LATTICE PHYSICS CODES COMPARISONS FOR THE NEA BWR-MOX BENCHMARK

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ABSTRACT

This work presents the comparison of the results obtained with three different lattice physics codes (HELIOS, CPM-3 and MCNP-4B) for the Nuclear Energy Agency (NEA/OECD) benchmark of a Boiling Water Reactor (BWR) assembly using uranium - plutonium mixed oxide fuel (MOX). The objective of the work is to compare the performance of different state of the art transport codes based on different methodologies. The benchmark considers an advanced 10 X 10 BWR fuel assembly with a square central channel in the place of nine fuel rods and five rods with Gd_2O_3 as burnable absorber. The results show some differences in the neutron multiplication factor between the three codes due to the difference of the method of solution and the difference of their neutron energy group structure. A consistent trend is observed in the difference of the neutron multiplication factor between HELIOS and CPM-3 related to MCNP-4B, as the void percentage increases. A sensitivity study on the energy group structure shows the importance of the choice of the energy discretization in the multigroup calculations in MOX lattices. The maps of local fission rates show a quite good agreement between the codes; comparable to the differences obtained for UO_2 assemblies. Finally the results obtained in the burn-up calculations show a good agreement between HELIOS and CPM-3.

1. INTRODUCTION

Several utilities in different countries in the world are nowadays using plutonium as fuel material in Light Water Reactors (LWR); a great effort has been done by different organizations in order to update and improve their calculational methods for better modeling the plutonium in the assembly and in the core. In particular the Nuclear Energy Agency through the Nuclear Science Committee has proposed a benchmark[1] to evaluate the performance of reactor physics codes used in standard BWR lattice calculations, to be extended to the case of the utilization of MOX in current reactors. This benchmark considers an advanced 10 X 10 BWR fuel assembly with a square central channel in the place of nine fuel rods and five rods with Gd_2O_3 as burnable absorber. The plutonium characteristics are those of recycled plutonium obtained from UO_2 fuel with a discharge burn-up higher than 50 GWd/t, and that must be able to achieve a mean discharge burn-up up to 50 GWd/t. The higher enrichment in Pu fissile is 6.3%.

The presence of plutonium in the fuel of light water reactors and in particular in BWR can have different neutronic effects that can impact the core design. For instance the use of plutonium reduce the control rod worth due to the hardening of the neutron spectra. The presence of MOX fuel together with UO_2 fuel in the same core can produce important power peaking factors in the interface of these two types of assemblies, if a good core and assembly design is not done. From the point of view of the reactor physics codes and the nuclear data libraries (cross sections), the presence of plutonium, in particular Pu-239, Pu-240 and Pu-241 (with important resonances in the range of low energies) imposes the necessity to review the standard lattice physics methodology, the neutron energy discretization of the cross sections library and the self-shielding of resonant isotopes methodology.

2. METHODOLOGY

The codes used in this study are MCNP-4B[2], HELIOS[3] and CPM-3[4]. MCNP-4B is a well-known code, which use the Monte Carlo method for the solution of the transport equation and can use a discrete or a continuos energy library. HELIOS uses a very efficient Current Coupling Collision Probabilities method and a discrete energy library based on the ENDF/B-VI. Three different libraries are available depending on the number of energy groups (35, 90 and 190 energy groups). CPM-3 is also one of the advanced lattice physics codes, which uses either the collision probabilities method or the characteristics method for the solution of the transport equation. The basic cross section library has 97 energy groups based on the ENDF/B-VI and has the capability to condense to fewer energy groups for the transport solution of the problem.

All these three codes have the capability to solve the problem in the exact geometry without introducing any approximation (Wigner-Seitz, cells grouping, etc.) and taking into account explicitly any heterogeneity in the lattice (water tubes, gadolinia rods, etc.). The benchmark geometry was set up in each code in accord with its own methodology.

Following the benchmark specification, the calculations were done with the three codes at beginning of life (BOL) at hot full power (HFP) conditions with no Xenon (Xe) and uncontrolled, for four different void contents, 0%, 40%, 80% and 100%. Cold zero power (CZP) uncontrolled calculations were also performed at 0% void. Burn-up calculations were done with HELIOS and CPM-3 at HFP, uncontrolled, Xe in equilibrium and 40% voids until 50 GWd/t. A sensitivity study was also performed with HELIOS and CPM-3 on the number of neutron energy groups used in the nuclear data library.

The HFP conditions are fuel temperature 900 ^{o}K, clad temperature 600 ^{o}K, moderator temperature 559 ^{o}K and power density 25 W/g of heavy metals. A temperature of 293 ^{o}K is used for fuel, clad and moderator at CZP conditions. Number densities for uranium and plutonium isotopes in each different fuel rod in the lattice are also prescribed in the benchmark.

3. RESULTS

Results include the neutron multiplication factor, the power peaking factor, and the fission rate maps for the fresh assembly at different operating conditions and void contents. For the burn up calculations, the evolution of the number density as well as the evolution of the fission and capture cross sections of selected isotopes are also reported.

The HELIOS results presented in this work used the 190 energy groups library, and the CPM-3 calculations were done with 97 energy groups. The MCNP-4B calculations were performed with the continuos energy library based on the ENDF/B-V, since only with this version we had cross sections at 900 °K for the fuel and 600 °K for the clad and water. Therefore an additional analysis was done to evaluate the effect of the ENDF/B-V versus ENDF/B-VI in the MCNP calculations.

3.1 BOL Calculations

Table I shows the neutron multiplication factor obtained with the three codes at different operating conditions and the differences between MCNP and the other codes (last three columns). The standard deviation presented in the last row is calculated over the absolute value of the differences.

Table I. Neutron Multiplication Factor

BOL	MCNP-4B	HELIOS	CPM-3 MoC $^{+}$	CPM-3 CP $^{++}$	MCNP-HELIOS	MCNP-CPM3 MoC $^{+}$	MCNP-CPM3 CP $^{++}$
Hot, 0% V.	1.17159 ± 0.00062	1.15987	1.16796	1.17221	0.01172	0.00363	-0.00062
Hot, 40% V.	1.14212 ± 0.00061	1.13063	1.14010	1.14592	0.01149	0.00202	-0.00380
Hot, 80% V.	1.10970 ± 0.00059	1.10237	1.10936	1.11888	0.00733	0.00034	-0.00918
Hot, 100% V.	1.10024 ± 0.00057	1.09798	1.10010	1.11294	0.00226	0.00014	-0.01270
Cold, 0% V.	1.17317 ± 0.00061	1.1758	1.18928	1.18581	-0.00263	-0.01611	-0.01264
Average					0.00603	-0.00200	-0.00779
Std. Deviation					0.00458	0.00667	0.00541

$^{+}$ MoC: Method of Characteristics
$^{++}$ CP: Collision Probabilities

The results show some differences in the neutron multiplication factor between the three codes due to the difference of the method of solution and the difference of their neutron energy group structure, which take into account in different way the resonances of isotopes like Pu-239, Pu-240 and Pu-241.

These results show that HELIOS and CPM-3 follow the same trend as the spectrum changes (compared with MCNP). It can be observed that when the void percentage increases (spectrum hardening) the variation of the difference of the neutron multiplication factor between MCNP and the other codes shows a negative slope, as can be seen in figure 1 (curves 1, 2 and 3). The shape of the curve is similar for HELIOS (current coupling collision probabilities) and CPM-3 with the collision probabilities, but different to CPM-3 with the method of characteristic. This trend could be explained by the sensitivity, relative to the spectrum changes, of the multigroup approximation in the calculation of MOX fuel assemblies with HELIOS and CPM-3 and could be dependent on the transport solution method. This behavior has also been observed in some UO_2 lattices as is showed in figure 1 for HELIOS and CPM-3 with collision probabilities (curves 5 and 6).

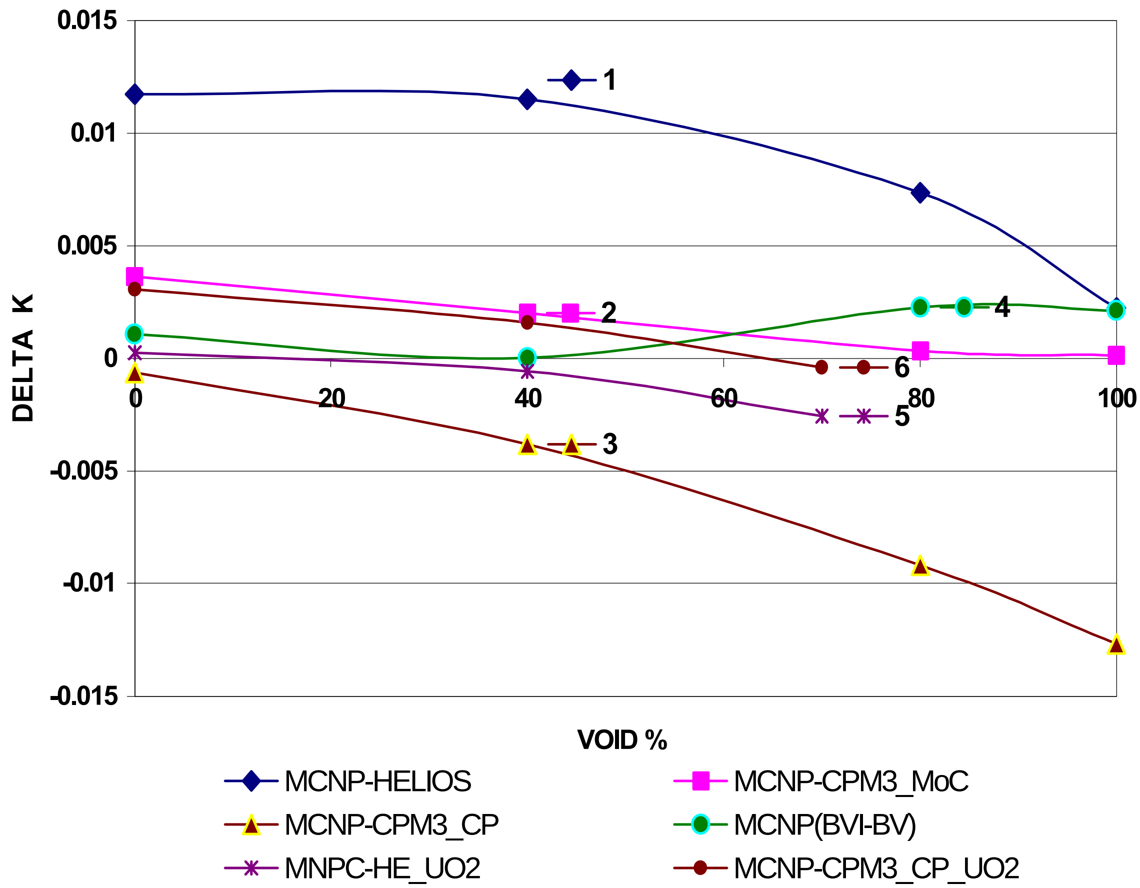

Figure 1. Variation of Delta K vs Void Percentage

Since the calculations of MCNP were done with an ENDF/B-V library and the calculations with HELIOS and CPM-3 with an ENDF/B-VI library, an additional analysis was performed with MCNP-4B comparing the neutron multiplication factor at different voids obtained with both libraries. In these two cases the fuel temperature was 300 °K. Table II shows the results obtained in these calculations, the values are quite close and do not show the same trend (negative slope) of the neutron multiplication factor in terms of the void percentage as can be seen in figure 1; where the neutron multiplication factor difference between the MCNP calculations with ENDF/B-VI and ENDF/B-V is also showed (curve 4).

Table III shows the fission rate peaking factor obtained with the three codes. The highest difference is showed in the cold case between the three codes and the values of CPM-3 with collision probabilities are in general lower than the other values. Local fission rates in each fuel rod in the assembly show a very good agreement between the three codes as can be seen in figure 2, with a standard deviation of the difference of all the rods close to 1.5%; which is comparable with values obtained for uranium lattices[5].

Table II. MCNP with ENDF/B-VI and ENDF/B-V libraries results

Void %	MCNP ENDF/B-VI	MCNP ENDF/B-V	K Difference BVI-BV
0	1.18388	1.18279	0.00109
40	1.1539	1.15388	0.00002
80	1.12494	1.12265	0.00229
100	1.1161	1.11397	0.00213

Table III. Power Peaking Factor

BOL	MCNP-4B	HELIOS	CPM-3 MoC +	CPM-3 CP ++
Hot, 0% V	1.254	1.236	1.223	1.228
Hot, 40% V	1.238	1.221	1.21	1.218
Hot, 80% V	1.231	1.233	1.223	1.199
Hot, 100% V	1.256	1.25	1.245	1.205
Cold, 0% V	1.371	1.319	1.252	1.261

+ MoC: Method of Characteristics
++ CP: Collision Probabilities

3.2 Burn up Calculations

Figure 3 shows the evolution of the main uranium and plutonium isotopes obtained with HELIOS and CPM-3. The results show that both codes perform very comparable and the agreement is very good. The same type of results are showed for the evolution of the fission and capture cross sections in figure 4 and figure 5.

3.3 Sensitivity Study

A sensitivity study was performed with the three different libraries of the HELIOS-1.4 version (34, 89 and 190 ENERGY groups). The results showed a difference of 261 pcm between the 34 energy groups and the 190 energy groups library. The difference between the 89 groups and the 190 groups library is negligible (25 pcm). Calculations with the new 35 energy groups working library of HELIOS-1.5 version, gave a difference of 76 pcm related to the 190 groups library result, which represents a higher improvement in the new energy group structure of the few groups library for MOX calculations.

Other study was carried out with CPM-3 (method of characteristics) using different energy groups in the transport solution. The results are presented in table IV. The values in this table show a good agreement between de 97 groups structure and the 33 groups result. The difference of the 21 energy groups calculation is also quite satisfactory. In CPM-3 the few energy groups transport solution is done with a collapsing spectra based on the 97 groups calculation performed at the first step; this can be the reason of these satisfactory results.

This study showed the importance of the choice of the neutron energy group structure, in particular in the thermal energy range near 1 eV in the plutonium resonances region.

	Standard Deviation
MC-HE	1,13%
MC-CP	1,51%
MC-MoC	1,88%

MC=MCNP-4A
HE=HELIOS
CP=CPM-3 Collision Probabilities
MoC=CPM-3 Method of Characteristics

-0,016 0,025 0,002									
-0,008 0,02 0	-0,02 0,001 -0,001								
-0,012 -0,007 -0,024	-0,01 -0,006 -0,002	0,012 0,009 0,026							
-0,005 -0,006 -0,024	-0,006 -0,009 -0,005	-0,012 -0,02 -0,005	-0,032 -0,044 -0,027						
0,003 -0,009 -0,023	0,005 0 0,004	0,002 0,002 0,011	-0,006 -0,027 -0,035						
0,009 -0,005 -0,022	-0,004 -0,011 -0,002	0,004 -0,001 0,012	0,02 0,009 0,013						
-0,007 -0,009 -0,026	-0,01 -0,017 -0,01	0,004 -0,003 0,012	0 -0,016 -0,021						
-0,01 -0,009 -0,025	-0,006 -0,004 0	0,001 -0,007 0,008	-0,01 -0,018 -0,002	0,006 0,003 -0,002	0,02 0,01 0,016	0,015 0 0,007	0,013 0,011 0,032		
-0,016 0,009 -0,011	-0,002 0,016 0,01	-0,013 -0,008 -0,002	-0,001 -0,005 0,009	0,013 0,011 0,023	0,022 0,017 0,032	0,007 0,007 0,024	0,012 0,013 0,033	0,003 0,02 0,037	
-0,018 0,023 -0,002	-0,011 0,015 -0,003	-0,014 -0,013 -0,025	0,003 0,001 -0,009	-0,01 -0,027 -0,033	-0,005 -0,021 -0,023	0,005 -0,003 -0,006	-0,005 -0,01 -0,008	0,004 0,023 0,021	-0,006 0,029 0,024

Figure 2. Local Fission Rates Differences, Hot Conditions, BOL, 40% Voids

Table IV. Energy groups sensitivity with CPM-3. HFP, BOL, 40% Voids

Energy groups	K-infinite	Diff. (pcm)
21	1.13899	95
33	1.13998	-5
97	1.13994	0

CONCLUSIONS

The results obtained in this work show a consistent and comparable behavior between the three codes. The multigroup approximation presented an appreciable impact in the neutron multiplication factor with the spectrum changes, and also shown the necessity to have a good selection of the neutron energy group structure if a working library is needed with few groups (30-40 groups). More studies will be performed on the modeling of the gadolinia burn-up for HELIOS and CPM-3 (more frequent burn-up intervals and more detailed radial and azimuthal meshing).

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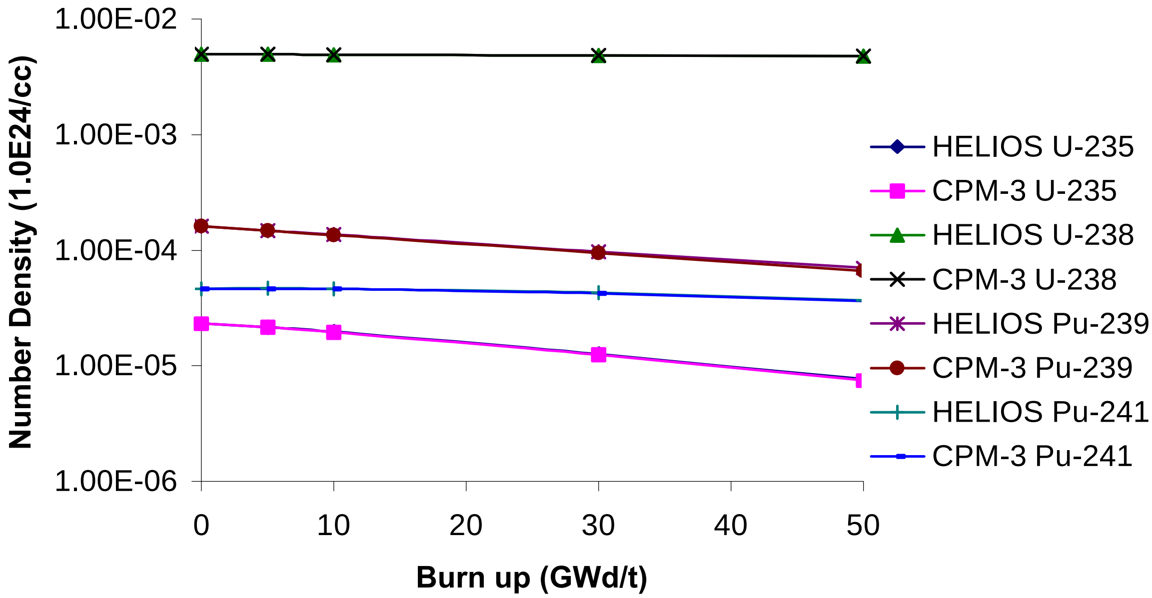

Figure 3. Evolution of the main uranium and plutonium isotopes

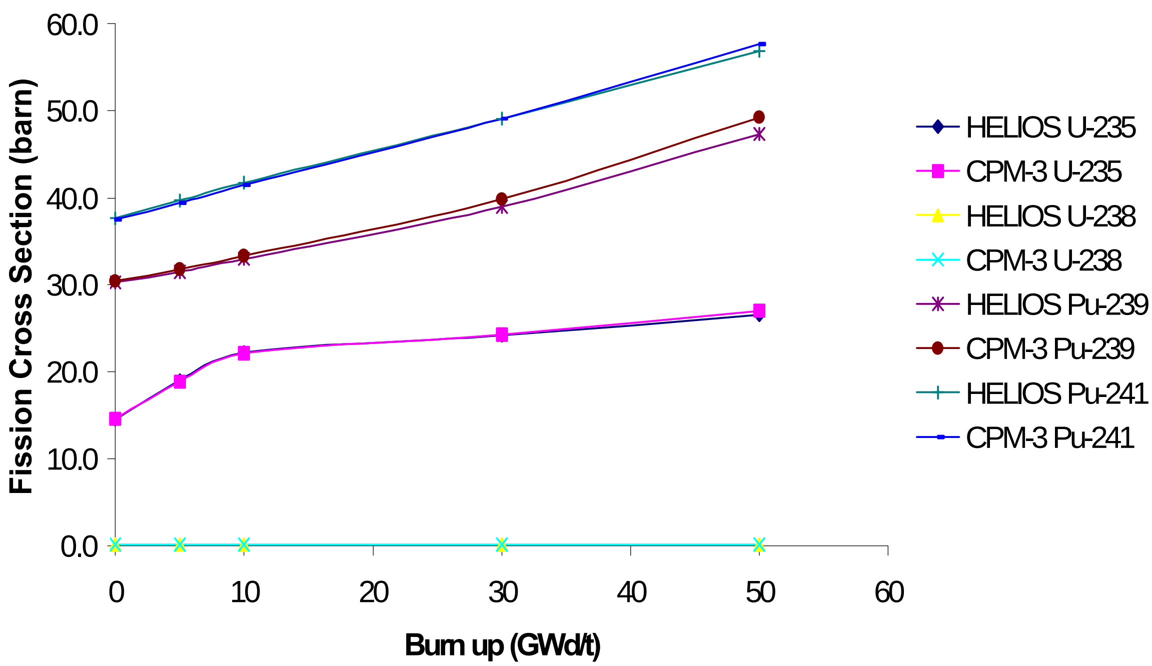

Figure 4. Evolution of the Fission Cross Section

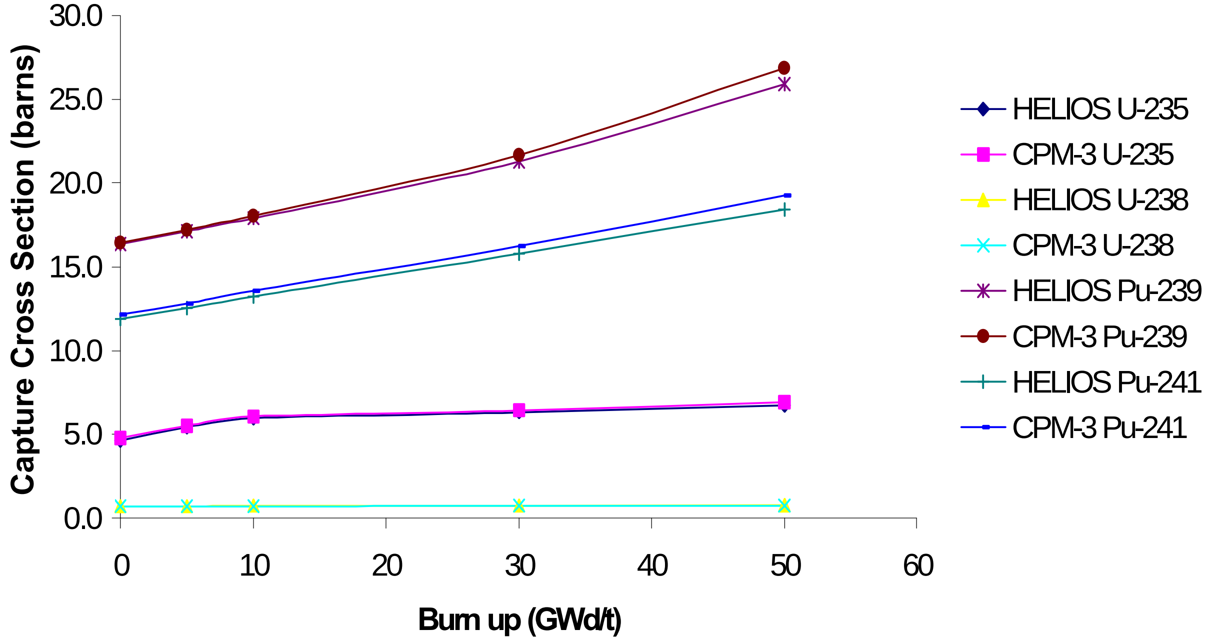

Figure 5. Evolution of the Capture Cross Section