# Multi-physics Simulation of BEAVRS Benchmark using CUPID/nTER

Youyeon Choi[a*], Hyoung Kyu Cho[b], Jin Young Cho[a], and Hwang Bae[a]
[a]*Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon 34057*
[b]*Department of Nuclear Engineering, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul 08826*
[*]*Corresponding author: yyc@kaeri.re.kr*

## 1. Introduction

In the field of nuclear reactor safety analysis, a one-dimensional system-scale approach has been widely used since the birth of commercial nuclear power plants. During the past decades, as a high performance computing (HPC) technology has been developed, a pin/subchannel scale three-dimensional nuclear reactor simulations have become available. In this context, multi-scale and multi-physics nuclear reactor simulation for LWR safety analysis has been considered to improve the economics of nuclear power plants by reducing unnecessary safety margins.

To achieve a safety analysis for the transient accident scenarios with reduced uncertainty, a high-fidelity simulation at the normal operating condition should be preceded. Therefore, the present study focused on multi-physics simulation for the steady-state operating conditions by using pin/subchannel scale neutronics and thermal-hydraulics coupled code.

In the previous study, the coupled code system consisting of a three-dimensional thermal-hydraulic analysis code, CUPID [1], and whole core neutron transport code, nTER [2] was established [3]. Furthermore, the preliminary multi-physics simulations for OPR1000 and validation against VERA Core Physics benchmark problem 9 was conducted [3,4].

In this study, further validation of CUPID/nTER was performed via a multi-physics simulation of the BEAVRS benchmark. The pin and subchannel scale parameters at the operating conditions were obtained from the first cycle depletion calculation. The performance of CUPID/nTER as a reactor core simulator was assessed by comparison of calculated boron concentration with the measured data and code-to-code comparison with VERA-CS.

## 2. Code and Problem Specifications

The following section illustrates the features of the coupled CUPID/nTER and the problem specifications of the BEAVRS benchmark cycle 1 depletion calculation.

### *2.1 Features of the coupled CUPID/nTER*

In the previous study, the coupled code system was established using CUPID and nTER where both codes were externally coupled via the socket-based server program [3]. For a numerical scheme of the coupled code, the Picard iterations between two codes continue until the converged solution is obtained in the neutronic solver of nTER.

As the fuel cycle progresses, the burnup of urania pellet increases, which contributes to the variation of the fuel material property. Therefore, to simulate the fuel depletion of the reactor core, the degradation of fuel thermal conductivity due to the burnup increase should be considered. Since the fuel temperature is one of the key parameters in thermal-hydraulic feedback, the fidelity of the fuel material property correlation should be carefully considered. In this study, the modified Nuclear Fuel Industries (NFI) model [5] was implemented in the fuel rod conduction model in CUPID as follows:

$$k_{NFI} = \frac{1}{A + BT + f(Bu) + (1 - 0.9\exp(-0.4Bu))g(Bu)h(T)} + \frac{E}{T^2}\exp\left(-\frac{F}{T}\right)$$

where T is fuel temperature (K) and Bu is fuel burnup (GWd/MTU).

### *2.2 BEAVRS benchmark*

The BEAVRS (Benchmark for Evaluation and Validation of Reactor Simulation) benchmark was released by MIT Computational Reactor Physics Group to provide the measured operational data that can be utilized for the validation of PWR core simulation [6]. The core geometry is based on Westinghouse type 17x17 fuel assembly and the layout of fuel loading pattern and absorber positions are shown in Fig. 1. The operational histories including power and boron concentration are provided over two cycles in the latest document.

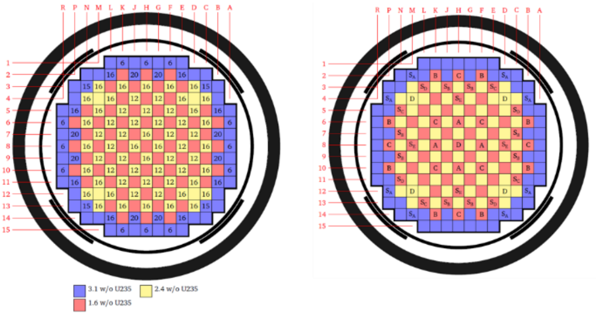


Fig. 1. Configuration of fuel loading and burnable absorber positions [6]

### *2.3 CUPID/nTER modeling of BEAVRS benchmark*

In this study, using a quarter symmetry condition, a quarter core is simulated for the first fuel cycle. Therefore, a computational mesh for 56 fuel assemblies was generated for CUPID calculation, while nTER modeled 73 assemblies including the reflector region. Fig. 2 illustrates the computational meshes of a single fuel assembly of each code. The four different types of subchannel were applied depending on the porous medium related parameters such as porosity and hydraulic diameter. In the axial direction, CUPID used 41 uniform meshes, while nTER used 26 non-uniform meshes.

As shown in Fig. 2, nTER adopted rod-centered geometry, while CUPID used channel-centered geometry. Due to the difference in geometrical modeling between two codes, data mapping was progressed for coupling variables, which are normalized power, fuel burnup, coolant temperature, density, and fuel temperature. The simulated power history was referenced from the VERA-CS simulation [7] for the code-to-code comparison of the calculated boron concentration. The key parameters used in BEAVRS simulation are listed in Table. 1.

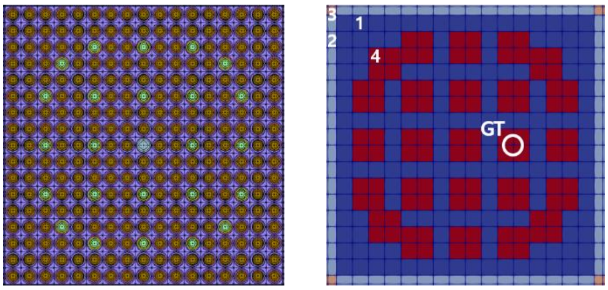


Fig. 2. The computational mesh of BEAVRS benchmark for nTER (left) and CUPID (right)

Table I: Key input parameters of BEAVRS benchmark simulation

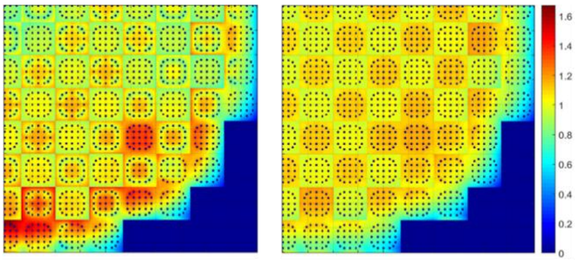
| **Parameter** | **Value** |
|---|---|
| Rated power | 3411 MW |
| Operating pressure | 15.51 MPa |
| Core flow rate | $61.5\times 10^6$ kg/hr |
| Initial liquid/solid temperature | 565K |
| # of state-points | 21 |

## 3. Simulation Results and Discussions

### *3.1 Simulation results*

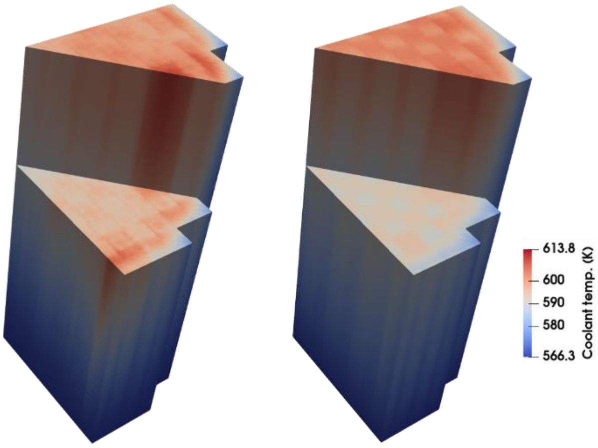
The key parameters of the operating reactor such as power, burnup, coolant properties, and fuel rod temperatures were obtained in the pin/subchannel scale at each burnup state-point. Fig. 3 shows the two-dimensional gamma smeared power distribution at the beginning (BOC) and the end of the cycle (EOC). As the fuel depletion progressed, the difference in relative power reduced due to the fuel burnup increase. The coolant temperature distributions are shown in Fig. 4. Since the local maximum power decreased as shown in Fig. 3, the predicted subchannel scale local liquid temperature also decreased from 613.8K to 605.9K. Besides, cladding and pellet centerline temperature distributions are shown in Fig. 5 and 6.

The number of fixed-point iterations between CUPID and nTER was about 9. Furthermore, the cycle length was evaluated as 317 EFPDs which is underestimated about 9 days compared to the given cycle length.



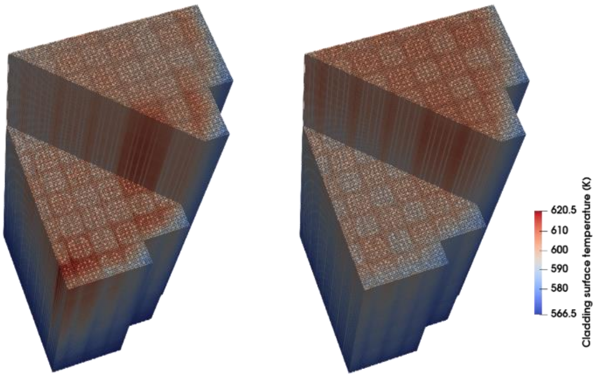
BOC (0.0 MWD/kgHM) EOC (13.73 MWD/kgHM)

Fig. 3. 2D gamma smeared power distributions



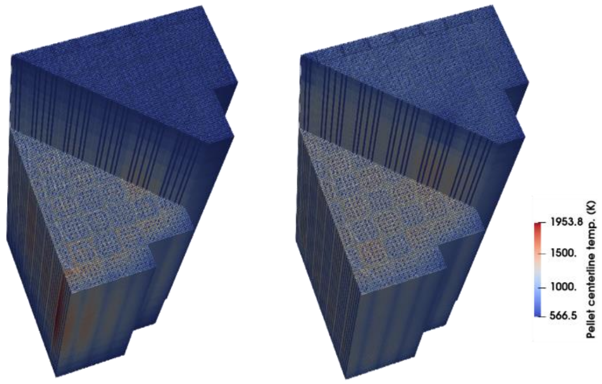
BOC (0.0 MWD/kgHM) EOC (13.73 MWD/kgHM)

Fig. 4. 3D contours of the coolant temperature



BOC (0.0 MWD/kgHM) EOC (13.73 MWD/kgHM)

Fig. 5. 3D contours of the cladding temperature



BOC (0.0 MWD/kgHM) EOC (13.73 MWD/kgHM)

Fig. 6. 3D contours of the pellet centerline temperature

### *3.2 Code-to-code comparison*

For the validation of CUPID/nTER, calculated boron concentrations were compared with the measured data. In addition, a code-to-code comparison was conducted with VERA-CS, which is a virtual reactor environment developed by CASL [7]. The VERA-CS simulation results, which were employed in this study, was conducted by the neutron transport and subchannel thermal-hydraulic coupled MPACT/CTF code.

The comparison of predicted critical boron concentration from both coupled codes and the measured data is shown in Fig. 6. As shown in the figure, the CUPID/nTER results showed good agreement with the measured data within 22ppm error. The average absolute difference between CUPID/nTER and the measured data was evaluated as 13 ppm, while VERA-CS showed a 21ppm difference in average [7]. The limitation in the modeling of the actual power history may cause the difference from the measured data. In conclusion, from the comparison results with the measured data and the VERA-CS prediction, the capability of the CUPID/nTER as a reactor core simulator at the operating conditions was successfully validated.

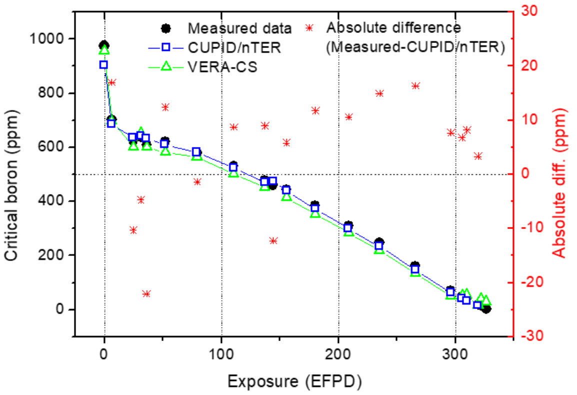


Fig. 6. Comparison of measured data and calculated boron concentration

## 4. Conclusions

In the present study, as an extension study of CUPID/nTER code validation, the multi-physics simulation for BEAVRS benchmark cycle 1 was carried out. The pin/subchannel scale neutron transport and subchannel thermal-hydraulic coupled simulation was performed and the local parameters at the normal operating conditions were obtained. The completion of the BEAVRS benchmark was evaluated by comparing the calculated critical boron concentration with the measured data and the VERA-CS prediction. The CUPID/nTER results showed good agreement with both measured data and VERA-CS results. Therefore, the CUPID/nTER code validation against BEAVRS benchmark cycle 1 was successfully performed.

The cycle 2 depletion calculation would be carried out and the uncertainty quantification and sensitivity analysis for the current methodology is recommended in the future study.

## REFERENCES

[1] Korea Atomic Energy Research Institute, CUPID Code Manuals Vol. 1: Mathematical Models and Solution Methods Version 2.2, 2018.

[2] J. Y. Cho et al., Performance of a Whole Core Transport Code, nTER, The 6th International Conference on Nuclear and Renewable Energy Resources (NURER 2018), Jeju, Korea, Sep. 30-Oct. 3, 2018.

[3]Y. Choi, H. K. Cho, and J. Y. Cho, Preliminary Multi-Physics Analysis of OPR1000 Reactor Core using coupled CUPID and nTER, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 23-24, 2019.

[4] Y. Choi, H. K. Cho, and J. Y. Cho, Multi-physics solution of VERA Core Physics Benchmark using CUPID and nTER, Transactions of the Korean Nuclear Society Autumn Meeting, Goyang, Korea, Oct. 24-25, 2019.

[5] K. Ohira and N. Itagaki, Thermal Conductivity Measurements of High Burnup UO2 Pellet and a Benchmark Calculation of Fuel Center Temperature, Proceedings of the International Topical Meeting on LWR Fuel Performance, Portland, OR, Mar. 2-6, 1997.

[6] N. Horelik et al., Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS) rev. 2.0.2, 2018.

[7] T. Downar, VERA-CS Verification & Validation Plan, CASL Technical Report: CASL-U-2017-1287-000, 2017.