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TRIPOLI4 SOLUTIONS OF VVER-1000 ASSEMBLY AND CORE BENCHMARKS

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ABSTRACT

The OECD VVER-1000 LEU and MOX assembly benchmark and two whole core benchmarks of the NURESIM European project were solved by TRIPOLI4. The objective is to test the code against consistent MCNP4B and APOLLO2 MOC simulations and to produce reliable reference solutions. The assembly benchmark model consists of a uniform UO_2 fuel assembly with 12 U-Gd rods and a profiled MOX fuel assembly with 12 U-Gd rods. These assemblies are typical of the advanced designs for VVER-1000 reactors and are similar to the designs that are expected to be used in the plutonium disposition mission. The 2D core benchmarks include fresh and depleted core calculations at zero power. TRIPOLI4 results were compared with available MCNP4B solutions from the OECD assembly benchmark report and APOLLO2 solutions by the higher-order linear surface method of characteristics (LS MOC). The comparison shows a good overall agreement with the MCNP4B and APOLLO2 solutions.

***Key words*:** TRIPOLI4, VVER-1000, assembly, core, benchmarks

1. INTRODUCTION

TRIPOLI4 is a general-purpose Monte-Carlo code [1], [2] used as reference tool by CEA as well as its partners and the NURESIM European project [3]. The code was used to solve VVER-1000 assembly and 2D core benchmarks for fresh and burnt fuel. These calculations are motivated by the need for reliable Monte-Carlo reference solutions.

It is well known that VVER-1000 is characterized by high dominance ratio which is a challenging issue in critical mode calculations. These simulations are contaminated by a cycle-to-cycle correlation that slows down the convergence of the fission source. The computed flux and power distributions can be degraded by flux oscillations and tilts [4]. In order to account for the effect of these oscillations in whole core solutions, a "super-cycle" post-processing technique [5] was applied.

We consider TRIPOLI4 assembly and core solutions in comparison with available MCNP4B assembly solutions from ref. [6] and deterministic solutions from refs. [7], [8], [9] obtained by the higher-order linear surface method of characteristics (LS MOC) [10] in APOLLO2 [11].

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2. VVER-1000 ASSEMBLY CALCULATIONS

The OECD VVER-1000 LEU and MOX assembly computational benchmark [6] was chosen as reference problem. The benchmark model consists of a uniform UO2 fuel assembly with 12 U-Gd rods and a profiled MOX fuel assembly with 12 U-Gd rods. These assemblies are typical of the advanced designs for VVER-1000 reactors and are similar to the designs that are expected to be used in the plutonium disposition mission. The states to be calculated are listed in Table I where Eq. means equilibrium values of ^{135}Xe and ^{149}Sm. For the present analysis the task is to compute the k_{inf} values and the pin-wise power distribution at zero burn-up.

Table I. Calculation states

State	Description	Fuel temp, K	Non-fuel temp, K	^{135}Xe ^{149}Sm	Boron, ppm
S1	Operating poisoned state	1027	575	Eq	600
S2	Operating non-poisoned state	1027	575	0.0	600
S3	Hot state	575	575	0.0	600
S4	Hot state without boron	575	575	0.0	0.0
S5	Cold state without boron	300	300	0.0	0.0

TRIPOLI4 continuous energy solutions were compared with MCNP4B continuous energy results from ref. [6] and well converged solutions obtained by the authors using the linear surface method of characteristics (LS MOC) [7] in APOLLO2 [8]. JEF2.2 cross-sections have been used in all simulations. An exception is the use of ^{1}H, ^{16}O, ^{152}Gd and ^{nat}Zr cross-sections from ENDFB6 in the MCNP4B calculation. The APOLLO2 simulation options were 172-group self-shielding calculation and 172-group LS MOC calculation with P1-scattering, 3 polar levels, 24 basic azimuth angles, 0.04 cm tracking step and automatic subdivision of all surfaces over a threshold size of 0.5 cm.

The TRIPOLI4 solutions were obtained with 100,000,000 particle histories and batch size of 1000 particles. The standard deviation is below 0.00012 for k-infinity (using the collision estimator) and 0.10 - 0.15% for the relative pin powers. The MCNP4B solutions [6] were obtained with 1,000,000 particle histories.

2.1. U-Gd assembly

TRIPOLI4 results for k-infinity are shown in Table II, in comparison with MCNP4B results from ref. [6]. Good agreement is displayed.

S2 state: Figure 1 shows the relative TRIPOLI4-MCNP4B differences in the computed pin-wise fission rates. The maximal in modulus difference is 1.2% and the average in modulus deviation is 0.44%. The difference in k-infinity is +2 pcm.
Figure 2 shows the relative APOLLO2-TRIPOLI4 differences in the computed pin-wise fission rates. The maximal in modulus difference is 1.3% and the average one is 0.26%. The difference in k-infinity is +30 pcm.

Table II. Multiplication factor

State	MCNP Kinf	TRIPOLI4 Kinf	T4 - MCNP pcm
UGD			
S2	1.18000	1.18002 ± 0.00011	+2
S3	1.19250	1.19401 ± 0.00011	+151
S4	1.25310	1.25452 ± 0.00011	+142
S5	1.32350	1.32363 ± 0.00012	+13
MOXGD			
S2	1.19220	1.19298 ± 0.00010	+78
S3	1.20910	1.21015 ± 0.00010	+104
S4	1.24300	1.24508 ± 0.00011	+208
S5	1.32560	1.32558 ± 0.00010	-2

S5 state: Figure 3 shows a TRIPOLI4-MCNP4B comparison of the computed pin-wise fission rates for the S5 state. The maximum in modulus difference is 1.1% and the average one is 0.36%. The difference in k-infinity is +13 pcm.
The comparison with MCNP4B shows good agreement in k-infinity and the pin powers.

2.2. MOX-Gd assembly

TRIPOLI4 results for k-infinity are shown in Table II, in comparison with MCNP4B results from ref. [6]. Acceptable overall agreement is displayed.

S2 state: Figure 4 shows the relative TRIPOLI4-MCNP4B differences in the computed pin-wise fission rates. The maximal in modulus TRIPOLI4-MCNP4B difference is 1.48% and the average in modulus deviation is 0.49%. The difference in k-infinity is +78 pcm.

S4 state: Figure 5 shows the APOLLO2-TRIPOLI4 comparison of pin-wise fission rates. The maximum in modulus difference is 1.29% and the average one is 0.49%. The difference in k-infinity is +83 pcm.
The comparison with MCNP4B shows an acceptable agreement in k-infinity and good agreement in the pin powers.

2.3. Discussion

Part of the differences in the TRIPOLI4 and MCNP4B results is attributed to the larger number of particle histories used by TRIPOLI4 and certain differences in the ^{1}H, ^{16}O, ^{nat}Zr and ^{152}Gd cross-sections used in the MCNP simulation. As the LS MOC solution is well converged, the APOLLO2-TRIPOLI4 differences in k-infinity are mainly due to the 172-group energy meshing.

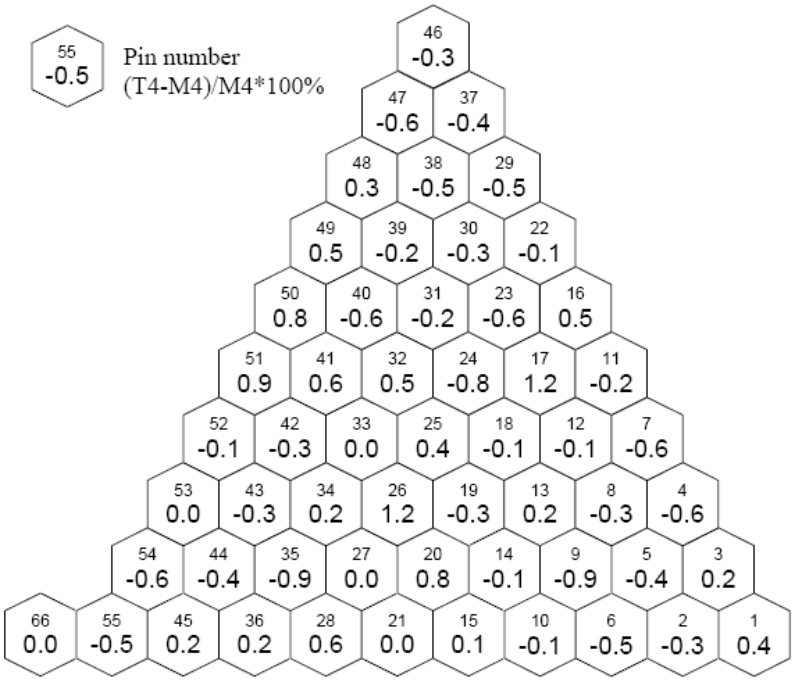

Figure 1 U-Gd assembly, S2. Relative difference of TRIPOLI4 to MCNP4B results
|δ| max = 1.2%, Average |δ| = 0.44%, δk = +2 pcm

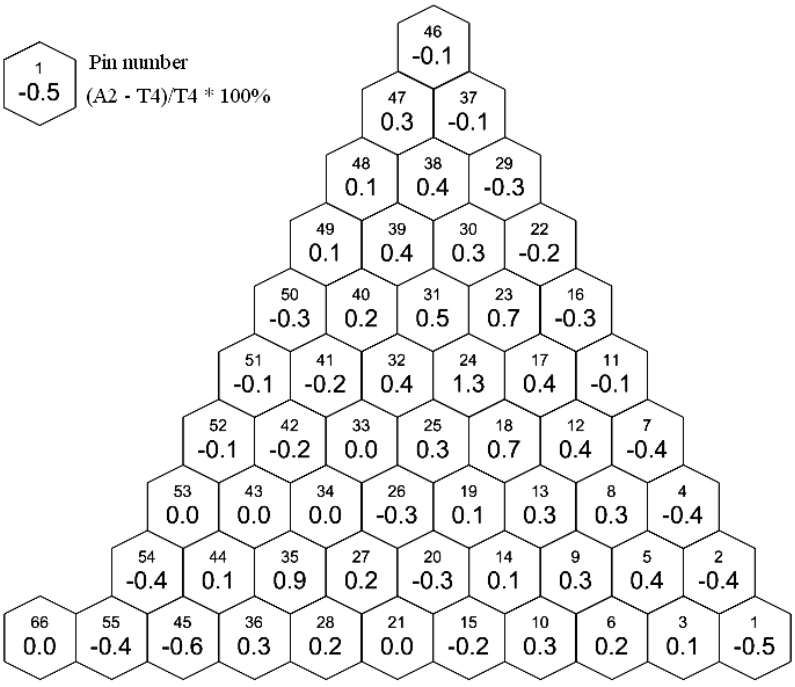

Figure 2 U-Gd assembly, S2. Relative difference of APOLLO2 toTRIPOLI4 results
|δ| max = 1.3%, Average |δ| = 0.68%, δk = +30 pcm

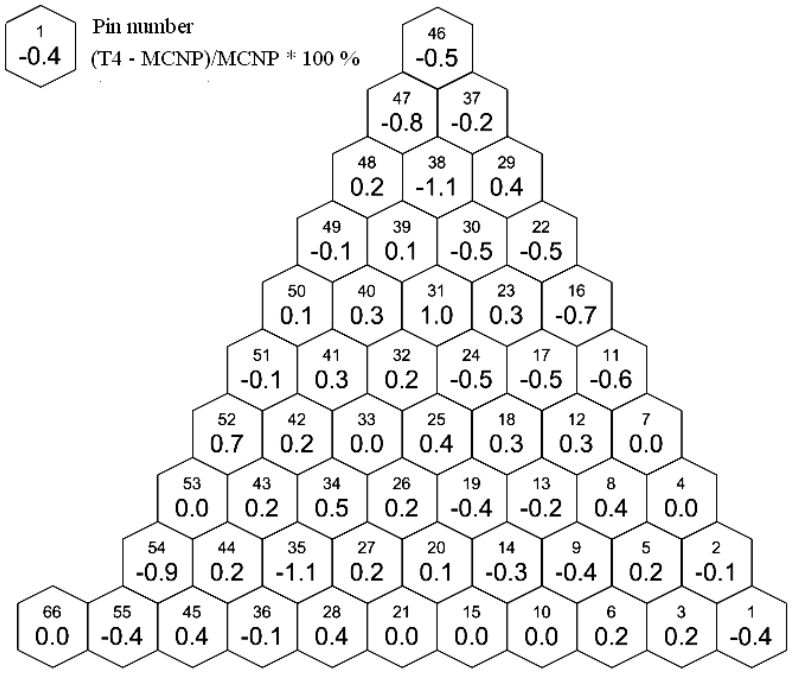

Figure 3 U-Gd assembly, S5. Relative difference of TRIPOLI4 to MCNP4B results
|δ| max = 1.1%, Average |δ| = 0.36%, δk = +13 pcm

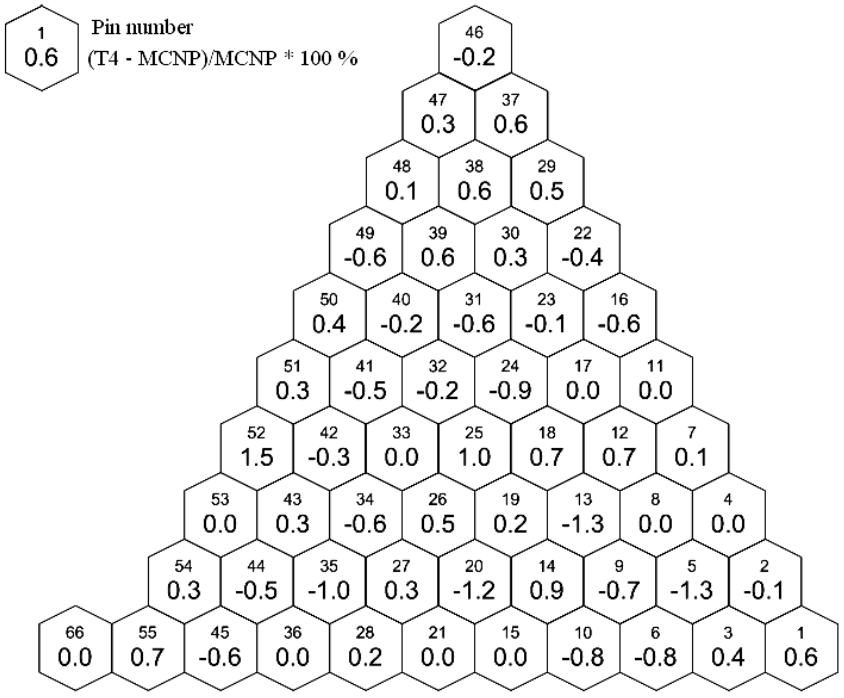

Figure 4 MOX-Gd assembly, S2. Relative difference of TRIPOLI4 to MCNP4B results
|δ| max = 1.48%, Average |δ| = 0.49%, δk = +78 pcm

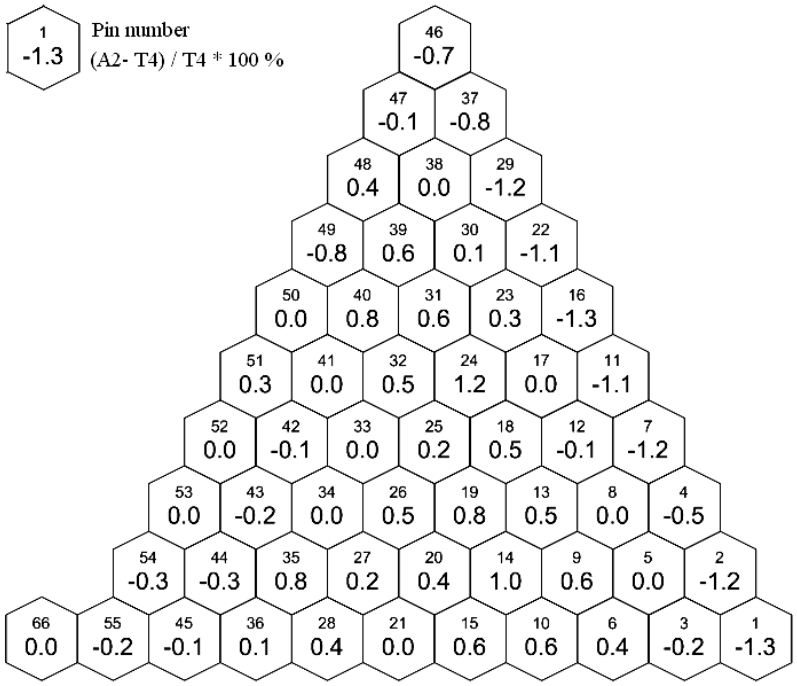

Figure 5 MOX-Gd assembly, S4. Relative difference of APOLLO2 toTRIPOLI4 results |δ| max = 1.29%, Average |δ| = 0.49%, δk = +83 pcm

3. VVER-1000 CORE SOLUTIONS

Two-dimensional problems for fresh and depleted VVER-1000 cores were solved. The objective is to test the TRIPOLI4 capabilities for a core characterized by high dominance ratio and to produce reliable reference solutions. We consider TRIPOLI4 continuous energy solutions of the V1000-2D-C1-tr benchmark [8], [12] and the V1000CT2-EXT1 benchmark [9] in comparison with APOLLO2 LS MOC solutions. JEF2.2 cross-sections were used in all simulations. The TRIPOLI4 calculation for the depleted core was performed with isotopic composition from APOLLO2. The domain of solution was 1/6 core with radial reflector containing 28 fuel assemblies as shown in Figure 6. The geometry models were prepared by the SILENE GUI [13].

Vacuum boundary conditions were imposed on the outer surface of the reactor vessel. The self-shielding in the reflector metal was taken into account in the APOLLO2 calculations. The TRIPOLI4 solutions were obtained by 64-processor runs and post-processing by “super-cycle” techniques to take into account the effect of cycle-to-cycle correlations on the real deviations of the reaction rates [5].

3.1. V1000-2D-C1-tr benchmark results

The V1000-2D-C1-tr benchmark loading pattern is described in Figure 7. The benchmark models a fresh VVER-1000 core at hot zero power, 575 K. Table III shows the TRIPOLI4 solutions for

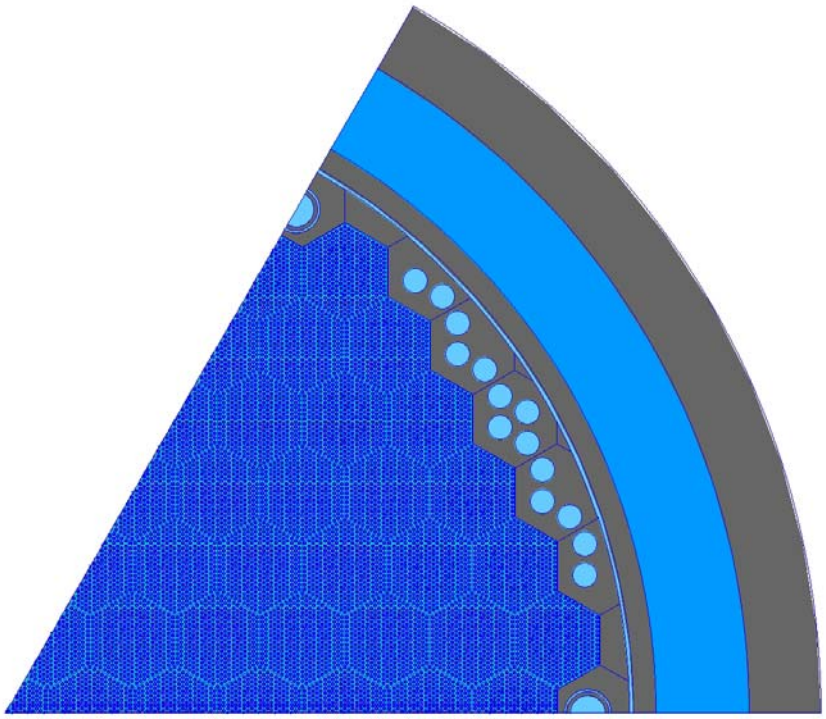

Figure 6 Domain of solution

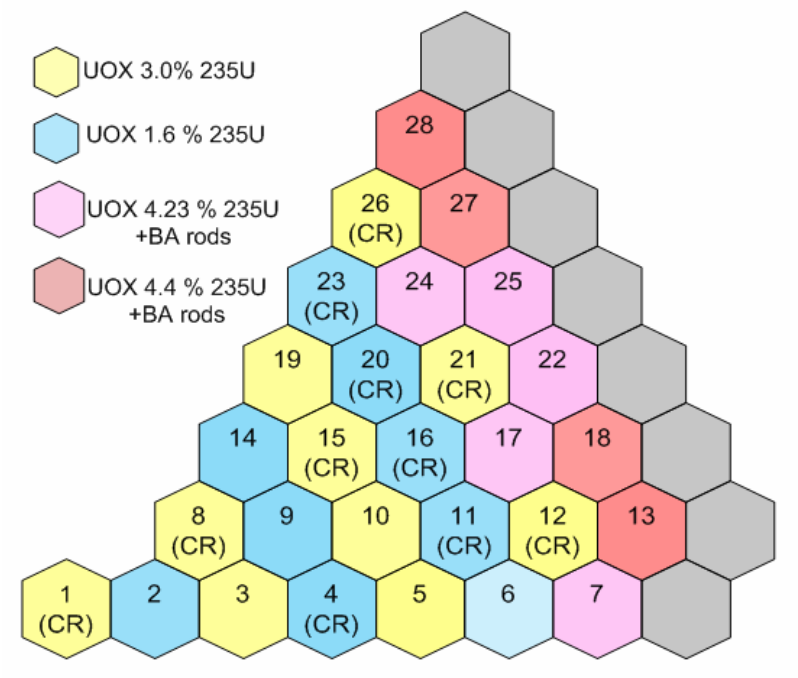

Figure 7 The V1000-2D-C1-tr benchmark loading pattern

Table III. V1000-2D-C1-tr benchmark: Keff and tripped rods worth

Parameter /state	TRIPOLI4 cont. energy	A2 LS MOC 172 groups	Discrepancies A2 – T4
Keff			
All rods OUT	1.05726 ±0.00003	1.05978	+252
All rods IN	0.96948 ±0.00003	0.97140	+192
TR worth, pcm			
All rods IN	8564 ± 3	8585	+21

Table IV. V1000-2D-C1-tr benchmark, ARO: assembly fission rates and Keff

FA #	TRIPOLI4 cont. en	Sigma	A2 LS MOC 281/26g	A2 –T4, %
1	1.047	0.17	1.024	-2.1
2	0.778	0.13	0.766	-1.5
3	1.203	0.10	1.191	-1.1
4	0.831	0.06	0.832	0.0
5	1.233	0.04	1.239	0.5
6	0.792	0.04	0.799	0.8
7	0.955	0.07	0.954	-0.2
8	1.200	0.11	1.186	-1.2
9	0.827	0.07	0.824	-0.4
10	1.251	0.06	1.253	0.2
11	0.839	0.06	0.845	0.8
12	1.146	0.09	1.149	0.2
13	0.668	0.11	0.662	-0.8
14	0.826	0.07	0.824	-0.2
15	1.253	0.05	1.256	0.3
16	0.869	0.04	0.875	0.8
17	1.311	0.06	1.317	0.5
18	0.886	0.09	0.881	-0.5
19	1.247	0.06	1.252	0.3
20	0.868	0.04	0.875	0.8
21	1.307	0.05	1.312	0.5
22	0.934	0.07	0.928	-0.4
23	0.836	0.06	0.843	0.8
24	1.309	0.06	1.316	0.5
25	0.933	0.07	0.929	-0.4
26	1.142	0.09	1.147	0.3
27	0.884	0.09	0.880	-0.5
28	0.666	0.11	0.661	-0.8
mean |δ|,%				0.62
Keff	1.05726 ± 0.00003		1.06049	δk = +323 pcm

Keff and tripped rods worth in comparison with the 172-group APOLLO2 solution from refs. [8], [15]. Generally good agreement is displayed. Part of the observed differences can be attributed to the energy meshing in APOLLO2.

The TRIPOLI4 solution for the assembly fission rates with all rods out (ARO) [14] is presented in Table IV in comparison with the APOLLO2 result. The solution was obtained by 64-processor run with 1,836,000,000 particle histories (244830 batches x7500 particles). The corresponding APOLLO2 solution was obtained by 281-group self-shielding calculation and 26-group LS MOC calculation with P1 scattering, 3 polar levels, 24 basic azimuth angles, 0.04 cm tracking step and automatic subdivision of all surfaces over a threshold size of 0.5 cm. Good agreement is displayed. The maximum discrepancy is 2.1 % and the average in modulus deviation is 0.62%.

The core power distribution is expected to be approximately symmetric with respect to the axis of symmetry formed by assemblies #1, 8, 15, 21. However, because of the contamination of the flux solution with higher azimuth and radial modes the solution has a slight azimuth tilt. The maximal residual tilt appears in assemblies #12 and #26. Using the super-cycle methodology to assess the real deviations in the power distribution, the observed tilt was estimated to be within 3σ-corrected for these assemblies (±0.27%), which is mathematically correct.

3.2 V1000CT2-EXT1 benchmark results

This benchmark is an extension of the OECD VVER-1000 MSLB benchmark (V1000CT-2) [16]. The objective is to provide a framework for testing heterogeneous core calculations for the V1000CT-2 reference core. The benchmark models MSLB related unrodded, fully rodded and stuck rod states at the EOL, 473 K and 55 ppm boron, near the coolant temperature minimum in a hypothetical MSLB transient.

The V1000CT2-EXT1 benchmark loading pattern is presented in Figure 8. The considered core consists of burnt UO_2 and UO_2+B fuel assemblies of the following types:

- A - Uniform UO_2 fuel assemblies of 3.3w/o 235U enrichment
- BH - Profiled UO_2 4.23w/o enriched assembly
- BA - Profiled UO_2 4.23w/o enriched assembly with 18 separable CrB_2 burnable absorber rods in the CR guide channels
- CH - Uniform UO_2 fuel assemblies of 4.4 235U enrichment
- CA- Uniform UO_2 4.4w/o enriched assembly with 18 separable CrB_2 burnable absorber rods in the CR guide channels.

Two TRIPOLI4 solutions were computed using atomic number densities from the APOLLO2 172 or 281-group burn-up calculations. The solutions were denoted TRIPOLI4/A2-172g and TRIPOLI4/A2-281g respectively. The simulation was performed on 64 processors with a total of 1398 million particle histories (186400 batches x 7500 particles) for theTRIPOLI4/A2-172g solution and 1087 million particle histories (144933 batches x 7500 particles) for the TRIPOLI4 /A2-281g solution.

Table V illustrates the TRIPOLI4 Keff values in comparison with APOLLO2 172g/20g and 281g/26g results. Good agreement is observed. The APOLLO2-TRIPOLI4 difference is +62 pcm in

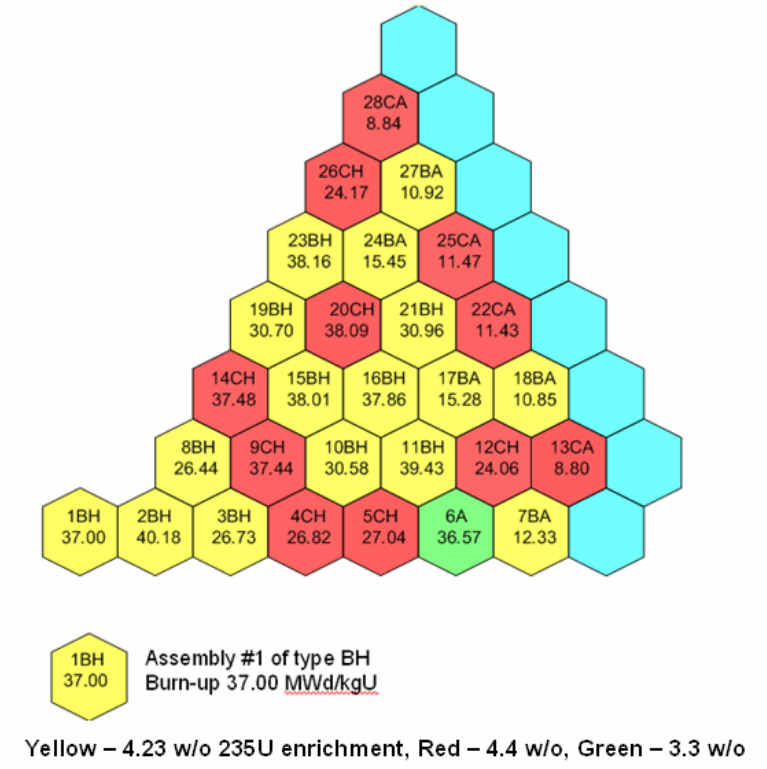

Figure 8 V1000CT2-EXT1 assembly types

case of 281g burn-up compared to +210 pcm for 172g burn-up. This indicates the importance of energy mesh refinement in depletion calculations.
Figure 9 shows the TRIPOLI4 /A2-172g solution for the assembly fission rates. The comparison of TRIPOLI4 and APOLLO2 results (done in ref. [14]) shows a good overall agreement in the assembly powers. The maximal difference of the APOLLO2 172/20g to TRIPOLI4/A2-172g solution is 2.4% and the average in modulus deviation is 1.04 %. The corresponding differences for the APOLLO2 281/26g to TRIPOLI4/A2-281g solution are 3.2% and 1.29 %.

Figure 10 shows the difference of TRIPOLI4/A2-172g results from the TRIPOLI4/A2-281g solution. The TRIPOLI-TRIPOLI comparison illustrates the significance of energy mesh refinement in depletion calculations.

Table V. Comparison of TRIPOLI4 and APOLLO2 solutions

Parameter	TRIPOLI4		A2 LS MOC		A2 – T4, pcm	
En. mesh: burn-up	172g	281g	172g	281g	172g	281g
En. mesh: core calc	cont	cont	20g	26g	20g	26g
Keff	1.05594 ± 0.00003	1.05729 ± 0.00003	1.05804	1.05791	+210	+62

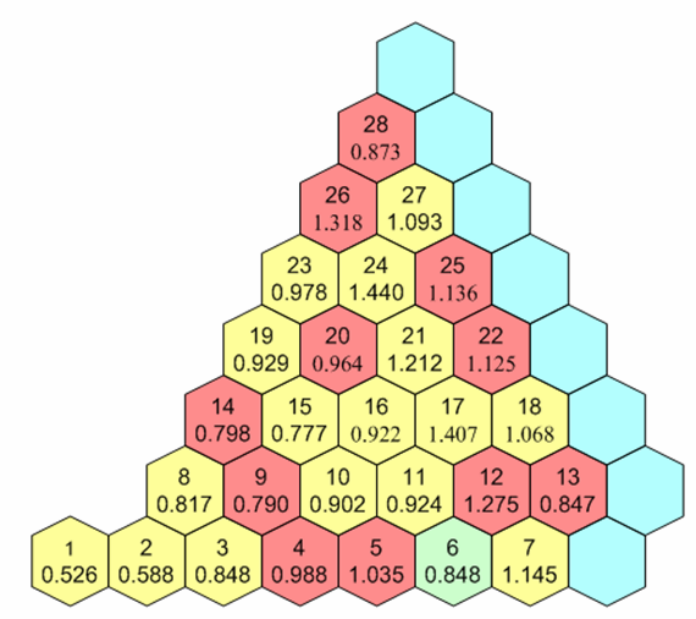

Figure 9 TRIPOLI4 /A2-172g solution of the V1000CT2-EXT1 benchmark

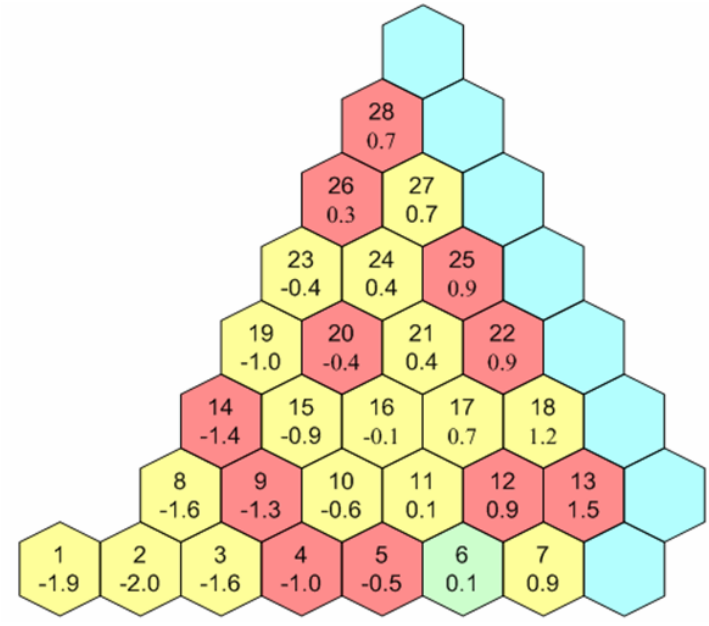

Figure 10 TRIPOLI4 /A2-172g -TRIPOLI4 /A2-281g differences. δk = -135 pcm

4. CONCLUSIONS

TRIPOLI4 solutions for VVER-1000 assemblies and 2D cores were tested in comparison with consistent MCNP4B and APOLLO2 MOC calculations.
The assembly results show an acceptable TRIPOLI-MCNP agreement in Keff and good agreement in pin powers. The TRIPOLI4 results agree well with the APOLLO2 LS MOC solutions.
The core calculations are in good overall agreement with the APOLLO2 LS MOC solutions. The whole core results can be further improved by applying super cycle techniques.

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