzed to be primarily attributed to the asymmetry of the localized Xenon transient behavior accompanying the load-following operation. Such irreversible changes in local power continuously affect the conditioning and deconditioning behavior of the nuclear fuel, and consequently, are considered to act as a major contributing factor that increases the likelihood of PCI occurrence.

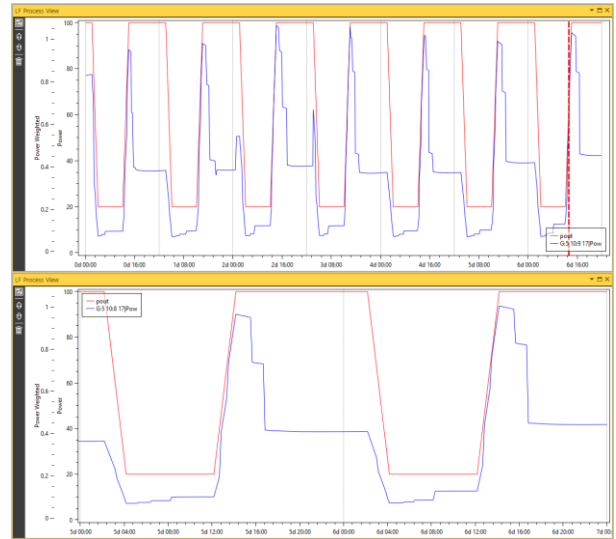


Fig. 4. Reactor Power (Red) and Local power graphs of a specific fuel rod node (Blue) exhibiting irreversible power changes. The graphs show the results for the entire one-week period and the last two days, respectively.

4. Conclusions

In this study, a visualization program was developed and its applicability was verified, overcoming the limitations of existing text-based design codes and enabling an intuitive preliminary evaluation of the load-following performance and PCI risk of SMR cores. As a result of simulating different control strategies, it was confirmed that significant behavioral differences occur in terms of control rod driving distance and local power changes depending on the established criteria of the strategy. In particular, the irreversible change trend of local power observed during load-following operations was identified as a key characteristic that increases the likelihood of future PCI occurrence. Through the feature that classifies and sorts fuel rod characteristics based on this trend, it is anticipated to be highly useful in performing actual PCI assessments by integrating with fuel design codes in the future.

In conclusion, the simultaneous multi-scenario comparison feature provided by this program is expected to make a vital contribution to establishing optimized control strategies for future nuclear power plants. Furthermore, by utilizing the systematized input system built into the program, it is anticipated that this program can be usefully expanded and applied to the multifaceted performance evaluation of innovative SMR cores adopting LEU+ /ATF in the future.

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