Criticality Analysis of VVER-1000 Mock-up with the Monte Carlo code MCS

Fathurrahman Setiawan, Matthieu Lemaire, Hyunsuk Lee, Deokjung Lee*

Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919, Republic of Korea

**Corresponding author: deokjung@unist.ac.kr*

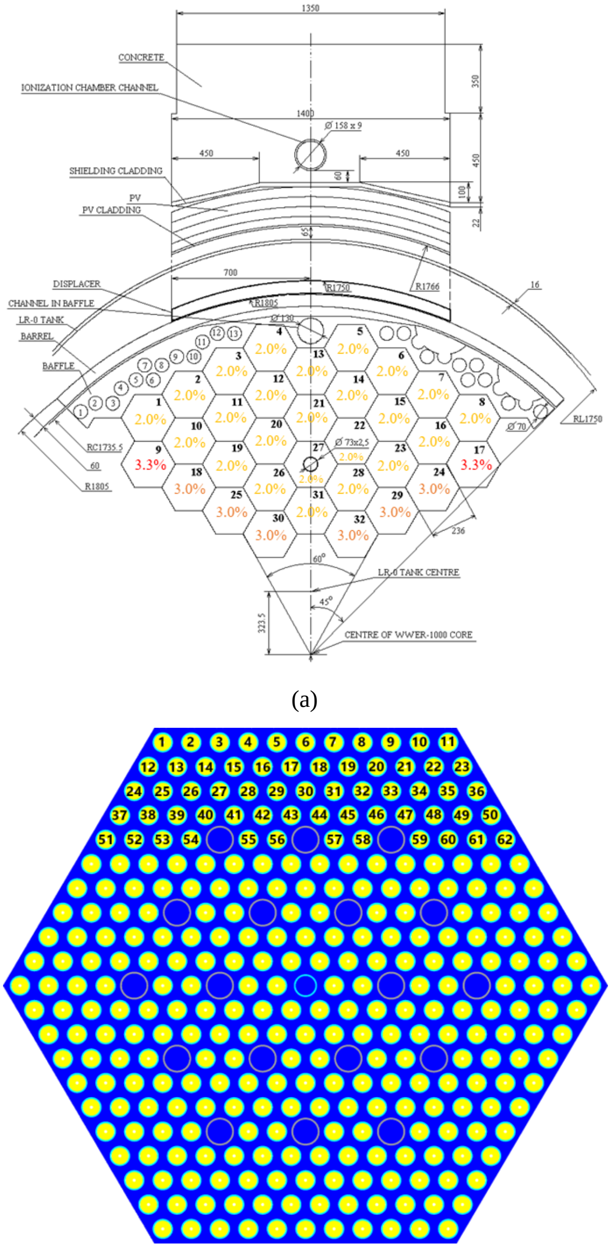
1. Introduction

The NEA-1517/82 benchmark from the OECD/NEA database SINBAD (Shielding Integral Benchmark Archive and Database) is a VVER-1000 mock-up experiment in the LR-0 reactor providing experimental criticality results (effective neutron multiplication factors, pin power measurements) and shielding results (measurement of neutron and photon flux in and outside of the core) [1]. MCS is a continuous-energy Monte Carlo code developed at Ulsan National Institute of Science and Technology with validated neutron/photon transport capability. Validation of the MCS neutron physics includes the BEAVRS core (Benchmark for Evaluation And Validation of Reactor Simulations) [2] for square lattices and the CEFR (China Experimental Fast Reactor) [3] for hexagonal lattices. Validation elements of MCS for hexagonal fuel lattices of light water thermal reactors are presented in this paper by conducting the criticality analysis of the NEA-1517/82 VVER-1000 mock-up. The MCS calculation of 260 pin powers is first verified against MCNP6 and then validated against the experimental pin data.

2. Experiment and Calculation

2.1. Experimental Arrangement

The VVER-1000 mock-up experiment is conducted in the LR-0 zero power reactor operated by the Nuclear Research Institute in the Czech Republic. The experiment consists of 32 hexagonal fuel assemblies (FA) and several reactor components: baffle, barrel, downcomer (simulated by a displacer), pressure vessel, and biological shielding. Figure 1 (a) shows the full radial view of the VVER-1000 mockup with the numbering and uranium enrichment for each assembly. Each fuel assembly is made of 312 fuel pins, with inner and outer diameter of 1.4 mm and 7.53 mm respectively, placed along 18 stainless-steel cluster tubes and a central tube as shown in Figure 1 (b). Fuel pins are cladded with 0.7 mm thick zirconium cladding tubes. Boron carbide is used as absorber rod to control the power during the experiment. The fuel active length is 125 cm with upper and bottom ends made of zirconium alloy of height ~5 cm. In the axial direction, five spacer grids are placed on each assembly. The first spacer grid is located 24.4 cm above the bottom of the active fuel and the others are placed at 25.5 cm intervals from the first one. To reduce the neutron leakage and improve the albedo, a 25-cm-thick axial water reflector is used at the top of the active core. During the criticality measurements, three absorber rods are half inserted in the assemblies #19 and #23 and the concentration of boric acid diluted in the light water moderator equals 4.6 ± 0.1 g/l. The measurements are conducted at atmospheric pressure and room temperature.



(a)

(b)

Figure 1 Full radial view of VVER-1000 mock-up with assembly enrichment and numbering (a) Radial view of 1 FA with pin numbering sequence (b)

2.2. Modelling and Calculation

A new 3D model of the VVER-1000 mockup has been written for the MCS Monte Carlo code based on the experimental arrangement described in the SINBAD benchmark documentation. The model is developed strictly with the same dimensions, material compositions, and operating conditions (i.e. temperature, boric acid concentration, and absorber rod position) as in the benchmark documentation. The full radial view of MCS model is shown in Figure 2. The complex honey-comb structure of VVER-1000 spacer grids is modelled using band-dissolution technique [4] in which the spacer grid and the moderator are homogenized in a certain volume. An identical VVER-1000 mock-up model is also developed for the MCNP6 code for direct comparison and verification. The calculations are conducted with one million neutron histories per cycle, 100 inactive cycles, and 1,000 active cycles. As the number of simulated neutron histories (1 billion) exceeds the period of the default random number generator (RNG) for both MCS and MCNP calculations (default period = ~460 million histories for default stride of 152,917), attention is paid to use the second RNG option in MCS and MCNP with a period > 10^{13} histories. The convergence of the fission source distribution during the 100 inactive cycles is checked by means of the Shannon entropy and (for MCS) of the center of mass of the fission sources. The nuclear data library ENDF/B-VII.1 with S(α,β) thermal data for hydrogen atom in the moderator is used in both calculations.

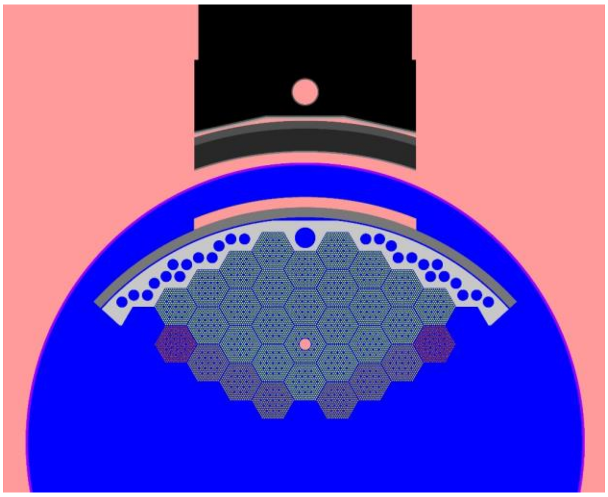


Figure 2 Full radial view of MCS model of VVER-1000 mock-up

3. Results

3.1. Verification against MCNP6

Preliminary verification against the MCNP6 Monte Carlo code is conducted to ensure that the MCS model and calculation does not include obvious error. The verification starts with the comparison of the effective neutron multiplication factors (Keff) from both codes. The MCS Keff value equals 0.99804 and differs from the MCNP6 value by only 2 pcm ± 3 pcm at one standard deviation. The next step is the comparison of pin-by-pin power distribution presented in term of $C_{MCS}/C_{MCNP} - 1$ as shown in Figure 3. The maximum discrepancy equals 2.4% ± 2.5% at three standard deviation. The root-mean-square (RMS) value of ($C_{MCS}/C_{MCNP} - 1$) discrepancies equals 0.4% with RMS standard deviation of about 1.1% at three standard deviation. An excellent agreement is therefore observed between the two codes, the observed discrepancies of pin power coming only from the statistical errors in the code calculations.

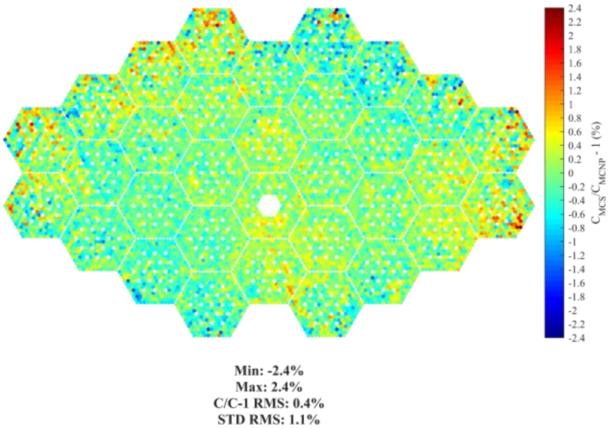


Figure 3 Pin-by-pin power comparison between MCS and MCNP6

The axial power distributions calculated by the two codes (normalized by the mean value) are shown in Figure 4. A good agreement is observed between the two distributions with discrepancies within one standard deviation.

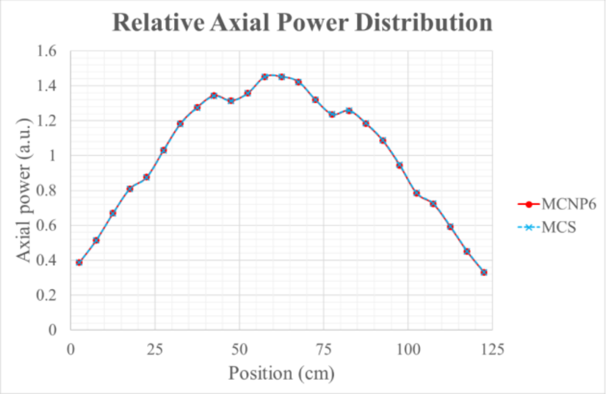


Figure 4 Comparison of relative axial power distribution of MCS and MCNP6

3.2. Validation against Benchmark

Validation elements for the MCS neutron transport capability in hexagonal fuel lattices of light water reactors are presented through the analysis of the VVER-1000 mockup benchmark experiment. The experiment includes the measurement of the pin power of 260 pins distributed in 7 assemblies (assembly #3, #4, #12, #13, #21, #27, and #31). The pin power was measured in the 5-cm length at the center of the fuel. Cell tally is used in MCS to get the pin power in the 260 measured pins. The tally values are then normalized according to the benchmark documentation by giving a mean power value of 1,000 to the 260 pins (the 260 tallies are divided by their mean value and then multiplied by 1,000). The normalized pin power tallies can then be directly compared against the experimental data contained in the benchmark documentation.

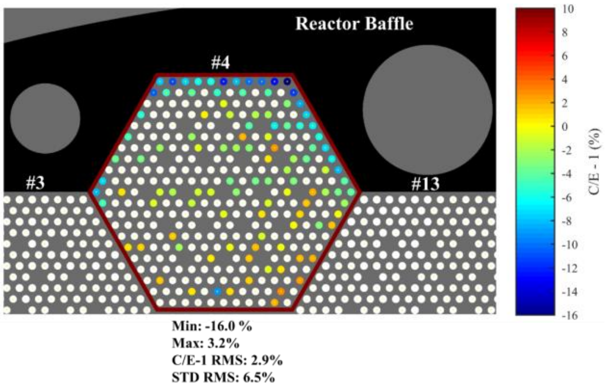


Figure 5 C/E – 1 of 103 pins on assembly #4

Figure 6 shows the calculation/experiment discrepancies (C/E – 1 values) for the 260 pins. The pins are distributed over 60% in the assemblies #4 (107 pins) and #13 (63 pins). Good agreement at three standard deviations is observed between the calculated and measured pin power for 259 pins, with only 1 pin in assembly #4 (pin number 11) outside of the three standard deviation zone with a C/E-1 of -16.0% ± 14.3%. The outlier pin is located at the top right corner of the fuel assembly #4 near the reactor baffle as shown in Figure 5. The calculated powers for the pins in assembly #4 near the baffle region underestimate the experimental values. The pins near the reactor baffle, where the fission power is lower due to the lower neutron thermalization and increased neutron absorption rate in the baffle, suffer from higher statistical standard deviations in the order of 2-2.5%.

4. Conclusions and perspectives

The criticality analysis of the VVER-1000 mock-up benchmark compiled in the SINBAD database (NEA-1517/82) has been conducted with the MCS Monte Carlo code to provide validation elements of MCS neutron transport capability in hexagonal fuel lattices of light water reactors. Code/code comparison between MCS and MCNP6 is conducted first and excellent agreement is observed for Keff values, radial pin-by-pin power, and axial power distribution. Validation is conducted by comparing the measured 260 pins against MCS calculations and a good agreement is observed overall with only one outlier pin outside of the three standard deviation agreement zone. Further planned work on the VVER-1000 mock-up benchmark includes the interpretation of the neutron-photon measurements as validation elements for the deep penetration shielding capability with weight-window-based variance reduction techniques recently implemented in MCS.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No NRF-2019M2D2A1A03058371.

References

[1] B. Ošmera and S. Zaritzky, "VVER-1000 Mock-up Experiment in the LR-0 Reactor," Nuclear Research Institute Řež, Czech Republic, 2002.

[2] H. Lee, W. Kim, P. Zhang, M. Lemaire, A. Khassenov, Y. Jo, J. Park, J. Yu and D. Lee, "Development at UNIST of Monte Carlo Multi-physics Code MCS for Power Reactor Analysis," in *M&C 2019*, Oregon USA, 2019.

[3] T. Q. Tran, J. Choe, X. Du, A. Cherezov, H. Lee and D. Lee, "Preliminary CEFR analysis by Monte Carlo codes," in *M&C 2019*, Oregon USA, 2019.

[4] X. B. Tran and N. Z. Cho, "A Study of Neutronics Effects of the Spacer Grids in a Typical PWR via Monte Carlo Calculation," *Nuclear Engineering and Technology*, vol. 48, no. 1, pp. 33-42, 2016.

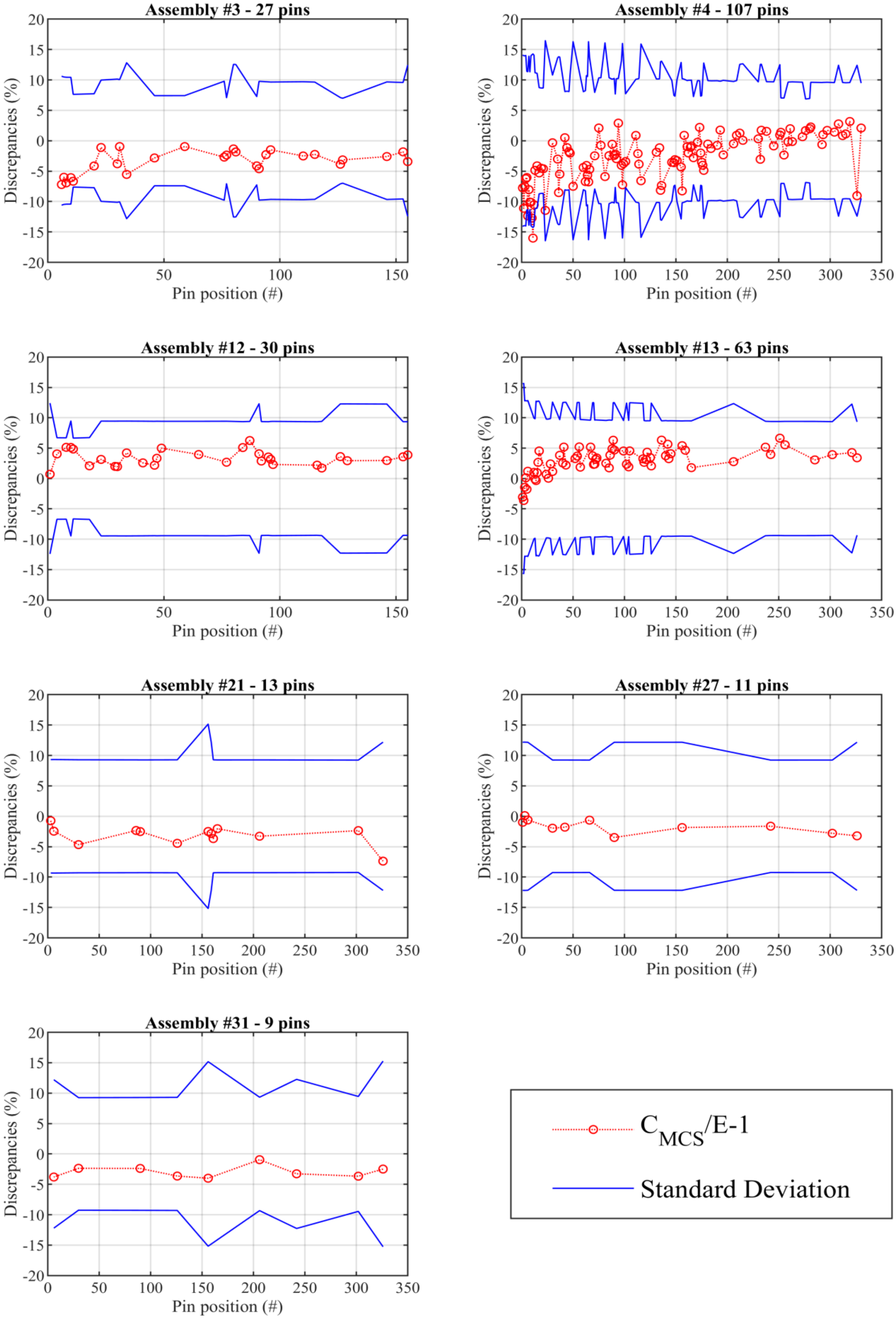


Figure 6. Discrepancies of MCS calculation against Experiment for the pin powers of 260 pins distributed in 7 assemblies