APPLICATION OF THE WIMS7B CODE TO COMPUTATIONAL BENCHMARK CALCULATIONS OF VVER ASSEMBLIES

N.V. Sultanov, M.N. Laletin, E.A. Kovalishin
RRC "Kurchatov institute"
123182 Moscow, RUSSIA
nsult@adis.vver.kiae.ru; laletin@adis.vver.kiae.ru

Keywords: benchmark, calculation, neutron, method

ABSTRACT

The computational benchmarks of unprofiled VVER-1000 assemblies with the UO_2 fuel and profiled VVER-1000 assemblies with the MOX fuel have been calculated by the CACTUS option of the WIMS7B code with three libraries of nuclear data. The obtained results of the K_∞ value have been compared with those of TVS-M, MCU-REA, APOLLO-2, CASMO-4, CONKEMO, MCNP, KENO codes. Calculation of a depletion of the VVER-440 assembly with the U+Gd fuel has been carried out. Comparison of dependency of the multiplication factor on depletion obtained by the WIMS-7B code and the TVS-M and MCU-REA codes has been performed.

1. INTRODUCTION

In this research, we aimed at applying the WIMS7B code (WIMS7B, 1996) for a calculation of the computational benchmarks of the VVER assemblies. It should be noted that the VVER assemblies are more heterogeneous than, for example, the PWR or BWR ones. Therefore it is interesting to know, how accurate can the WIMS7B code calculate them? Such attempts have been undertaken for calculations of some ZR-6 cores (Powney, 1998) and the VVER-440 assemblies (Mikolas, 2000). In our research we used three libraries: the 1986 library based on the UKNDL files and two 1996 libraries based on the JEF-2.2 files, of which one has 69 group cross-sections, and the other - 172 group cross-sections. We also wanted to get some acquaintance with the new option of WIMS-7B – CACTUS. The variant of WIMS-7B was placed at our disposal by the code authors for a temporal use for 9 months. It was natural to make comparisons with analogous values of TVS-M, MCU-REA, APOLLO-2, CASMO-4, CONKEMO, MCNP, KENO codes, where other libraries and methods were used. In accordance with our aims, calculations of unprofiled and profiled assemblies of the VVER-1000 reactor have been carried out by the option CACTUS. This option provides calculations by the characteristics method. The calculation results have been compared with the K_∞ values obtained by other codes in work (Lazarenko, 2000). The conclusion from this analysis is the following: the methodical parts of errors of these codes have nearly the same values. Spacing in K_{eff} values can be explained mainly by differences in library of cross-sections.

The calculation of a depletion of VVER-440 assembly with the U+Gd fuel has been carried out by the WIMS7B code with three libraries of nuclear data up to 50 MWd/kgHE. The comparison of dependency of the multiplication factor on the depletion has been performed for results obtained by WIMS-7B with different libraries and TVS-M and MCU-REA codes

2. CALCULATIONS OF VVER-1000 ASSEMBLIES

From a number of computational benchmarks considered in the paper (Lazarenko, 2000) two VVER-1000 assemblies (see Fig 1,2) were chosen. Each assembly contains 331 pin cells. The first unprofiled assembly (see Fig. 1) contains 312 pin cells with the UO_2 fuel (input data for this pin cell are given in Table 1), one central cell with a tube (Table 2) and 18 pin cells with either absorber rods (Table 4) or tubes (Table 3). The VVER-1000 assembly with absorber rods is the most heterogeneous assembly from all the assemblies considered here. The second profiled assembly (see Fig. 2) contains 312 pin cells with the MOX fuel of different Pu enrichment (Table 7), one central cell with a tube (Table 2) and 18 pin cells with either absorber rods (Table 4) or tubes (Table 3). To calculate the considered assemblies, the CACTUS option of the WIMS7B code was used. The characteristic method is applied in this option. Calculation results of the K_∞ values obtained by the CACTUS option and the other codes (Lazarenko, 2000) at the room and hot temperatures are given in Tables 5,6,8,9. All the calculations obtained by the CACTUS option have been carried out within 16 energetic groups. To demonstrate typical pin power distribution in the VVER-1000 assembly, the latter was calculated with the TVS-M code, and deviations from the other code results in per cents in the UO_2 assembly with one central cell with a tube and 18 cells with absorber rods are shown on Fig. 5.

From a comparison analysis of the VVER-1000 assembly calculation results with the different fuel (see Tables 5,6,8,9 and Fig. 5) by the WIMS7B code and other codes one can draw the following conclusions:

- In all assemblies considered, the differences of the K_∞ values are less than or equal to 0.2% for all three nuclear data libraries of the WIMS7B code.

- The differences of the K_∞ values are more significant at hot temperature (about 0.6%) comparing with those obtained for the room one (about 0,3%). This result, however, does not hold for APOLLO-2 and CASMO-4 codes.

- In the APOLLO-2 code, VVER-1000 assembly is calculated by the interface current method with solving transport equation within a cell by the collision probability method. The interface current method uses approximation of the uniform and isotropic angular flux (UP0) (Lazarenko, 2000). Since the VVER-1000 assembly is very heterogeneous, approximation of the uniform and isotropic angular flux is likely to be insufficient for APOLLO-2 code. Perhaps, it is necessary to use a higher-order approximation of either uniform and anisotropic angular flux (UP1) or linear and isotropic angular flux (LP0) (Lazarenko, 2000).

- In the CASMO-4 code, the K_∞ values are systematically higher than those in the other codes for the assemblies with MOX fuel. The neutron data library of the CASMO-4 code is mainly based on the ENDF/B-IV files with some correction of resonance shielding for the Pu isotopes (Lazarenko, 2000). It seems that the Pu isotopes in the CASMO-4 code are the main reasons for that. Therefore, the Pu isotopes should be defined more precisely.

- The differences of the pin by pin power distribution between the WIMS7B and other codes for the VVER-1000 assembly with the UO_2 fuel and the absorber rods appear to be less than 2-3% (see Fig. 5).

3. CALCULATIONS OF VVER-440 ASSEMBLY BURNUP

The profiled VVER-440 assembly with the UO_2 fuel of two enrichments and the UO_2 fuel poisoned with gadolinium has been chosen for verification of the burnup process in the WIMS7B code. The VVER-440 assembly contains 120 pin cells with the UO_2 fuel of two enrichments (see Fig. 3), 6 pin cells with the UO_2 fuel poisoned with gadolinium and one central cell with a tube. Input data for the whole assembly and all pin cells are given in Table 10.

The profiled VVER-440 assembly (see Fig. 3) has been calculated by the CACTUS option of the WIMS7B code with three libraries of nuclear data: one library of the year 1986 (WIM86) and two libraries of the year 1996 (WIM96 has 69 groups and WIM172 has 172 groups). Calculations obtained by the CACTUS option have been carried out in 16 energetic groups. K_∞ values obtained by the CACTUS option of the WIMS7B code, the TVS-M code and the MCU-REA Monte-Carlo code are shown in Table 11. The differences (in %) of the K_∞ values obtained for different codes from those of the WIM172 are given in Table11 and Fig.4.

From Table 11 and Fig. 4 one can draw the following conclusions:

- In the initial point of a burnup, the differences of K_∞ values between the WIMS7B results with all three libraries and the MCU-REA results are less than or equal to 0.1%. These differences are within the statistical error (0.1%) of the MCU-REA.

- The differences of the K_∞ values between the WIM96 and WIM172 results are within 0.1-0.2% in all points of a burnup from 0 to 50 Mwd/kgHE.

- The differences of the K_∞ values between the WIM86 and WIM96 results are within 0.2% from 0 to 20 Mwd/kgHE and then gradually increase up to 0.6% at 50 Mwd/kgHE.

- The differences of the K_∞ values between the WIM96, WIM172 and MCU-REA results are less than or equal to 0.1-0.2% up to 30 Mwd/kgHE and then increase to 0.5-0.7% at 50 Mwd/kgHE.

- The differences of the K_∞ values between the WIM86 and MCU-REA results are within ±0.3% up to 30 Mwd/kgHE and then decrease to 0.1-0.2% after a 30 Mwd/kgHE mark.

- The difference of the K_∞ values between the WIM172 and TVS-M results amounts to 0.3% at 0 Mwd/kgHE. Then this difference decreases to 0% at 5 Mwd/kgHE, rises up to 0.7% at 12 Mwd/kgHE mark and then declines to –0.9% at 50 Mwd/kgHE. In the end of a burnup we observe such picture how in a case of the VVER-1000 pin cell burnup (Laletin, 2000): the difference of the K_∞ values between the WIM172 and TVS-M results increases to 1.0% at 50 Mwd/kgHE. Perhaps the burnup process in the TVS-M code should be defined more precisely.

4. CONCLUSIONS

Calculations made for the VVER-1000 assembly benchmarks by WIMS7B with three different libraries of nuclear data have shown that differences of the K_∞ values obtained are sufficiently small. At the same time, differences of the K_∞ values between results obtained using different codes appear to be significant and should be taken into account in cross-section adjustment studies.

Calculations made for the VVER-440 assembly depletion benchmark by WIMS7B with three various libraries of nuclear data have shown that differences of the K_∞ values are not large. Moreover differences of the K_∞ values obtained using WIMS7B and MCU-REA codes are also not so large.

ACKNOWLEDGMENTS

Authors are grateful to the AEA Technology colleagues for giving an opportunity of working with the WIMS7B code and for fruitful consultations during the research. Authors are also thankful to Prof. N.I.Laletin and P. Mikolas for useful discussions and V.D. Sidorenko for providing us with the VVER-440 assembly burnup results obtained by the MCU-REA and TVS-M codes. The work was supported by the Russian Fund of Fundamental Researches, Grant N99-01-00348.

REFERENCES

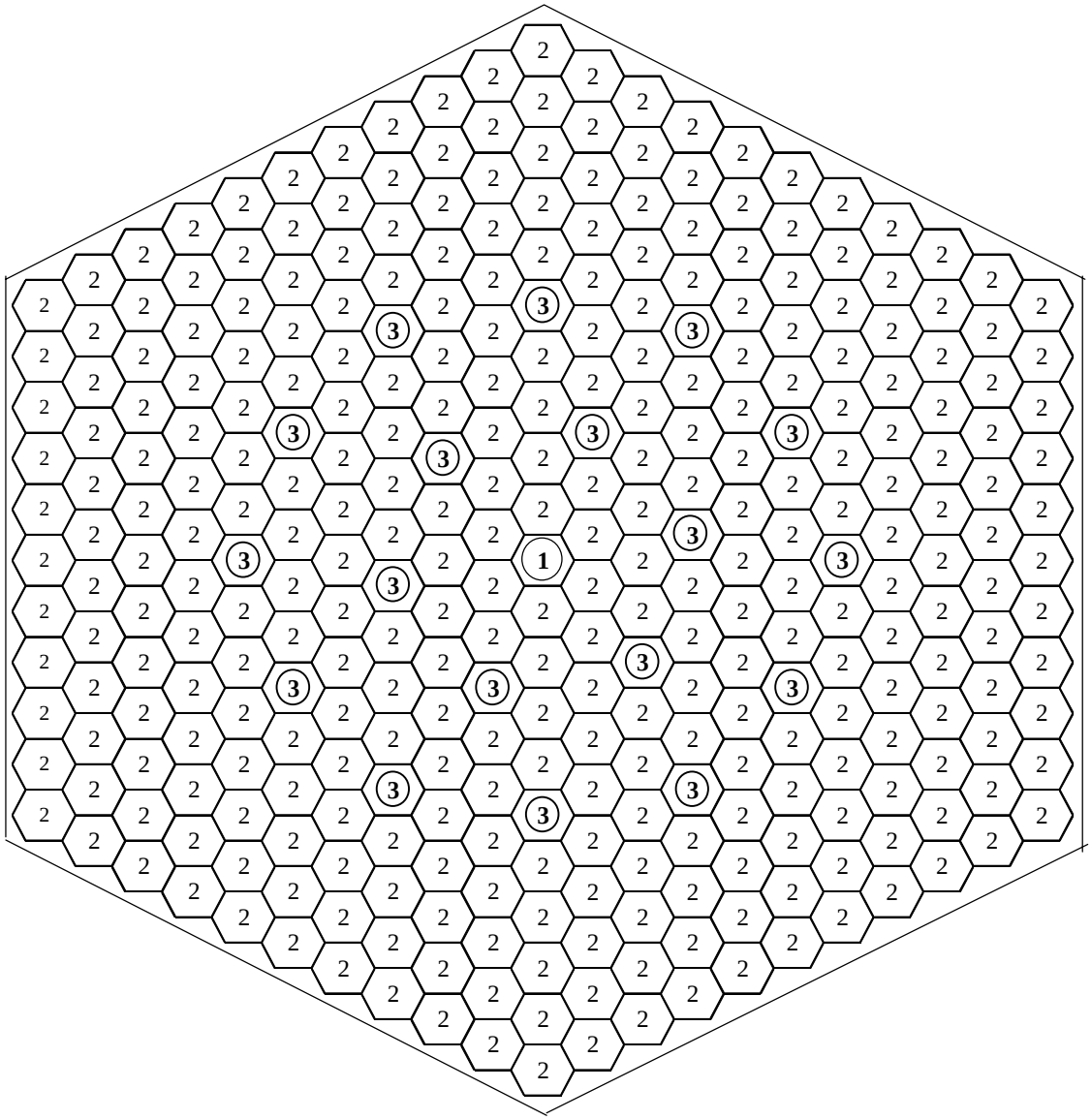
N.I.Laletin, N.V.Sultanov, 2000, Calculations of VVER Cells and Assemblies by WIMS7B Code, Proc. Int. 10 AER Symposium on VVER Reactor Physics and Reactor Safety, Sept. 18-22 2000, Moscow, Russia

A.Lazarenko, et al. 2000, Benchmark Calculations for VVER-1000 Fuel Assemblies Using Uranium or MOX Fuel, Proc. Int. Topical Meeting on Advances in Reactor Physics and Mathematics and Computation into the Next Millennium, May 7-12, 2000, Pittsburgh, Pennsylvania, USA

P. Mikolas, 2000, Spectral Calculations of VVER-440 FA with Gd Burnable Absorbers, Proc. Int. 10 AER Symposium on VVER Reactor Physics and Reactor Safety, Sept. 18-22 2000, Moscow, Russia

D. Powney, B. Franklin, 1998, Benchmarking of Square and Hexagonal Pitch Critical Assemblies Using WIMS. Proc. Int. Conf. on Nuclear Science and Technology, 5-9 Oct. 1998, Long Island, New-York, pp.1571-1578.

WIMS7B, 1996, A WIMS Modular Scheme for Neutronics Calculations. User Guide, ANSWERS/WIMS(95)4, Winfrith, UK.



Nomenclature: 1 – cell with a tube;
2 – cell with UO_2 fuel (3,7%);
3 – cell with a tube or an absorber rod.
Fuel assembly pitch is 23,6 cm. Lattice pitch is 1,275 cm.

Fig. 1. Cartogram of unprofiled fuel assembly of the VVER-1000 reactor

Table 1. Input data for the VVER-1000 pin cell with the UO_2 fuel

Zone number	Radius cm	Material	Nuclear density 10^{-24} cm^{-3}	Tempera-ture (^{0}K)
1	0.386 (3.7%)	U-235 U-238 O	8.6264E-4 2.2169E-2 4.6063E-2	300 (1027)
2	0.4582	Zr Hf Nb	4.259E-2 6.597E-6 4.225E-4	300 (575)
3	0.6694	H O B(natur. compos.) H O B(natur. compos.)	6.717E-2 3.358E-2 3.3578E-5 4.843E-2 2.422E-2 2.4214E-5	300 575

Table 2. Input data for the central cell with the tube.

Zone number	Radius cm	Material	Nuclear density 10^{-24} cm^{-3}	Temper-ture (^{0}K)
1	0.48	H O B(natur. compos.) H O B(natur compos.)	6.717E-2 3.358E-2 3.3578E-5 4.843E-2 2.422E-2 2.4214E-5	300 575
2	0.5626	Zr Hf Nb	4.259E-2 6.597E-6 4.225E-4	300 (575)
3	0.6694	H_2O	See composition of zone 1	300 (575)

Table 3. Input data for the VVER-1000 cell with the tube

Zone number	Radius cm	Material	Nuclear density 10^{-24} cm^{-3}	Temper-ture (^{0}K)
1	0.545	H O B(natur.compos.) H O B(natur. compos.)	6.717E-2 3.358E-2 3.3578E-5 4.843E-2 2.422E-2 2.4214E-5	300 575
2	0.6323	Zr Hf Nb	4.259E-2 6.597E-6 4.225E-4	300 (575)
3	0.6694	H_2O	See composition of zone 1	300 (575)

Table 4. Input data for the VVER-1000 cell with the absorber rod

Zone number	Radius cm	Material	Nuclear density 10^{-24} cm^{-3}	Temper-ature (^{0}K)
1	0.35	B_4C B (natur. compos.) C	 7.855E-2 1.964E-2	300 (575)
2	0.41	Zr Hf Nb	4.259E-2 6.597E-6 4.225E-4	300 (575)
3	0.545	H_2O	See composition of zone 5	300 (575)
4	0.6323	Zr alloy	See composition of zone 2	300 (575)
5	0.6694	H O B(natur. compos.) H O B(natur. compos.)	6.717E-2 3.358E-2 3.3578E-5 4.843E-2 2.422E-2 2.4214E-5	300 575

Table 5. K_∞ values of VVER-1000 unprofiled assembly with the UO_2 fuel.

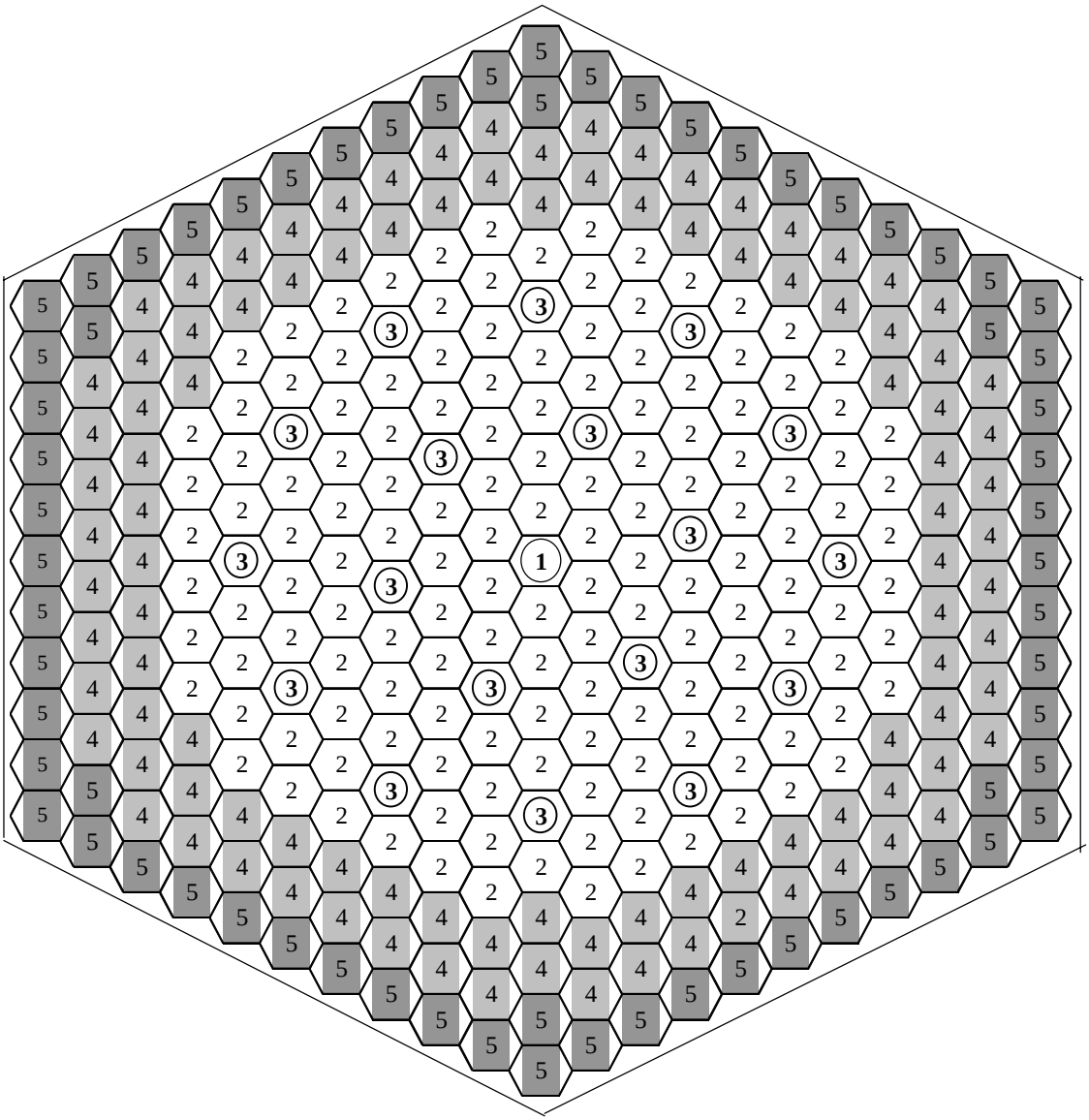
Tempe-rature	K_∞ *)							
	WIMS7B		APOL-LO-2	TVS-M	MCU-REA	CASMO-4	CONKE-MO	MCNP
	Library	CACTUS						
Fuel 1027^{0}K Other 575^{0}K	86y. (69gr.) 96y. (69gr.) 96y. (172gr.)	1,2845 (0,1) 1,2848 (0,1) 1,2835	1,2939 (0,8)	1,2858 (0,2)	1,2865 (0,2)	1,2843 (0,1)	1,2843 (0,1)	1,2918 (0,6)
All 300^{0}K	86y. (69gr.) 96y. (69gr.) 96y. (172gr.)	1,3296 (0,2) 1,3293 (0,2) 1,3273	1,3354 (0,6)	1,3241 (-0,2)	1,3260 (-0,1)	1,3243 (-0,2)	1,3316 (0,3)	1,3314 (0,3)

*) In brackets the percentage difference of the given value from the one of the WIMS7B code with the 172 group library is shown.

Table 6. K_∞ values of VVER-1000 unprofiled assembly with the UO_2 fuel and absorber rods.

Tempe-rature	K_∞ *)						
	WIMS7B		CONKE-MO	TVS-M	MCU-REA	CASMO-4	KENO
	Library	CACTUS					
Fuel 1027^{0}K Other 575^{0}K	86y. (69gr.) 96y. (69gr.) 96y.(172gr.)	0,9306 (-0,1) 0,9337 (0,2) 0,9317	0,9336 (0,2)	0,9360 (0,5)	0,9355 (0,4)	0,9403 (0,9)	-

*) In brackets the percentage difference of the given value from the one of the WIMS7B code with the 172 group library is shown.



Nomenclature: 1 – cell with a tube;
2 – cell with MOX fuel (4,2% wt Pu);
3 – cell with a tube or absorber rod;
4 – cell with MOX fuel (3,0% wt Pu);
5 – cell with MOX fuel (2,0% wt Pu).
Fuel assembly pitch is 23,6 cm.
Lattice pitch is 1,275 cm.

Fig. 2. Cartogram of profiled fuel assembly of the VVER-1000 reactor

Table 7. Input data for the VVER-1000 pin cell with the MOX fuel

Zone number	Radius cm	Material	Nuclear density 10^{-24} cm^{-3}	Temper-ture (^{0}K)
1	0.386	4.2w% Pu		300
		U-235	4.1652E-5	(1027)
		U-238	2.0522E-2	
		O	4.3043E-2	
		Pu-239	8.9071E-4	
		Pu-240	5.7225E-5	
		Pu-241	9.4980E-6	
		3.0 w% Pu		
		U-235	4.2209E-5	
		U-238	2.0797E-2	
		O	4.3045E-2	
		Pu-239	6.3621E-4	
		Pu-240	4.0875E-5	
		Pu-241	6.7842E-6	
		2.0 w% Pu		
		U-235	4.2672E-5	
		U-238	2.1025E-2	
		O	4.3047E-2	
		Pu-239	4.2414E-4	
		Pu-240	2.7250E-5	
		Pu-241	4.5228E-6	
2	0.4582	Zr	4.259E-2	300
		Hf	6.597E-6	(575)
		Nb	4.225E-4	
3	0.6694	H	6.717E-2	300
		O	3.358E-2	
		B(natur. compos.)	3.3578E-5	
		H	4.843E-2	575
		O	2.422E-2	
		B(natur. compos.)	2.4214E-5	

Table 8. K_∞ values of VVER-1000 profiled assembly with the MOX fuel.

Tempe-rature	K_∞ *)							
	WIMS7B		APOL-LO-2	TVS-M	MCU-REA	CASMO-4	CONKE-MO	MCNP
	Library	CACTUS						
Fuel 1027^0K	86y. (69gr.)	1,2363 (0,0)	1,2481 (1,0)	1,2501 (1,1)	1,2426 (0,5)	1,2523 (1,3)	1,2429 (0,5)	1,2478 (0,9)
Other 575^0K	96y. (69gr.)	1,2387 (0,2)						
	96y. (172gr.)	1,2362						
All 300^0K	86y. (69gr.)	1,3839 (-0,2)	1,3957 (0,7)	1,3900 (0,3)			1,3873 (0,1)	
	96y. (69gr.)	1,3895 (0,2)						
	96y. (172gr.)	1,3864						

*) In brackets the percentage difference of the given value from the one of the WIMS7B code with the 172 group library is shown.

Table 9. K_∞ values of VVER-1000 profiled assembly with the MOX fuel and the absorber rods,

Tempe-rature	K_∞ *)							
	WIMS7B		CONKE-MO	TVS-M	MCU-REA	CASMO-4	KENO	MCNP
	Library	CACTUS						
Fuel 1027^0K	86y. (69gr.)	0,9471 (0,2)	0,9485 (0,3)	0,9564 (1,1)	0,9506 (0,5)	0,9646 (2,0)	0,9505 (0,5)	0,520 (0,7)
Other 575^0K	96y. (69gr.)	0,9479 (0,2)						
	96y. (172gr.)	0,9455						

*) In brackets the percentage difference of the given value from the one of the WIMS7B code with the 172 group library is shown.

Table 10. Input data for VVER-440 profiled assembly with the U_2O and U-Gd pin cells.

Fuel assembly pitch, cm	14.7
Gap between assemblies, cm	0.3
Shell thickness, cm	0.15
Lattice pitch, cm	1.22
Fuel rod radius, cm	0.386
Clad thickness, cm	0.07058
Tube inner radius, cm	0.44
Thickness of tube, cm	0.07639
Fuel temperature, K	830
Temperature of other materials, K	558

Fuel density

	Type 1, U_2O 4.6%	Type 2, U_2O 3.3% Gd_2O_3 3.35%	Type 3, U_2O 4.0%
U235	9.76370E-4	8.18270E-4	8.49030E-4
U238	1.99930E-2	1.93910E-2	2.01190E-2
O	4.19390E-2	4.04190E-2	4.19360E-2
GD54		2.29790E-5	
GD55		1.56030E-4	
GD56		2.15480E-4	
GD57		1.63930E-4	
GD58		2.58510E-4	

Density of Zr alloy

	Zr	Nb	Hf
Clad	4.28138E-2	4.24759E-4	6.63241E-6
Tube	4.28138E-2	4.24759E-4	6.63241E-6
Shell	4.21649E-2	1.06190E-3	6.63241E-6

Moderator density

Tempera-ture	H	^{16}O	^{10}B	^{11}B
	C_B= 400 ppm			
558K	5.02200E-2	2.51100E-2	3.31400E-6	1.34234E-5

The burnup range of the VVER-440 assembly is 0- 50 000 MWd/tHM
The specific power of assembly is 86.28 MW/m^3.

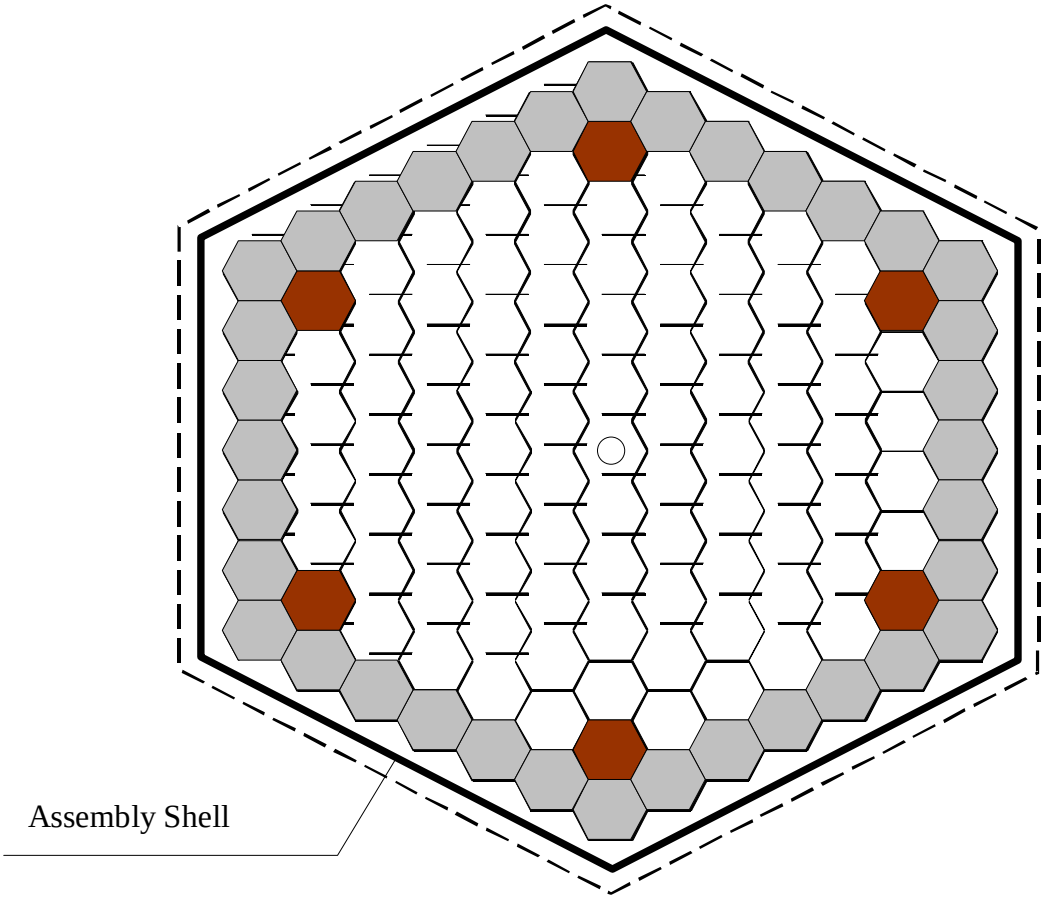


Fig. 3. Cartogram of profiled fuel assembly of the VVER-440 reactor

Central cell with tube

Fuel cell of type 1 (enrichment 4.6%)

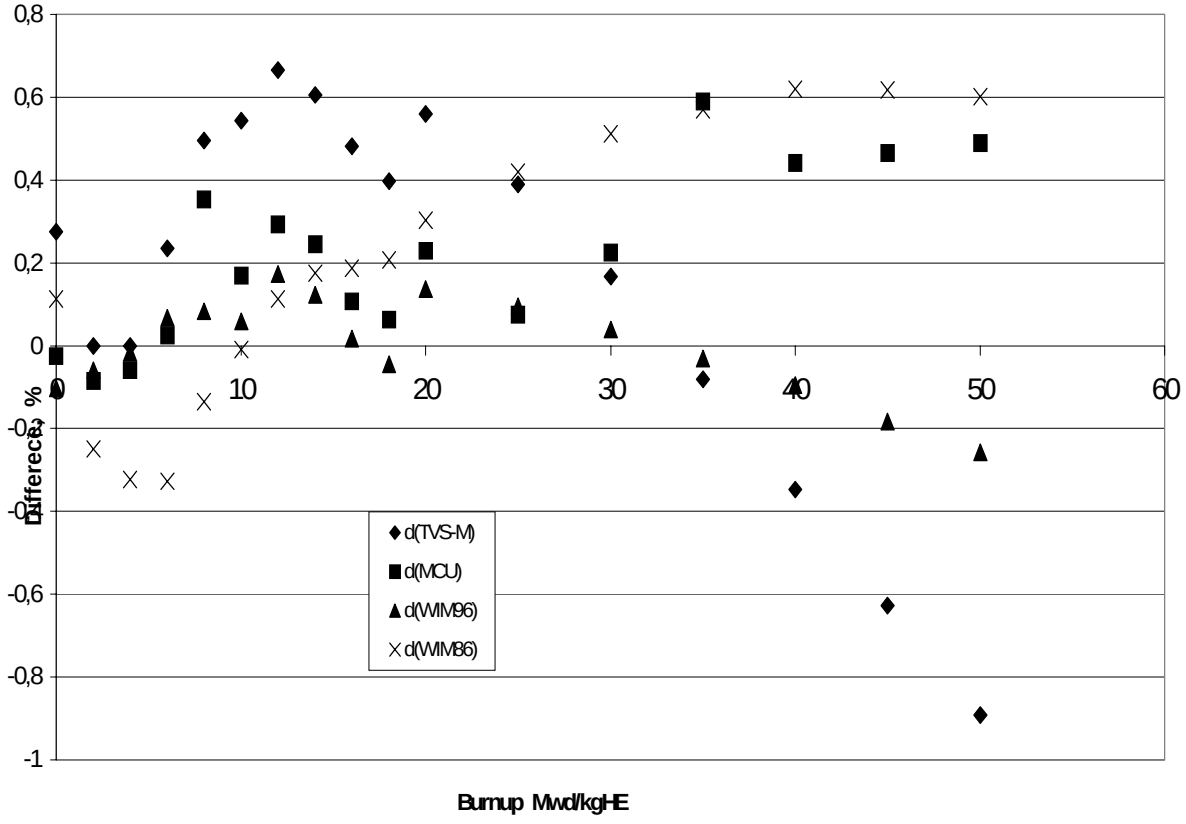
Fuel cell of type 2 (with 3.35% Gd_2O_3)

Fuel cell of type 3 (enrichment 4.0%)

Table 11. K_∞ values and deviations from results of WIM172 in %.

B ,Mwd/kg	TVS-M	MCU	WIM96	WIM86	WIM172	d(TVS-M)	d(MCU)	d(WIM96)	d(WIM86)
0	1,161	1,1575	1,1566	1,1591	1,1578	0,276386	-0,02591	-0,10364	0,112282
2	1,1684	1,1674	1,1677	1,1655	1,1684	0	-0,08559	-0,05991	-0,2482
4	1,1787	1,178	1,1785	1,1749	1,1787	0	-0,05939	-0,01697	-0,32239
6	1,1912	1,1887	1,1892	1,1845	1,1884	0,235611	0,025244	0,067317	-0,32817
8	1,1942	1,1925	1,1893	1,1867	1,1883	0,496508	0,353446	0,084154	-0,13465
10	1,1818	1,1774	1,1761	1,1753	1,1754	0,544495	0,170155	0,059554	-0,00851
12	1,1637	1,1594	1,158	1,1573	1,156	0,66609	0,294118	0,17301	0,112457
14	1,1454	1,1413	1,1399	1,1405	1,1385	0,606061	0,245938	0,122969	0,17567
16	1,1277	1,1235	1,1225	1,1244	1,1223	0,481155	0,106923	0,017821	0,187116
18	1,1107	1,107	1,1058	1,1086	1,1063	0,397722	0,063274	-0,0452	0,2079
20	1,0943	1,0907	1,0897	1,0915	1,0882	0,560559	0,229737	0,137842	0,303253
25	1,055	1,0517	1,0519	1,0553	1,0509	0,390142	0,076125	0,095157	0,418689
30	1,0179	1,0185	1,0166	1,0214	1,0162	0,16729	0,226333	0,039362	0,51171
35	0,9828	0,9894	0,9833	0,9892	0,9836	-0,08133	0,589671	-0,0305	0,569337
40	0,9495	0,957	0,9519	0,9587	0,9528	-0,34635	0,440806	-0,09446	0,619228
45	0,9182	0,9283	0,9223	0,9297	0,924	-0,62771	0,465368	-0,18398	0,616883
50	0,8891	0,9015	0,8948	0,9025	0,8971	-0,89176	0,490469	-0,25638	0,60194

Fig. 4. Deviations of the Kinf. value of the VVER-440 assembly from the WIM172 results



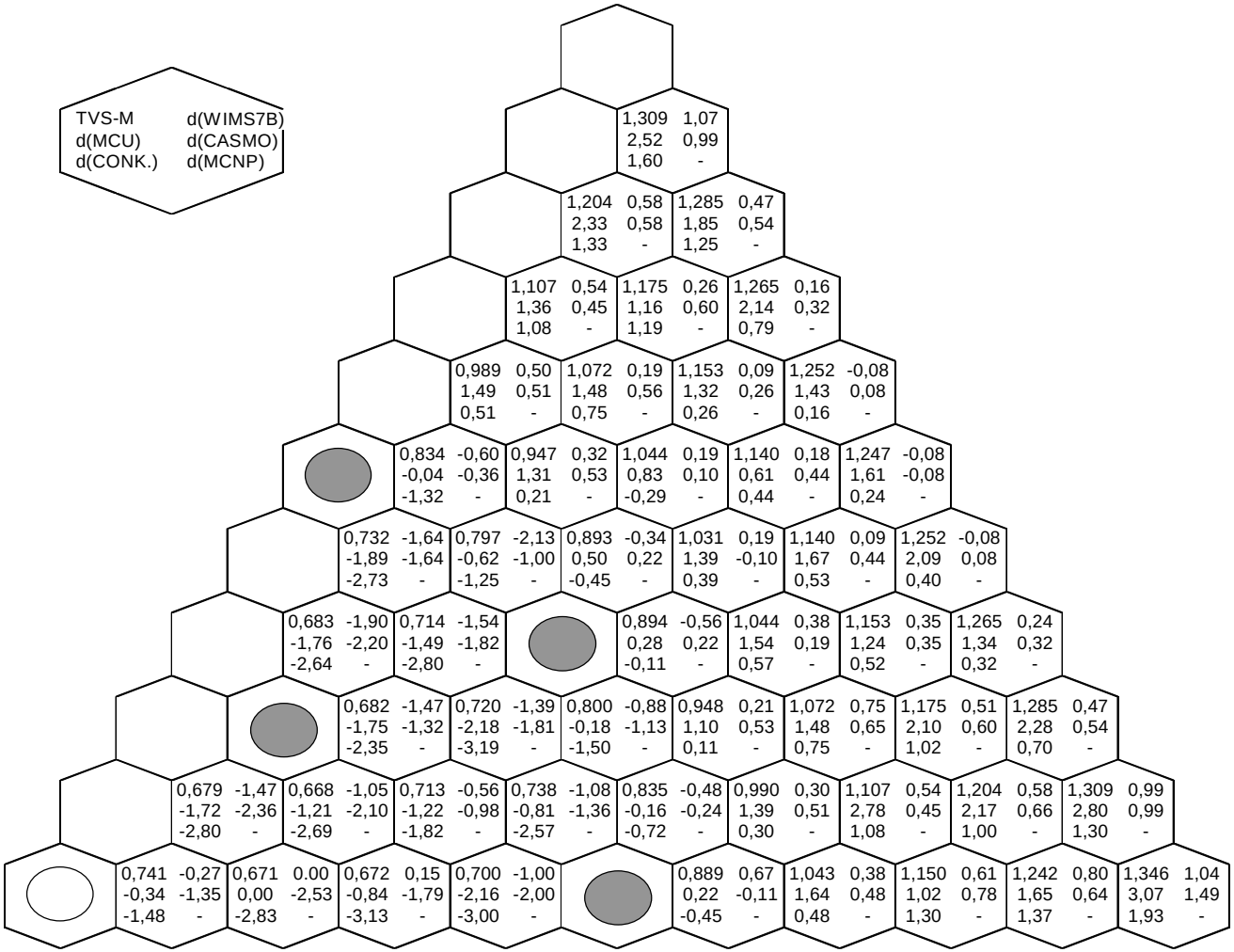


Fig. 5. Pin by pin power distribution calculated with TVS-M codes and deviations of other code results (%) in the UO2 assembly with absorber rods