

VVER-1000 BENCHMARK INTERPRETATION WITH MONTE CARLO CODE MCS

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ABSTRACT

An interpretation of the NEA-1517/82 benchmark from the SINBAD shielding database has been conducted with the MCS Monte Carlo code developed at the Ulsan National Institute of Science and Technology (UNIST) and the ENDF/B-VII.1 nuclear data library. The NEA-1517/82 benchmark corresponds to experiments on a VVER-1000 critical mock-up (thermal reactor with hexagonal fuel lattice) inside the LR-0 research reactor operated by the Nuclear Research Institute (NRI) in the Czech Republic. A new 3D model of the VVER-1000 mock-up core is developed for MCS based on the SINBAD documentation. The model includes the top and bottom parts of fuel pins, the spacer grids and core components: baffle, barrel, downcomer, tank, reactor pressure vessel (RPV) and concrete block used as biological shielding. The quality of the model is verified first by code/code comparison of MCS against MCNP6 for criticality and power distributions (pin-by-pin and axial power). The validation of MCS results is then performed against six critical cases, 260 measured pin powers and benchmark calculations of the axial power profile. Finally, a comparison of calculated and measured neutron spectra inside the mock-up core is presented as a preliminary study for upcoming works on the deep-penetration shielding capability of MCS.

KEYWORDS: MCS Monte Carlo, VVER-1000 mock-up, criticality analysis, benchmark validation

1. INTRODUCTION

This paper presents an interpretation of the NEA-1517/82 SINBAD benchmark with the MCS Monte Carlo code, developed at the Ulsan National Institute of Science and Technology (UNIST), and the ENDF/B-VII.1 nuclear data library. MCS has been developed since 2013 for the primary purpose of high-fidelity and high-performance criticality and depletion analysis of large-scale nuclear reactors with thermal-hydraulics feedback [1]. The neutron-transport kernel of MCS has been validated for thermal-reactor square fuel lattices, notably ~300 ICSBEP criticality benchmarks [2] and the BEAVRS benchmark [3], and verified for fast-reactor hexagonal fuel lattices with criticality calculations of the China Fast Experimental Reactor (CEFR) [4]. Photon and coupled neutron-photon transport capabilities have recently been implemented in MCS to extend its range of applications to reactor shielding and deep-penetration problems. MCS photon transport kernel has been verified for shielding problems with a fixed photon source by comparison against the Monte Carlo code MCNP6 [5] and validation studies of the coupled neutron-photon transport capability have been conducted using gamma-leakage measurements from 14-MeV neutron transmission SINBAD benchmarks [6].

The NEA-1517/82 benchmark (a.k.a VVER-1000 mock-up) experiments were conducted in the LR-0 research reactor, a light-water zero-power reactor designed for the measurements and validation of

neutron and photon parameters in VVER-type reactors. The VVER-1000 mock-up consists of 32 hexagonal fuel assemblies (FAs) with 1.25 m active height placed inside the LR-0 reactor tank along with internal components (baffle, barrel, and displacer). Outside the LR-0 reactor tank, reactor pressure vessel (RPV) and biological shielding are set for neutron and photon measurements. The NEA-1517/82 benchmark compiles measurements of radial (260 pins) and axial power profiles, and of neutron and photon spectra in certain positions. Additional measurements available in the literature detail six critical configurations of the VVER-1000 mock-up [7] [8]. Thus, this benchmark is well suited for the criticality and deep-penetration shielding validation of MCS on thermal-reactor hexagonal fuel lattices. This paper covers the verification (against MCNP6) and validation (against measurements) of MCS for the six criticality configurations, axial and radial power distributions and the neutron spectrum measured in the dry experimental channel inside the VVER-1000 mock-up core.

2. VVER-1000 MOCK-UP

2.1. Description and Experimental Configuration

The VVER-1000 mock-up is a critical experiment in the LR-0 research reactor operated by the Nuclear Research Institute (NRI) in the Czech Republic. This mock-up reproduces one sector of VVER core (32 hexagonal fuel assemblies) with full-scale component simulators: baffle, barrel, displacer (to simulate the downcomer behavior of commercial VVER plant), RPV and biological shielding [9]. The active fuel length is 1.25 m and fuel pins are ~1.35 m long accounting for the upper and bottom ends made of zirconium metal. Each FA contains 312 fuel pins in a triangular lattice with a pitch of 12.75 mm. Fuel pellets are placed inside zirconium-alloy cladding tubes with inner and outer diameter of 7.7 mm and 9.1 mm respectively. A hole of diameter 1.4 mm is drilled in the center of each fuel cell. Each FA contains 18 absorber cluster tubes made of stainless steel and a central zirconium-alloy tube. The absorber elements are made of natural boron carbide. Per FA, there are five spacer grids (of height two cm) located (coordinates of the grid centers) at 24.4, 49.9, 75.4, 100.9 and 126.4 cm from the bottom of the active core. Figure 1 shows the full radial view of the VVER-1000 mock-up arrangement (left figure) and a close-up on the mock-up core (right figure). The assemblies in yellow, orange (FA #18, #24, #25, #29, #30, #32), and red (FA #9, #17) color correspond to a uranium enrichment of 2.0%, 3.0%, and 3.3% respectively. The assemblies with blue numbering (FA #3, #4, #12, #13, #21, #27, #31) are the assemblies for which pin power measurements are available.

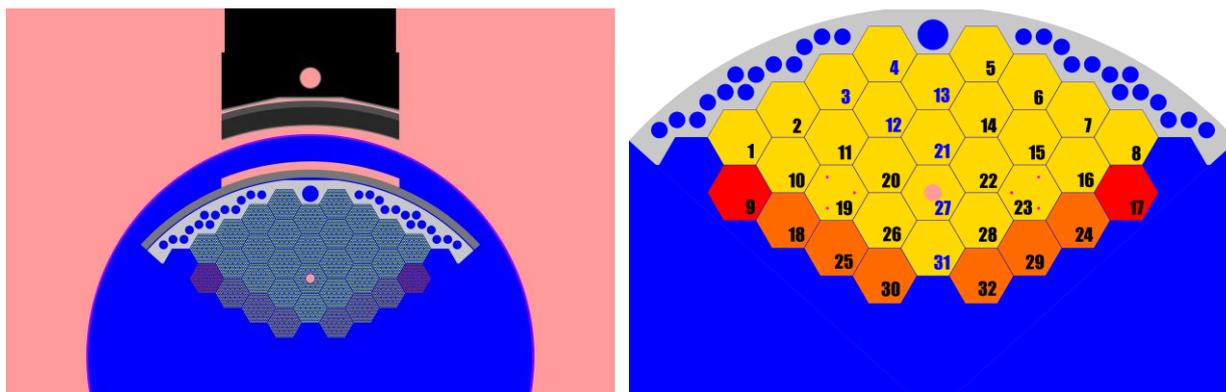


Figure 1. Radial arrangements of the VVER-1000 mock-up (left) and zoom on the mock-up core (right)

All the measurements on the VVER-1000 mock-up were conducted at atmospheric pressure and room temperature. Six critical configurations of the VVER-1000 mock-up have been experimentally determined with different moderator levels and boric acid concentrations as listed in Table I [7]. For those six cases, the effective neutron multiplication factor (k_{eff}) is experimentally determined to be unity (experimental uncertainties on the k_{eff} values are not documented). For the first five cases, criticality is

achieved without insertion of any absorber rods while for the last case (Case 6), six absorber rods are inserted in FA #19 and #23 (three rods in each assembly). Based on the benchmark documentation [8], the VVER-1000 mock-up reactor configuration during the radial (260 pins) and axial power measurements and neutron spectra measurements can be considered the same as the configuration of Case 6.

Table I. Critical configurations of the VVER-1000 mock-up

| Mock-up Configuration | Moderator level [cm] | | Boric acid concentration [g/kg] | |
|-----------------------|----------------------|------|---------------------------------|------|
| | Value | Unc. | Value | Unc. |
| Case 1 | 51.34 | 0.05 | 2.85 | 0.06 |
| Case 2 | 65.91 | 0.05 | 3.63 | 0.05 |
| Case 3 | 79.11 | 0.05 | 4.06 | 0.05 |
| Case 4 | 96.71 | 0.05 | 4.44 | 0.05 |
| Case 5 | 103.37 | 0.05 | 4.53 | 0.05 |
| Case 6 | 150.00 | 0.05 | 4.68 | 0.08 |

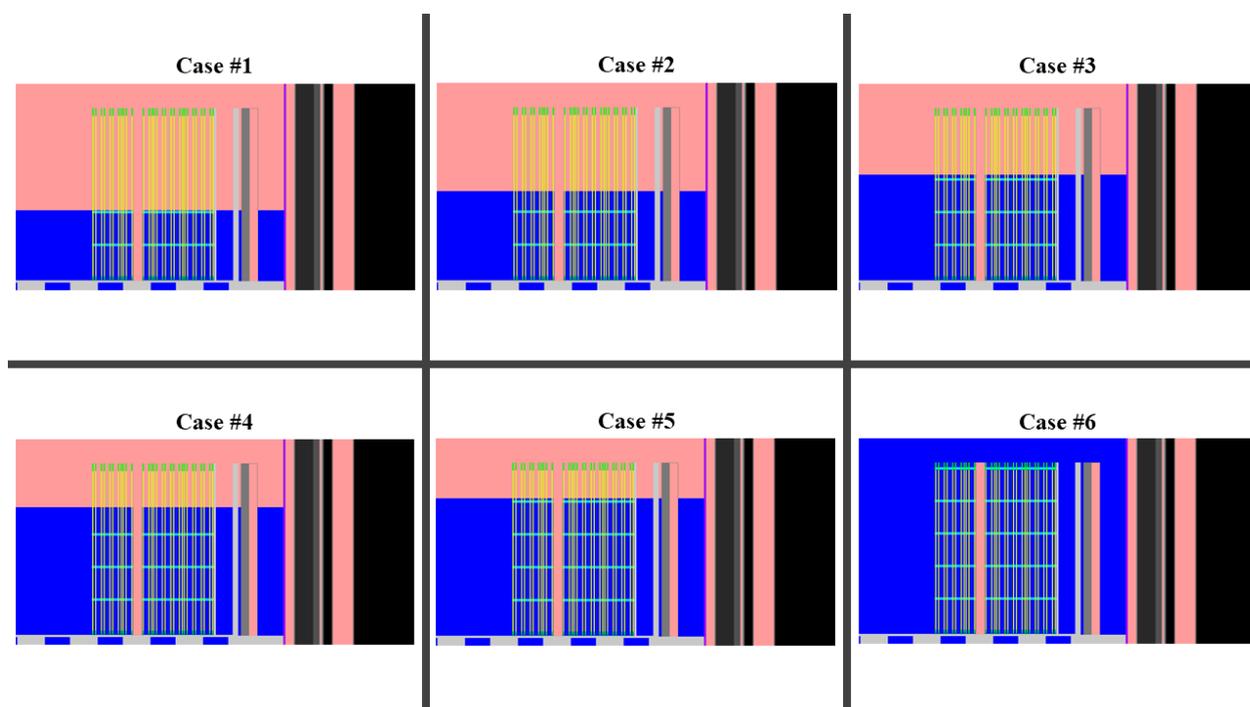


Figure 2. Axial view (YZ-plane) of the six VVER-1000 mock-up critical configurations

2.2. MCS Modelling and Calculation

A new 3D model of the VVER-1000 mock-up is developed for MCS based on the benchmark documentation. The model includes the mock-up core (32 FAs), baffle, barrel, displacer, pressure vessel and biological shielding. Upper and lower support structures are modelled as closely as possible with the information from SINBAD documentation. Band dissolution technique [10] is adopted for the modelling of the spacer grids as the complex structure of honeycomb hexagonal fuel assemblies makes it unpractical to model the spacer grids in a realistic and heterogeneous manner. Figure 2 shows the axial view (along the YZ plane) of the six critical cases with the different moderator levels and the two-cm-tall dissolution bands containing homogenized moderator and spacer-grid steel.

An identical MCNP6 model of the VVER-1000 mock-up is developed for direct comparison with MCS. Both codes use the same ACE files: neutron continuous-energy cross-section libraries and $S(\alpha,\beta)$ thermal data of hydrogen in moderator from ENDF/B-VII.1 nuclear data library. Cross sections processed at room temperature are employed for the simulations in accordance with the experimental conditions. For the six criticality calculations, 100 inactive cycles and 300 active cycles of 500,000 neutron histories each are employed. For the pin power, axial power and neutron spectrum calculation, 100 inactive cycles and 1,000 active cycles of one million neutron histories each are employed. More neutron histories and active cycles are used for the power and neutron spectrum calculation to make sure that the tallied values do not suffer from too large statistical uncertainties. For each calculation, the variations of the cell-wise Shannon entropy and of the center of mass of the fission source distribution are checked to ensure that 100 inactive cycles are sufficient for the fission source distribution to converge.

3. RESULTS

3.1. Criticality

Table II lists the comparison of k-eff for the six critical configurations between MCS, MCNP6 and the experimental k-eff value (=unity). Excellent agreement between MCS and MCNP6 is observed with a maximum difference of 14 ± 23 pcm at three standard deviations (3σ). The calculated k-eff values are close to each other for the six critical cases (within 40 pcm of each other) and they all underestimate the experimental value ($k\text{-eff} = 1$) by about 470 pcm. The evaluation of the modelling uncertainties is ongoing to assess the possible causes for the observed discrepancy between calculation and experiment.

Table II. Comparison of k-eff between MCS, MCNP6 and experiment (=unity)

| Case | MCS | MCNP6 | Diff (MCS–MCNP6) $\pm 3\sigma$ [pcm] | Diff (MCS-Exp) [pcm] |
|--------|---------|---------|--------------------------------------|----------------------|
| Case 1 | 0.99509 | 0.99502 | 7 ± 23 | -491 |
| Case 2 | 0.99518 | 0.99504 | 14 ± 23 | -482 |
| Case 3 | 0.99543 | 0.99544 | -1 ± 23 | -457 |
| Case 4 | 0.99527 | 0.99533 | -6 ± 21 | -473 |
| Case 5 | 0.99549 | 0.99544 | 5 ± 21 | -451 |
| Case 6 | 0.99550 | 0.99541 | 9 ± 23 | -450 |

3.2. Radial Pin Power

The radial pin-by-pin power distribution of MCS is first verified against MCNP6. A cell tally is used to calculate the power in each fuel pin (260 fuel pins in total). The comparison of pin-by-pin power between MCS and MCNP6 shows excellent agreement with a root mean square (RMS) of $(C_{\text{MCS}}/C_{\text{MCNP6}} - 1)$ differences equal to $0.4\% \pm 1.1\%$ (3σ), a minimum difference equal to $-2.4\% \pm 2.5\%$ (3σ) and a maximum difference equal to $2.4\% \pm 1.8\%$ (3σ).

The comparison of calculated and measured pin powers is now performed. The experimental pin powers of 260 pins across 7 assemblies of VVER-1000 mock-up core are available (FA #3, #4, #12, #13, #21, #27, and #31, see Figure 1). Over 60% of the measured pins are located in the assemblies #4 (107 measured pins) and #13 (63 measured pins). The pin powers were measured in the 5-cm-length at the central mid-plane of the core and the calculated pin powers are therefore only tallied in the central 5-cm region of each fuel pin. The experimental pin power data is normalized to a mean power value of 1,000 (arbitrary value) for the 260 pins so only relative comparison is possible between the measurements and calculations. The comparisons of calculated and measured pin powers for the assemblies #3, #4, #12 and #13 (227 pins in total) are presented in Figure 3. The plots show the $(C/E - 1)$ discrepancies in % along with the total uncertainty (experimental uncertainty combined with statistical uncertainty from calculation) at three standard deviations. For one pin, the experimental uncertainty amounts to about 2.5% - 4.0% at one standard deviation whereas the statistical uncertainties amount to about 0.9% - 1.7% at one standard deviation. The pin numbering in an assembly is shown in Figure 4.

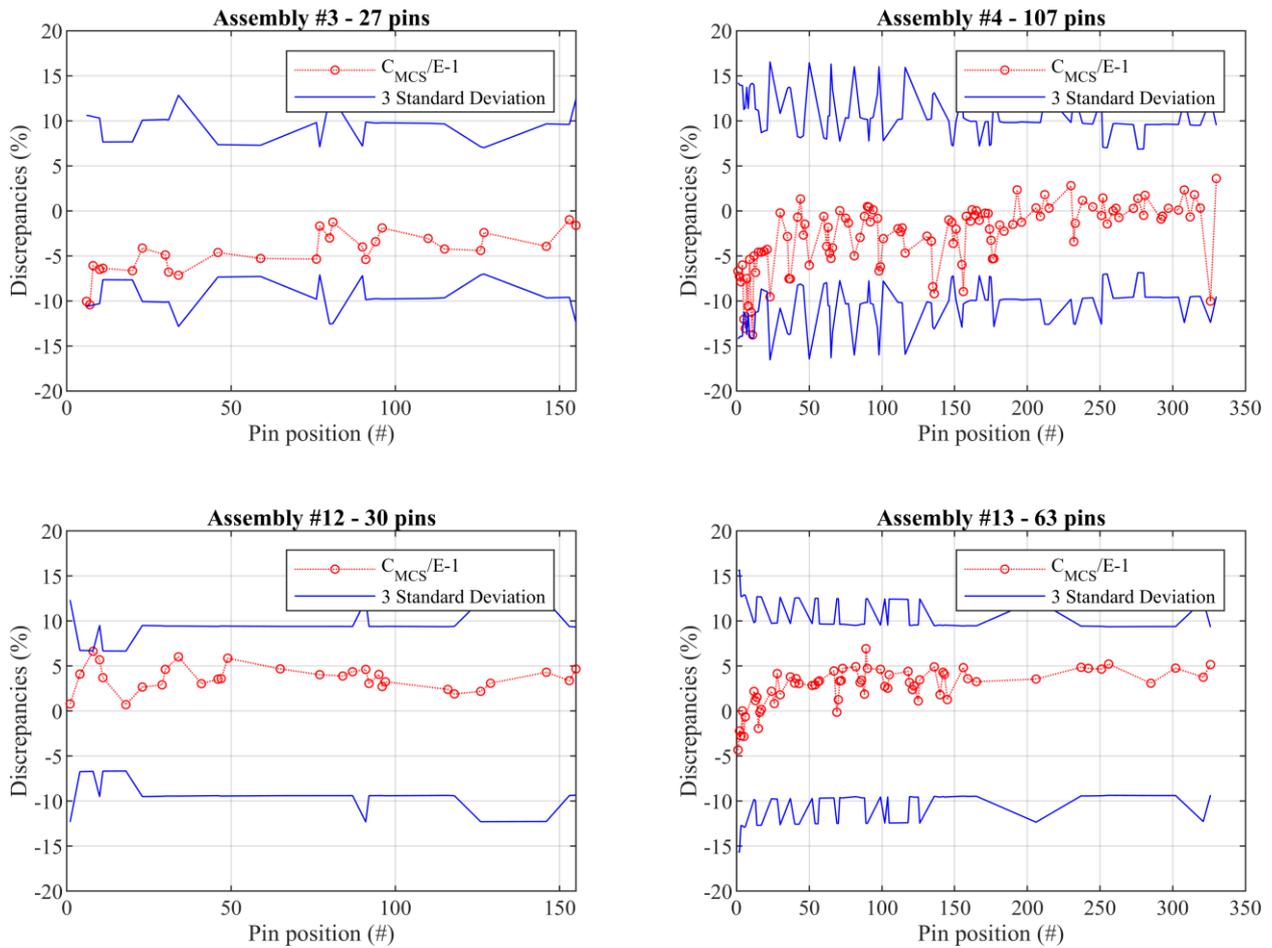


Figure 3. Pin power comparison ($C/E - 1$) between MCS calculations and measurements

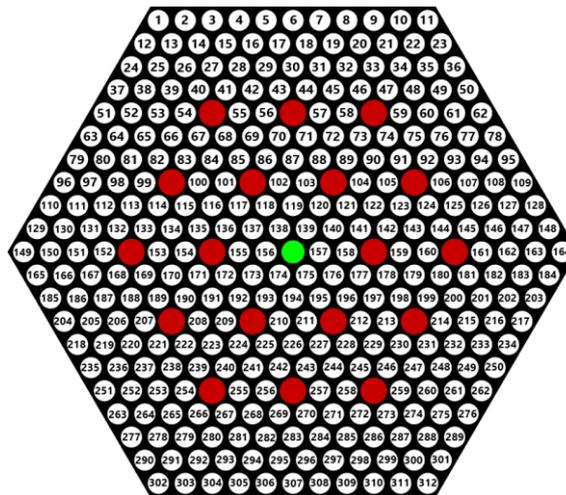


Figure 4. Pin numbering of measured FAs #4 and #13

In the assemblies #12 and #13, the calculated pin powers mostly overestimate the measured pin powers by about $\sim 5\%$ on average. The maximum overestimation $(C/E - 1) = +7.0\% \pm 12.5\%$ (3σ) is observed for pin #86 in assembly #13 as shown in Figure 5. The pins near the reactor steel baffle suffer from higher statistical standard deviations, in the order of $2 - 2.5\%$ (1σ), due to the lower fission power. In the

assemblies #3 and #4, the calculated pin powers mostly underestimate the measurements. The largest underestimation $(C/E - 1) = -13.8\% \pm 14.2\%$ (3σ) is observed for pin #11 in assembly #4 as shown in Figure 5. The other calculated pins in FA #21, #27 and #31 (33 pins in total) agree well with measurements, with $(C/E - 1)$ discrepancies below 5%. The RMS value of $(C/E - 1)$ differences for the 260 pins amounts to $4.1\% \pm 10.7\%$ (3σ). Overall, good agreement is observed between pin power calculation and measurements.

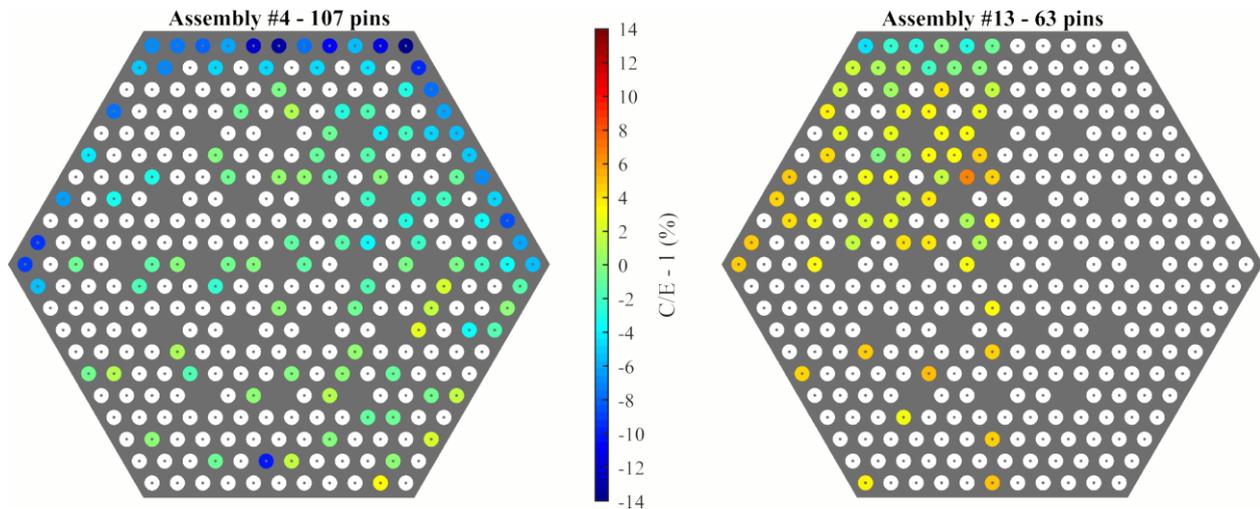


Figure 5. $(C/E - 1)$ differences between MCS and measurements in assembly #4 (left) and #13 (right)

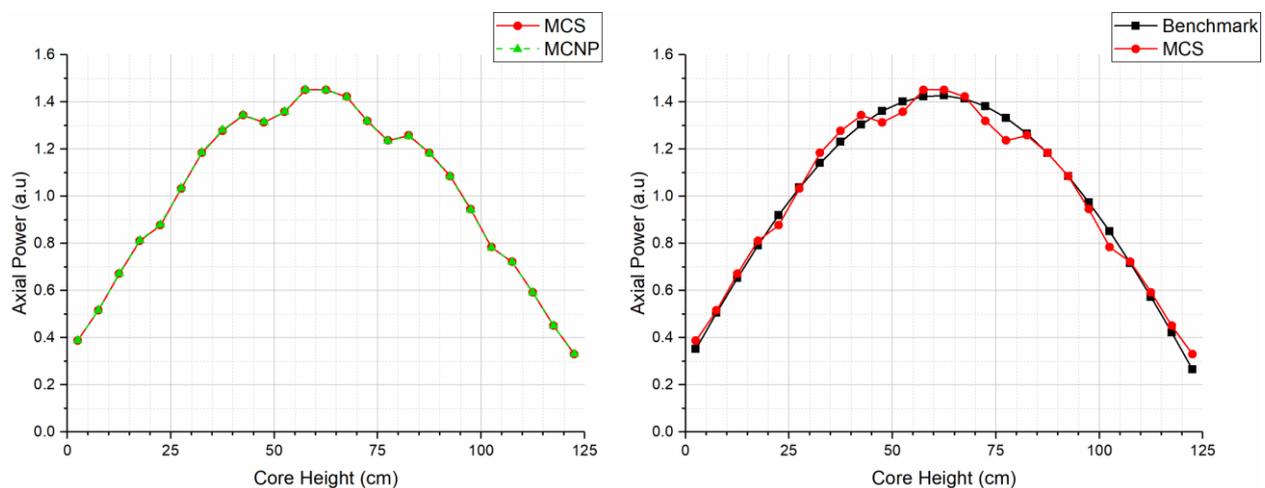


Figure 6. Comparison of relative axial power distribution: MCS against MCNP (left) & MCS against benchmark (right)

3.3. Axial Power Profile

The axial power profile calculated by MCS is first verified against MCNP6. The axial power distribution of the mock-up core is tallied with 25 uniform axial cells (height of a cell = 5 cm) on each fuel pin. The 25 axial tally values are then radially averaged over all the fuel pins (9954 pins). The comparison shows good agreement as shown in Figure 6 (left) with code/code discrepancies smaller than one standard deviation. The comparison of radially-averaged calculated and benchmark axial power profile is then performed. The benchmark documentation provides a relative axial power profile (benchmark profile) determined with the diffusion code MOBY-DICK. The comparison of relative power distributions

between MCS and the benchmark profile is shown in Figure 6 (right). The effect of the spacer grid modelling in MCS calculation is clearly visible on the axial power profile (especially at core height 50 and 75 cm) compared to the benchmark profile which was determined without modelling the spacer grids. The MCS calculation accurately describes the axial power distribution of the VVER-1000 mock-up.

3.4. Neutron Spectrum inside the Core

Measurements of the neutron flux were carried out in the central dry channel of assembly #27 with a proton recoil spectrometer for energies above 1 MeV and hydrogen chambers for energies below 1 MeV. The measured neutron spectra were grouped into the BUGLE energy group format, a 24 energy-group structure ranging from 0.111 MeV to 10 MeV. The experimental uncertainties at one standard deviation on the measured flux reach about 5.7% below 1 MeV, 7.5% between 1 and 2.5 MeV, 4% between 2.5 MeV and 8.5 MeV, and 8.7% above 8.5 MeV. The neutron flux is tallied inside the dry channel of the assembly #27 at the central axial plane of the mock-up core. The tallied spectrum is then normalized in the same way as the experimental spectrum, that is, the integral of the flux in unit $1/(\text{cm}^2 \cdot \text{MeV})$ over the energy range from 1 MeV to 10 MeV is set equal to unity. The comparison of the calculated and measured normalized integrated flux is shown in Figure 7 (left). The neutron flux for the energy groups from 2.23 MeV to 2.47 MeV are summed together in one single energy group both in the measured and calculated data according to the recommendations of the benchmark documentation. The corresponding $(C/E - 1)$ discrepancies are shown in Figure 7 (right). The “three standard deviations” line corresponds to the total uncertainties from experiment and calculation (statistical uncertainties). The statistical uncertainties range from 0.4% to 3.3% with an average value of about 1.0% at one standard deviation. The neutron flux comparison shows good agreement between calculation and measurement.

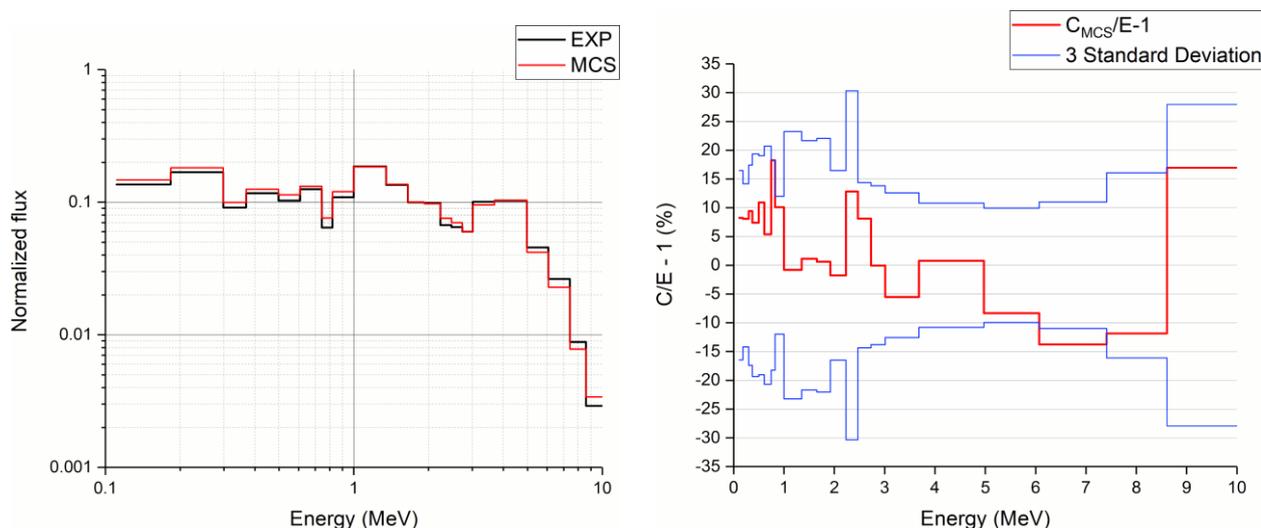


Figure 7. Comparison between MCS calculation and measurement of the neutron spectrum inside of the core in terms of relative units (left) and $C/E - 1$ (right)

4. CONCLUSIONS

A first interpretation of experiments conducted in the VVER-1000 mock-up in the LR-0 experimental reactor of the Nuclear Research Institute in the Czech Republic is conducted with the MCS Monte Carlo under development at UNIST and the ENDF/B-VII.1 nuclear data library. The interpretation is carried out with a detailed model of the VVER-1000 mock-up prepared for MCS and MCNP6 in order to provide verification and validation elements of MCS for thermal-reactor hexagonal fuel lattice geometries. The tackled validation data from the VVER-1000 mock-up experiments includes six critical configurations,

260 radial pin powers, reference axial power profile and the neutron spectrum in the core central dry channel. Excellent agreement is observed between MCS and MCNP6 and good agreement is observed between MCS and the measurements. The presented interpretation is a first step towards the full interpretation of the NEA-1517/82 SINBAD benchmark, which includes measured neutron and photon spectra in the external components (displacer and RPV) of the VVER-1000 mock-up. The interpretation of this deep-penetration shielding problem is to be solved with weight-window-based variance reduction techniques recently implemented in MCS. Additional work includes the quantification of the modelling uncertainty (propagation of geometrical uncertainties and material composition uncertainties) on the VVER-1000 mock-up parameters calculated with MCS.

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