NEPHTIS: 2D/3D Validation Elements Using MCNP4c and TRIPOLI4 Monte-Carlo Codes

Tanguy Courau*[1] and Enrico Girardi[1]
Frédéric Damian[2] and Mathilde Moiron-Groizard[2]

[1]*EDF R&D/SINETICS*
1 av du Général de Gaulle
F92141 Clamart CEDEX, France

[2]*DEN/DM2S/SERMA/LCA*
C.E.A Saclay
F91191 Gif-sur-Yvette CEDEX, France

Abstract

High Temperature Reactors (HTRs) appear as a promising concept for the next generation of nuclear power applications. The CEA, in collaboration with AREVA-NP and EDF, is developing a core modeling tool dedicated to the prismatic block-type reactor. NEPHTIS (NEutronics Process for HTr Innovating System) is a deterministic codes system based on a standard two-steps Transport-Diffusion approach (APOLLO2/CRONOS2). Validation of such deterministic schemes usually relies on Monte-Carlo (MC) codes used as a reference. However, when dealing with large HTR cores the fission source stabilization is rather poor with MC codes. In spite of this, it is shown in this paper that MC simulations may be used as a reference for a wide range of configurations. The first part of the paper is devoted to 2D and 3D MC calculations of a HTR core with control devices. Comparisons between MCNP4c and TRIPOLI4 MC codes are performed and show very consistent results. Finally, the last part of the paper is devoted to the code to code validation of the NEPHTIS deterministic scheme.

KEYWORDS: (V)HTR, MCNP, TRIPOLI, NEPHTIS, APOLLO2, CRONOS2, Deterministic Scheme Validation

1. Introduction

The CEA is developing a core modeling tool dedicated to the prismatic block-type reactor. NEPHTIS [1] is a deterministic codes system based on standard Transport-Diffusion approach using the codes APOLLO2 and CRONOS2. [2, 3] Due to the lack of usable experimental results, the reliability of the codes system used for the future HTR design studies is essentially based on comparisons with reference MC calculations. MC codes allow to model the core

*Corresponding author, Tel. (+33)147653882, E-mail: tanguy.courau@edf.fr

geometry without any physical approximations inherent to the deterministic approach: spatial and multigroup discretizations, resonant nuclides self-shielding. However, HTR fuel coated particles are dispersed in a graphite matrix which implies to deal with a stochastic geometry. Moreover, due to the large size of the core, some sources stabilization problems occur while calculating HTR core with MC codes.

In a previous paper, we presented the first part of this validation effort which was performed on various configurations: a fuel cell (a fuel compact surrounded by a graphite matrix), a standard fuel assembly, a 10 block column and a 2D annular core. [4] In this paper, we intend to extend our validation process to a 2D and 3D core with control devices. The first part is devoted to the neutronic analysis of the prismatic block-type VHTR core for various configurations. Here, we used the MC codes MCNP4c and TRIPOLI4 (developed at CEA). [5, 6] The configurations studied are representative of a 2D/3D annular core with inserted/extracted control rods. In the second part of the paper, the MC simulations are used to validate the HTR deterministic model by comparing the reactivities and the fission rates map.

2. General features

2.1 Computational Methods and Nuclear Data

The first part of the paper is dedicated to the VHTR modeling with MC codes. A comparison between MCNP4c and TRIPOLI4 is performed. The nuclear cross-sections associated with the materials in the core are point-wise data derived from JEF2.2 evaluation at the room temperature (300K) for an uranium fresh fuel. In order to avoid additional uncertainties, all geometrical parameters used are identical in both MC simulations.

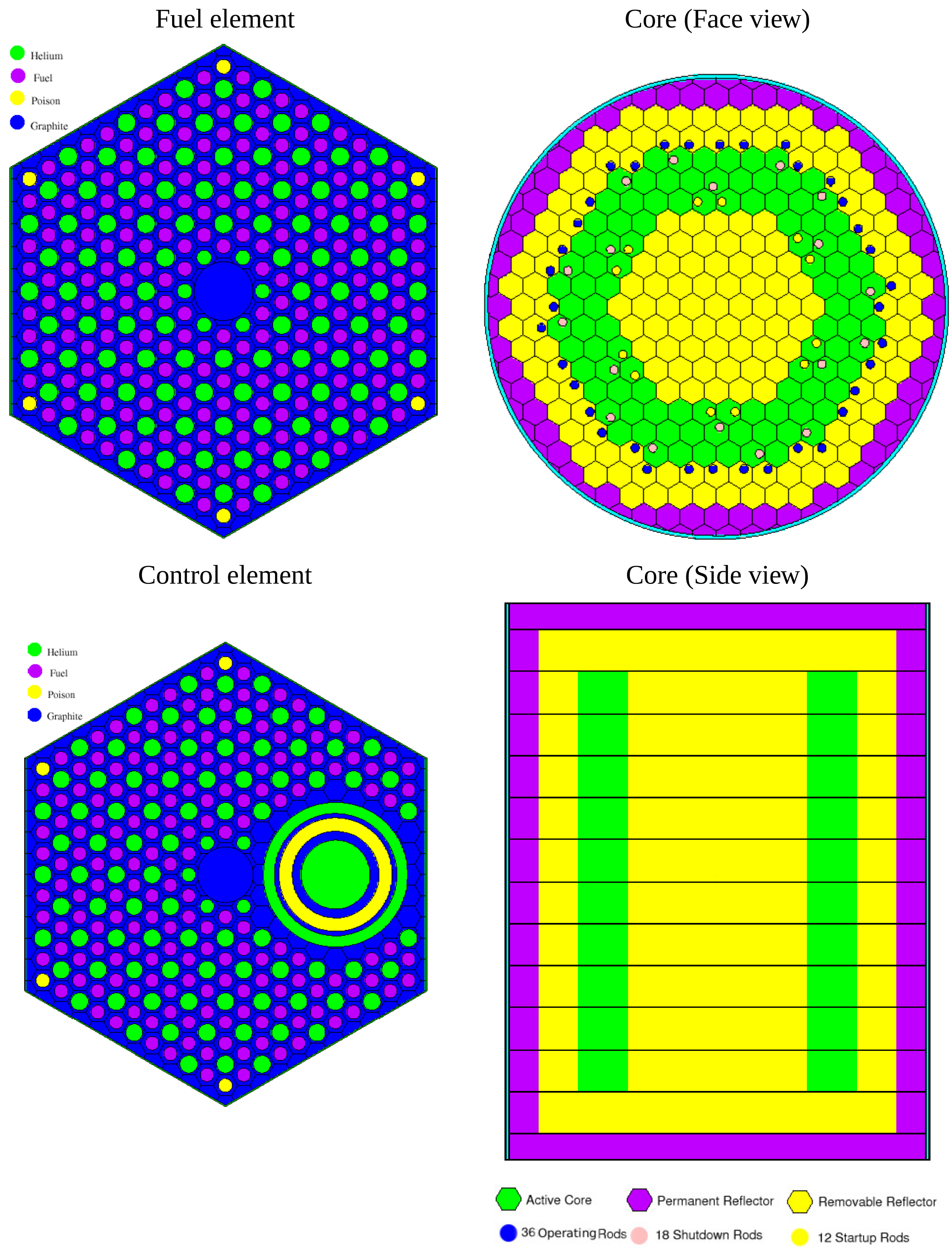
The core calculations are performed in 2D and 3D geometries, with diffusion theory (8 energy groups), using the CRONOS2 code. In these core calculations, the fuel element is homogenized and the flux is calculated considering 37 points in the prismatic block (linear flux interpolation). For the control element, 2 media are considered for the homogenization process, the number of points used for the flux calculation is then increased to 57. The fuel element cross-sections used in CRONOS2 are calculated by APOLLO2 in transport theory, using the probability collision method in a general geometry. A transport-diffusion equivalence procedure modifies the cross-sections calculated by APOLLO2. It ensures the reaction rates conservation between the transport (APOLLO2) and the diffusion (CRONOS2) calculation steps. NEPHTIS calculation scheme (NEutronic Process for HTr Innovating System) uses several CEA codes like: THEMIS/NJOY (cross-section production), APOLLO2 (transport), CRONOS2 (diffusion-transport) and TRIPOLI4 (MC calculations).

2.2 Configurations studied

The 2D and 3D core geometries are represented on Fig. 1. Depending on the control devices position and taking into account the fact that the shutdown rods are always extracted, the configurations studied are: all rods extracted, all startup rods inserted, all operating rods inserted and all rods inserted.

Results presented are the k_{eff}, its associated logarithmic control rod worth and the fission rate map. Discrepancies for k_{eff} are presented in pcm using : $\delta k_{eff} = 10^5(\ln k_{eff}^2 - \ln k_{eff}^1)$. Here, the superscripts 1 and 2 refer to the two states that are compared. For the other data, discrepancies are expressed in %. Due to symmetry properties, data are presented only on a fraction (1/6th) of the core.

Figure 1: Fuel element, Face and side views of the core



3. Monte-Carlo Calculations

In this section, results are presented for MCNP4c and TRIPOLI4 calculations in 2D and 3D configurations. Taking advantage of the symmetry, the uncertainty of the averaged fission rate is significantly reduced compared to local values. The number of particles simulated for MCNP4c calculations is equal to 5 millions to reach a variance (σ) less than 0.35% in 2D and 0.65% in 3D. These values are respectively less than 0.45% and 0.6% for TRIPOLI4 calculations with a number of particles simulated ranging from 3 to 8 millions depending on the configuration studied.

3.1 2D Analysis

Table 1 compares the k_{eff} and associated control rod worth for all the configurations studied.

Table 1: k_{eff} and control rods worth for the 2D core

Rods configuration	All rods out	Startup rods in	Operating Rods in	All rods in
	k_{eff} results – σ (pcm)			
MCNP4c	1.43472 (34)	1.33347 (35)	1.31610 (36)	1.15813 (40)
TRIPOLI4	1.43539 (54)	1.33600 (72)	1.31775 (70)	1.16116 (48)
δk_{eff} (pcm)	+47	+190	+125	+261
	Reactivity results: $\rho = \delta k_{eff}^{worth}$			
MCNP4c	0	-7319	-8630	-21416
TRIPOLI4	0	-7176	-8551	-21202
$\delta\rho$ (%)	–	-1.95	-0.92	-1.00

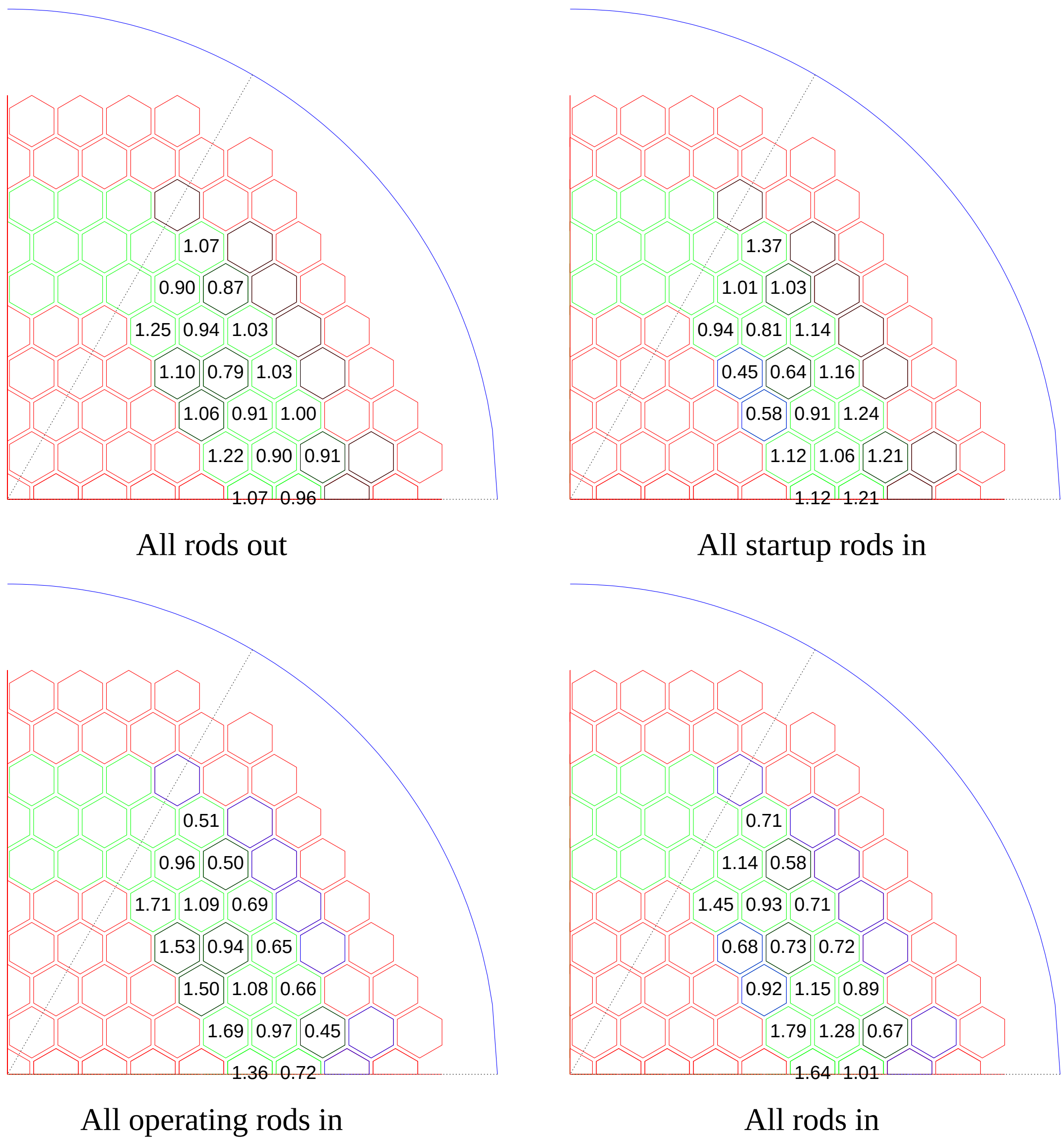
Fig. 2 presents the fission rate map obtained with MCNP4c for the 2D core. It is normalized to the number of blocks (102), in such a way that a value equal to one is corresponding to the average value. Table 2 presents the discrepancies (δ) of the local fission rates between MCNP4c and TRIPOLI4, MCNP4c is used as a reference.

Table 2: Fission rate discrepancies (%) for the 2D core

Rods configuration	All rods out	Startup rods in	Operating Rods in	All rods in
δ_{min}	-1.12	-0.74	-0.89	-0.73
δ_{max}	0.77	0.64	1.45	0.70
δ_{av}	0.45	0.41	0.61	0.46

When comparing k_{eff} values between MCNP4c and TRIPOLI4 (Table 1), a good consistency is observed between the 2 codes with discrepancies compatible with the variance (σ) in all cases except the last configuration which is slightly degraded. TRIPOLI4 tends to overestimate the MCNP4c k_{eff} and to underestimate the associated control rod worth with discrepancies less than 2%. Table 2 confirms the consistency observed between the 2 MC codes, and yield a practical evaluation of the local fission rate convergence of some 0.6% which is in agreement with values given by the codes.

Figure 2: Fission rate map over the 2D core



3.2 3D Analysis

Table 3 compares the k_{eff} and the associated control rod worth for all the configurations studied. The fission rate map presented in Fig. 3 is associated with the center of the 3D core. However, the radial effects are characterized by the same trends whatever the axial position is.[a] The fission rate map is normalized to the number of blocks (1020), in such a way that a value equal to one is corresponding to the average value. Finally, the MCNP4c 3D results will be compared to NEPHTIS calculation in Section 4.

Table 3: k_{eff} and control rods worth for the 3D core

Rods configuration	All rods out	Startup rods in	Operating Rods in	All rods in
	k_{eff} results – σ (pcm)			
MCNP4c	1.43357 (34)	1.32972 (35)	1.31331 (39)	1.15458 (39)
TRIPOLI4	1.43363 (47)	1.33048 (45)	1.31419 (46)	1.15606 (41)
δk_{eff} (pcm)	+4	+57	+67	+128
	Reactivity results: $\rho = \delta k_{eff}^{\text{worth}}$			
MCNP4c	0	-7520	-8762	-21643
TRIPOLI4	0	-7467	-8699	-21519
$\delta\rho$ (%)	–	-0.70	-0.72	-0.57

Here again and as in 2D, a good consistency between the 2 codes is observed with discrepancies compatible with the computed variance (σ). TRIPOLI4 tends to overestimate MCNP4c for the k_{eff} and to underestimate the associated control rod worth with discrepancies less than 1%.

Table 4 presents the discrepancies (δ) of the local fission rates between the codes MCNP4c and TRIPOLI4.

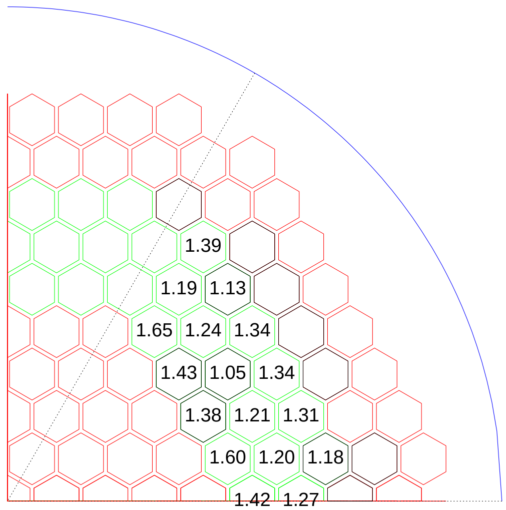
Table 4: Fission rate discrepancies (%) for the 3D core

Rods configuration	All rods out	Startup rods in	Operating Rods in	All rods in
δ_{min}	-1.27	-1.17	-1.45	-1.33
δ_{max}	0.92	1.43	1.98	1.33
δ_{av}	0.59	0.68	0.50	0.61

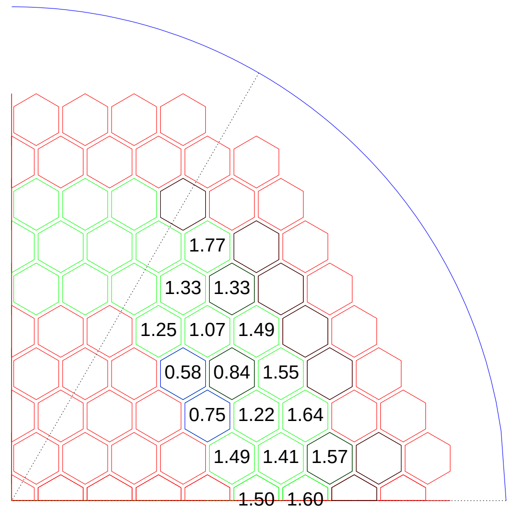
These results confirm the consistency observed between the 2 MC codes. We observe average discrepancies values of 0.7% for the local fission rate, which is very close to the calculated variance of each code.

[a] Calculations for the levels comprised between 1 to 5 of the 3D core (Fig. 1) have been performed, they are not presented here.

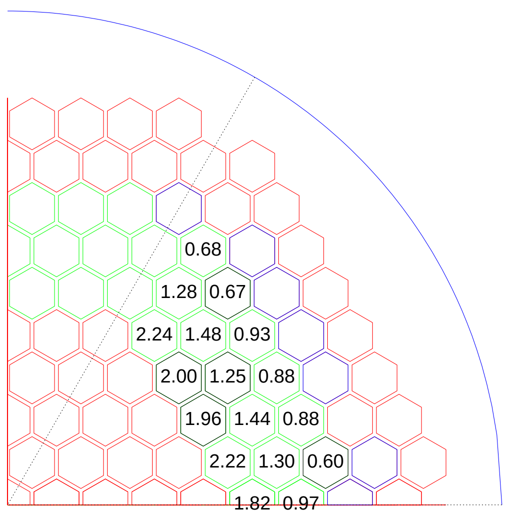
Figure 3: Fission rate map in the center of the 3D core



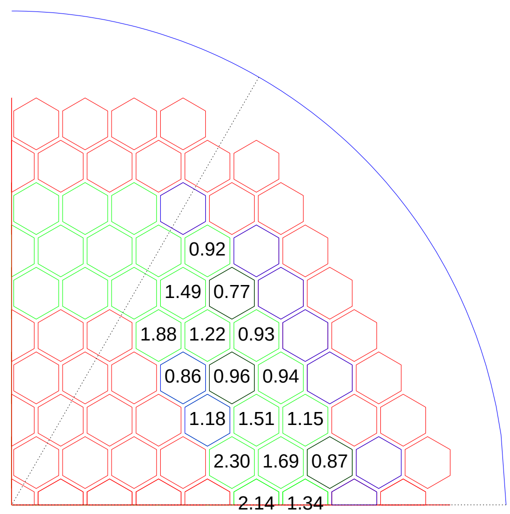
All rods out



All startup rods in



All operating rods in



All rods in

3.3 Physical analysis

A first remarkable point is that 2D and 3D calculations are characterized by similar results in terms of k_{eff} and control rods worth. In 2D configurations, the core is axially infinite. Consequently, it is represented by a 74 cm high core layer with a reflection boundary condition. When considering 3D configurations, the core comprises 10 axial layers separated by a 6 cm graphite gap and two axial reflectors. In 3D, the graphite gap and the axial reflectors tend to increase the reactivity which is compensated by the axial leakage.

Concerning the control rods, one may notice that the startup and operating rods worths are of the same order of magnitude despite the fact that the number of operating rods is 3 times bigger than the number of startup rods (Fig. 1). This is related to the fact that the startup rods are inserted in the active part of the core whereas the operating rods are inserted in the reflector.

The cumulated control rod worth of the startup and operating rods is higher than the sum of the control rod worths. This may be explained by the fact that either the startup or control rods prevent the neutrons from being reflected by the inner or outer radial reflector. When only one group of rods is inserted the outer or inner reflector remains efficient, it is not the case anymore when all the rods are inserted. The flux spectrum is then hardened and the neutrons have a high probability to be captured before producing any fission.

Due to the neutronic captures in the absorber, the insertion of a group (startup/operating) of rods significantly decreases the fission rate in and around the inserted control elements. Consequently, the fission rate distribution tends to move towards the opposite reflector. When the two groups of rod are inserted simultaneously, the fission rate distribution is increased around the startup control elements at the interface between the fuel and the inner reflector.

One can observe that the fission rates are significantly greater in 3D compared to the 2D case (Figs. 2 and 3). In 3D and due to the axial leakage, the axial flux is higher in the center of the core. Consequently, the 3D configuration which corresponds to the center of the core yields a higher fission rate distribution compared to the 2D case which corresponds to an average value.

4. NEPHTIS Validation

This section is devoted to the validation of the deterministic scheme NEPHTIS. The agreement observed between the MC codes allows us to use those results as a reference.

4.1 2D Analysis

Results have been presented in a previous paper and showed a good consistency between TRIPOLI4 and NEPHTIS. [1] Moreover, the coherence between MCNP4c and TRIPOLI4 shown in Section 3.1 indicates that the numerical tools used are globally consistent for the 2D configurations.

4.2 3D Analysis

Tables 5 compares the k_{eff} and the control rod worth for the 3D core. Fig. 4 presents the fission rate discrepancies map associated with the 3D core.

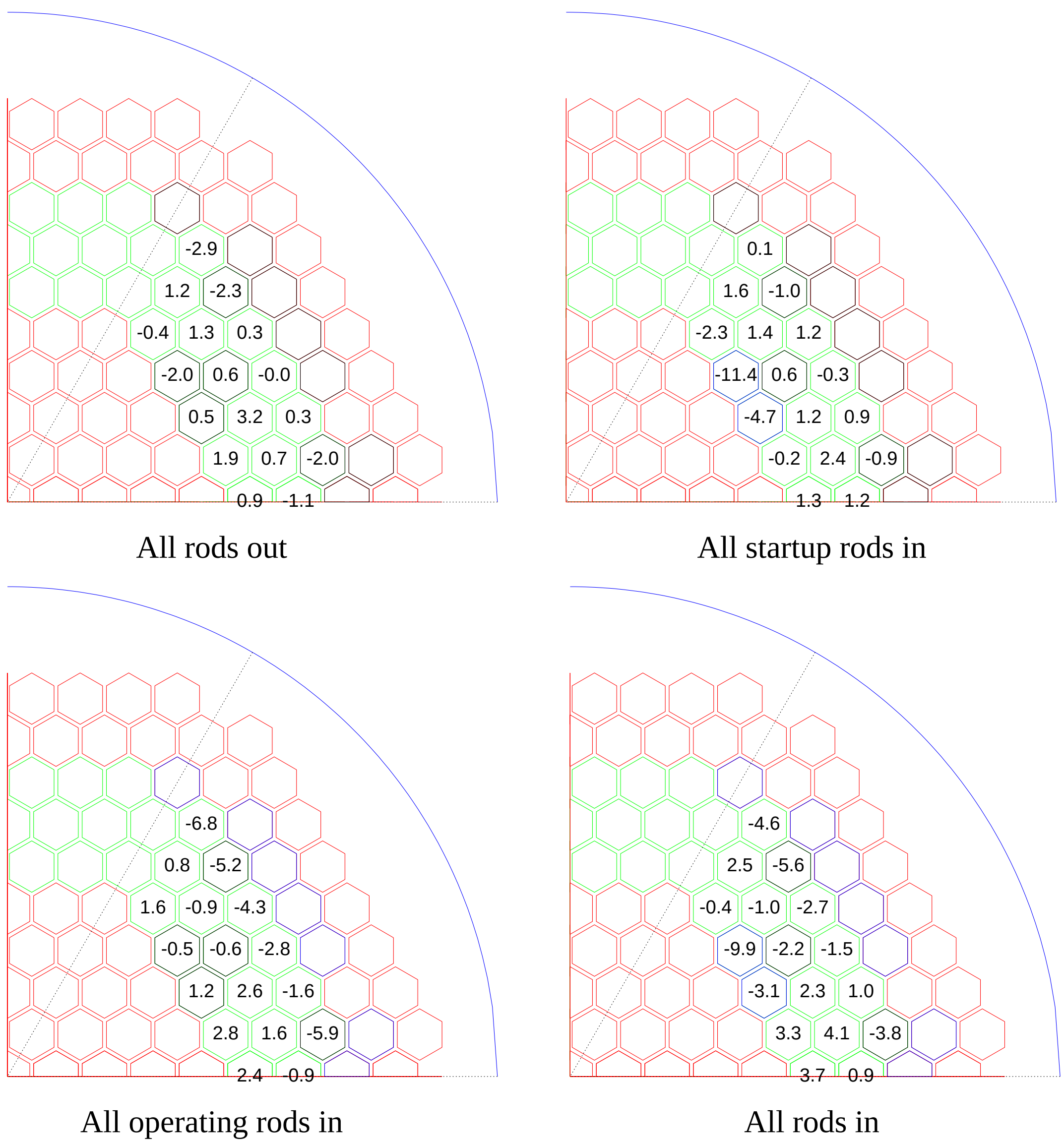
Table 5: k_{eff} and logarithmic control rods worth for the 3D core

Rods configuration	All rods out	Startup rods in	Operating Rods in	All rods in
	k_{eff} results – σ (pcm)			
MCNP4c	1.43357 (34)	1.32972 (35)	1.31331 (39)	1.15458 (39)
NEPHTIS	1.43205	1.32807	1.31690	1.15587
δk_{eff} (pcm)	-106	-124	+273	+112
	Reactivity results: $\rho = \delta k_{eff}^{worth}$			
MCNP4c	0	-7520	-8762	-21643
NEPHTIS	0	-7538	-8383	-21425
$\delta\rho$ (%)	–	+0.2	-4.3	-1.0

The k_{eff} values are in agreement within a few hundred pcm and the control rods worth discrepancy is limited to some 5% when the operating rods are inserted which corresponds to the most degraded configuration. When all the control rods are extracted, there is a good coherence between the two codes on the fission rate map with discrepancies less than 3%. As soon as control rods are inserted the discrepancies between the 2 codes increase with a systematic underestimation of NEPHTIS fission rates in the inserted rods vicinity. When the startup rods are inserted, the discrepancies between the 2 codes increase to reach 11% in the inserted control rods. When the operating rods are inserted, the discrepancies between the 2 codes reach 7% around the inserted control rods. Finally, when all the control rods are inserted, the discrepancies between the 2 codes reach 10% in the inserted operating rods. The discrepancies observed are relative values. If they may seem rather high, these results have to be mitigated by the fact that the fission rate is low when the discrepancies are significant (11.4%) as presented on Figs. 3 and 4 (eg. fission rate: 0.58 – discrepancy: 11.4%).

All the results indicates that NEPHTIS is a suitable tool for core design studies with biases less than 5% for control rod worth, and around 2-3% for the power peak in all configurations.

Figure 4: Fission rate map discrepancies (%) in the center of the 3D core



5. Conclusion

This paper is a contribution to the validation of NEPHTIS calculation scheme. It is dedicated to an annular HTR core, loaded with fresh uranium oxide at room temperature (300K). The calculations on the 2D and 3D cores consisted in various configurations: all control rods out, all startup rods in, all operating rods in and finally, all control rods in.

MCNP4c and TRIPOLI4 comparisons performed on the 2D and 3D core showed a good coherence between the 2 codes. In term of reactivities and control rod worth, the 3D core calculations showed the same general trends as what was observed in 2D.

The comparison between MCNP4c and NEPHTIS on the 3D cores showed a good consistency between the stochastic and the deterministic approach. When all the control rods are extracted, the agreement between the codes is rather good with discrepancies on the k_{eff} of 100 pcm and an agreement on the fission rate map within 3%. The insertion of one or several groups of control rods slightly increases the discrepancies that remain generally lower than 300 pcm for the k_{eff} and and reach a maximal value of 12% for the fission rate distribution. This gap mainly occurs in the inserted control rods vicinity where NEPHTIS underestimates the fission rates in and around the inserted control rods.

Further work is in progress in order to improve NEPHTIS calculation scheme. It is mostly devoted to core burnup calculations, control rods modeling and fuel loading patterns analysis.

Acknowledgements

The authors wish to thank AREVA-NP for the financial support which permitted to carry out this work and publish this paper.

References

1) F. DAMIAN, X. RAEPSAET, B. STEPNICK, C. CAVALIER, “Presentation of the HTR neutronics tool NEPHTIS”, European Nuclear Congress ENC2005, Versailles, France, December 2005.

2) R. SANCHEZ, A. HEBERT, Z. STANKOVSKI, M. COSTE, S. LOUBIERE, C VAN DER GUCHT and I. ZMIJAREVIC, “APOLLO2 Twelve Years Later”, Mathematics and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications, Madrid, September 1999.

3) J.J. LAUTARD, S. LOUBIERE, C. MAGNAUD “CRONOS, A Modular Computational System for Neutronic Core Calculations”, IAEA Specialists Meeting, France, September 1990.

4) F. DAMIAN, M. GROIZARD, C. POINOT, T. COURAU, S. THAREAU “VHTR neutronic calculation scheme: validation elements using MCNP and TRIPOLI4 Monte-Carlo codes”, International Conference MC2005, Avignon, France, September 2005.

5) Ed. J.F. BRIESMEISTER. MCNP-A General Monte Carlo N-Particle Transport Code. Version 4C. Report LA-13709-M, April 2000.

6) J.P. BOTH, A. MAZZOLO, Y. PENELIAU, O. PETIT, B. ROESSLINGER, Y. K. LEE and M. SOLDEVILA, “TRIPOLI4, a Monte-Carlo Particles Transport Code. Main Features and Large Scale Applications in Reactor Physics”, International Conference on Supercomputing in Nuclear Application, SNA’ 2003, Paris, September 2003.