Benchmark calculation AER VVER-1000 - ETE using BIPR8

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Abstract. This article presents AER VVER-1000 – ETE benchmark results using the BIPR-8 nodal sparse-grid program. This paper contains a description of the benchmark AER VVER-1000 – ETE and short description of calculations using the BIPR-8 nodal sparse-grid program. Calculation were carried out at the full scale then the pin-by-pin power distribution was reconstructed, and results is compared with the results obtained in the MCNP program.

1. Introduction
The VVER-1000 - ETE benchmark [1] was proposed by the ŠKODA JS specialists in 2011 in order to test the VVER fuel cell simulation programs. The main task of this benchmark is to test the pin-by-pin power distribution calculated by different macro-codes in selected fuel assemblies that are placed mainly at and close to the core periphery. Motivation for the benchmark setup is due to an observed phenomenon at calculation of the 9th fuel load of Temelin NPP (VVER-1000 core, fuel load completely composed from TVSA-T fresh fuel assemblies). The task organizers suggested comparing the results with the results of the Monte Carlo MCNP program. This paper presents the solution of the problem with the help of the nodal sparse-grid program BIPR-8 with the pin-by-pin power reconstruction.

2. Benchmark description
Main task is to calculate of the power distribution in selected state of the reactor core. This way is used to be able to use Monte Carlo method used to obtain a reference solution. This selected state of reactor core.

2.1. Basic approximations:
1) Two-dimensional model;
2) Zero burnout in all fuel assemblies;
3) Zero reactor power; respectively there is no Xe and no Sm;
4) Boric acid concentration of 6.5 g / kg;
5) All rods of the control and control system are raised from the core; temperature of the fuel and coolant 600 K. The pressure of the coolant is 15.7 MPa.

2.2. Task features:
1) Zero burnout, as a result, a fresh cassette of 4.0% at the corner of the core;
2) Assemblies with a large enrichment difference;
3) Sensitivity of the simulation results to the zero power reflector model.
The fresh fuel load in the task is represented by six types of fuel assemblies: 1.3%, 2.0%, 3.0%, 3.5%, 3.9%, 4.0%. The cartogram is shown in figure 1.

This benchmark was already calculated by MCNP, MOBY-DICK, MCU, PERMAK-A codes.

![Fuel Assembly Diagram](image)

**Figure 1.** Fuel assembly.

The characteristics of fuel assemblies used in the fuel load are presented in table 1. In the fuel load, there are both simple assemblies and assemblies with Gd absorber.

| Type  | Number of pins / uranium enrichment [%] | Number of pins with Gd/ uranium enrichment [%] / quantity of Gd2O3 |
|-------|----------------------------------------|-------------------------------------------------------------------|
|       | First type                             | Second type                                                       |
| A1300 | 312 / 1.3                              | -                                                                  |
| A2000 | 312 / 2.0                              | -                                                                  |

**Table 1.** Characteristics of fuel assemblies used in the U1C9 fuel load.
Maps of the all fuel assemblies types are presented in figures 2 - 4.

|    |    |    |    |
|----|----|----|----|
| A30E9 | 303 / 3.0 | - | 9 / 2.4 / 5 |
| P36E9 | 243 / 3.6 | 60 / 3.3 | 9 / 3.3 / 5 |
| P40E9 | 243 / 4.0 | 60 / 3.6 | 9 / 3.3 / 5 |
| A40E6 | 306 / 4.0 | - | 6 / 3.3 / 5 |

**Figure 2.** Map of A2000 and A1300 assemblies.
Figure 3. Map of A30E9 assembly.
3. **Software description**

First step of calculation was preparation of constants. It was carried out using the software TVS-M [2]. This program uses first collision probability method (FCP) to solve the transport equation of neutron transfer under multi-group approximation with arbitrary number of neutron energy groups from 4 to 48. The result of the program is a library of neutron-physical constants for a VVER-1000 reactor with a given load. The resulting library will be used in further calculations with BIPR8.

**Figure 4.** Map of P36E9 and P40E9 assemblies.
Next step is state calculation in BIPR8 [3] program. The three-dimensional two-group nodal sparse-grid program BIPR8 is intended for conducting neutron-physical calculations of VVER-type reactors. The BIPR8 program calculates: three-dimensional fields of fuel burnup depths; temperature and density of the coolant; energy release and neutron projects; effects of spatial distribution of Xe-135, Sm-149 and Pm-149 isotopes; irregularity coefficients of energy release in the core; system reactivity. Using the perturbation theory, the reactivity coefficients are calculated: by the density and temperature of the coolant, by the temperature of the fuel, by the power of the reactor. It determines the following kinetics parameters: average lifetime of nearby ones, effective fraction of delayed neutrons, average decay constant of predecessors, delay of interesting neutrons. BIPR8 is also included in the ATHLET / BIPR-VVER software package [4], which is used for Reactivity-Initiated Accident (RIA) analyses of VVER-type reactor.

After state calculation goes pin-by-pin power reconstruction [5]. Already calculated solution is used to reconstruct energy distribution inside assembly. The system of equations that describe neutron balance in reactor is shown below.

\[
\begin{align*}
\text{div} D_r \text{grad} \Phi_f - (\Sigma_{ef}^+ + \Sigma_{ef}'^+) \Phi_f + \frac{1}{K_{\text{eff}}} (\nu \Sigma_{ef}' \Phi_f + \nu \Sigma_{ef}^+ \Phi_f) &= 0 \\
\text{div} D_r \text{grad} \Phi_r - \Sigma_{rf}^+ \Phi_r + \Sigma_{rf}' \Phi_r + \Sigma_{rf}^+ \Phi_f &= 0
\end{align*}
\]

Solution of this system is defined as follows:

\[
\Phi_f = X + tY
\]

Here \(X\) – asymptotic mode; \(Y\) – transitional mode:

\[
X(r, \phi) = \sum_{m=0}^{6} A_m Z_m(r) \cos(m \phi - \delta_m)
\]

\[
Y(r) = Y' e^{-\left(\frac{E}{2} - r\right)}
\]

Values of asymptotic mode and transitional mode is used for reconstruct pin by pin power distribution.

\[
\Phi_r = rX + Y
\]

4. Results of calculation

After constants preparing, and BIPR8 input file configuring results were obtained. \(K_{\text{eff}}\) calculation results is shown in table 2. Visualization of power distribution\((K_q)\) field is shown in figure 5:

| \(K_{\text{eff}}\) (BIPR8) | \(K_{\text{eff}}\) (MCNP) | \(\delta K_{\text{eff}}\) |
|-----------------|-----------------|-----------------|
| 1.003012 | 1.00289 | 0.012% |
Figure 5. Power distribution in assembly.

Normal deviation of power distribution from MCNP results is 0.7%, maximum deviation is 1.37%, map of deviation is shown in figure 6.

Figure 6. Power distribution discrepancies between BIPR8 and MCNP calculation results.
Pin by pin power distribution visualization is shown in figures 7-9.

**Figure 7.** Pin by pin power distribution in 8 assembly.

Max = 1.34  Min = 0.00  Average = 1.0
Cell# 275  Cell# 62
Figure 8. Pin by pin power distribution in 28 assembly.

Max = 1.06    Min = 0.00
Cell# 323   Cell# 62   Average = 1.0
Figure 9. Pin by pin power distribution in 54 assembly.

Pin by pin power distribution discrepancies between BIPR8 and MCNP is shown in figures 10-12.
Figure 10. Power distribution discrepancies between BIPR8 and MCNP in pin-by-pin calculation results for assembly #8.
Figure 11. Power distribution discrepancies between BIPR8 and MCNP in pin-by-pin calculation results for assembly #28.

Max = 0.04  Min = 0.00  Average = 0.01
Cell# 277  Cell# 62
Figure 12. Power distribution discrepancies between BIPR8 and MCNP in pin-by-pin calculation results for assembly #54.

This figure 9 and 10 shows that the maximum deviation is concentrated in in the outer layer of the assembly. The obtained results indicate the potential for optimization of the pin by pin reconstruction algorithm, which is being carried out now.

Results for non-peripheral assemblies is shown in table 3.

| Assembly number | 8   | 11  | 28  | 54  |
|-----------------|-----|-----|-----|-----|
| Maximum deviation of BIPR-8 from MCNP results | 3.3% | 3.4% | 5.1% | 2.9% |
5. Conclusion

Benchmark VVER 1000 - ETE was solved with the help of the BIPR-8 code at the full-scale and fuel sampling level. The results of the calculations allow us to make the following conclusions:

- Maximum deviation in the full-scale calculation is 1.37%. Deviation of neutron multiplication factor is 0.012%.
- Deviation in pin by pin solution is less than 5.1% - it is well result for sparse-grid nodal code.
- The results obtained showed the possibility of optimizing the procedure for restoring of energy field into assembly in order to refine this solution.

References

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