NEPHTIS: core depletion validation relying on 2D transport core calculations with the APOLLO2 code

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Abstract

The CEA, in collaboration with EDF and AREVA-NP, is developing a core modelling tool called NEPHTIS, for *Neutronic Process for HTGR Innovating Systems* and dedicated at present day to the prismatic block-type HTGR (High Temperature Gas-Cooled Reactors). Due to the lack of usable HTGR experimental results, the confidence in this neutronic computational tool relies essentially on comparisons to reference or best-estimate calculations. In the present analysis, the APOLLO2 deterministic transport code has been selected as reference for validating core depletion simulations carried out within NEPHTIS. These reference calculations were performed on fully detailed 2D core configurations using the Method of Characteristics. The latter has been validated versus Monte Carlo method for different static core configurations [1], [2] and [3]. All the presented results come from an annular HTGR core loaded with uranium-based fuel (15% enrichment). During the core depletion validation, reactivity, reaction rates distributions and nuclei concentrations have been compared. In addition, the impact of various physical and geometrical parameters such as the core loading (one-through or batch-wise reloading) and the amount of burnable poison has been investigated during the validation phases. The results confirm that NEPHTIS is able to predict the core reactivity with uncertainties of ± 350 pcm. At the end of the core irradiation, the U^{235} consumption is calculated within ± 0,7 % while the plutonium mass discharged from the core is calculated within ± 1 %. As far as the core power distributions are concerned, small discrepancies (< 2.3 %) can be observed on the fuel block-averaged power distribution in the core.

KEYWORDS ***High Temperature Gas-Cooled Reactor, Core depletion analysis, Calculation Scheme validation, NEPHTIS, APOLLO2, CRONOS2***

1. Introduction

Today, HTGRs appear as a promising concept for the next generation of nuclear power applications. At CEA, a calculation scheme NEPHTIS -*Neutronic Process for HTR Innovating Systems*- has been developed in collaboration with EDF and AREVA-NP, and is dedicated at present to the prismatic block-type HTGR. This calculation scheme is based on a standard two-steps Transport–Diffusion approach (using APOLLO2 and CRONOS2 codes) [1].

One of the great challenges for a HTGR analysis tool like NEPHTIS is that they can be used with confidence to ensure that the reactor meet the performances and safety objectives required by the designers. Therefore, the development of these neutronic tools implies an intensive qualification and validation program. Most of the validation steps rely on comparison with

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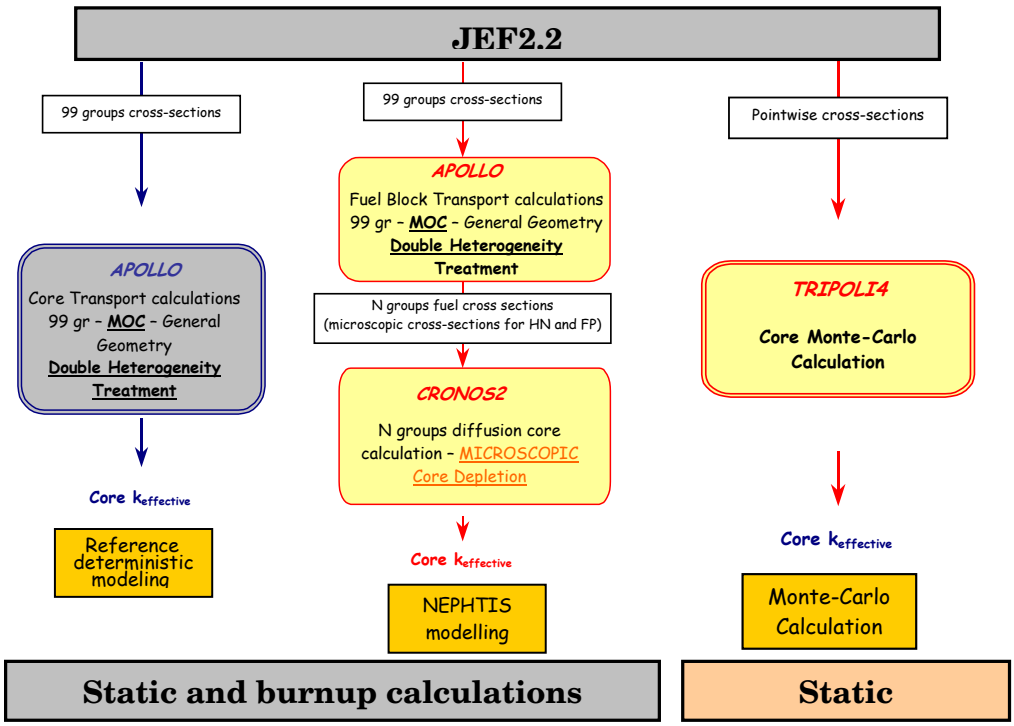
reference or best-estimate calculations. Such reference calculations are usually obtained with Monte-Carlo codes. Commonly, these codes allow modelling the core geometry and its particularities without any physical approximations. However, first, the Monte-Carlo method is not considered today as a practical reference for validating core burnup calculation and second, the HTGR fuel is made up of dispersed particles (coated fuel particles, embedded in a graphite matrix) imposing unavoidable approximations related to the geometrical description. This may question, for the HTGR, the principle of the absolute reference granted to the Monte-Carlo methods [2]. Moreover, due to the large size of the HTGR core, stabilisation problems of the source shapes occur while calculating HTGR core with Monte-Carlo codes [3].

In the present study, reference deterministic calculations carried out with the APOLLO2 transport code [4] have been selected for validating the core burnup calculations of NEPHTIS. In the first part of the paper, the 2D detailed core calculations, performed with APOLLO2 and using the Method Of Characteristics [5], are compared to the reference Monte-Carlo calculations (TRIPOLI4) for different static core configurations. Parameters such as core $k_{effective}$, fuel element fission and absorption rates distributions but also pin-by-pin fission rates map are analysed. In the second part of the paper, the 2D core APOLLO2 calculations allowed validating the core depletion calculations in NEPHTIS.

2. Computational methods and nuclear data

The implementation of the NEPHTIS neutronic calculation scheme relies on the existing computational tools available in the code package SAPHYR developed at CEA. For the analysis, the Monte-Carlo code TRIPOLI4 [7,8] the diffusion code CRONOS2 [9,10] and the transport code APOLLO2 [4] have been used associated to a database produced with THEMIS/NJOY and based on JEF2.2. The various calculation routes used in this study are described Figure 1.

Figure 1: Description of the three different calculation routes used for the core depletion analysis



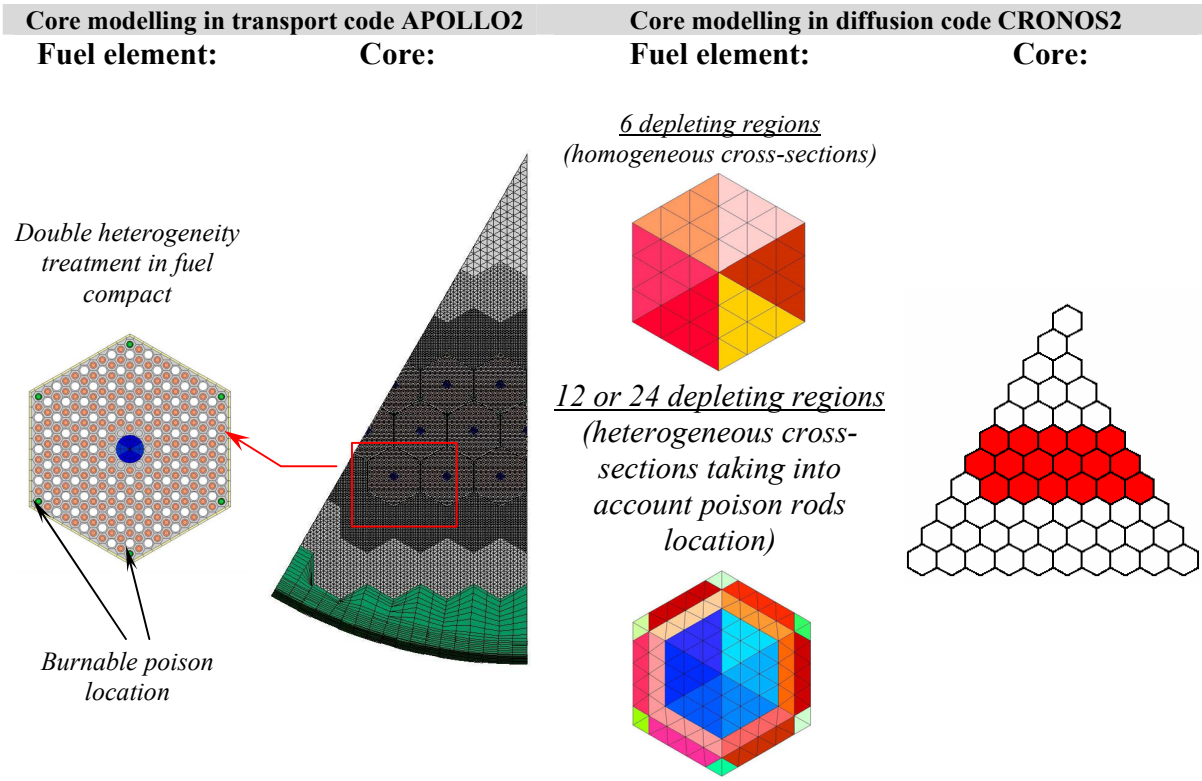
2.1. Core static calculations

The first part of the analysis concerns static core calculations, the objective being the validation of the 2D reference core modelling in APOLLO2 used hereafter to validate burnup calculations with NEPHTIS. These 2D core calculations are performed in transport theory with 99 groups and using the methods of characteristics (MOC) [5,6]. In these calculations, the core heterogeneous structure, i.e. coated fuel particles embedded in a fuel compact and fuel compacts loaded in the prismatic block, is also explicitly taken into account by using the double heterogeneity formalism (Figure 2). Besides, another reference calculation is performed using the Monte-Carlo code TRIPOLI4. For the latter, the nuclear cross-sections associated to the materials in the core are point wise data derived also from JEF2.2 evaluation.

2.2. Core burnup calculations

The second part of the analysis is devoted to the 2D core burnup calculations. Although NEPHTIS is a 3D core calculation scheme, the core burnup calculations are validated in 2D geometry. In CRONOS2 -diffusion theory 8 groups - the fuel element is described either with homogeneous cross-sections or with heterogeneous cross-sections in order to take into account the burnable poison location (Figure 2).

Figure 2: Characteristics of the core modelling in APOLLO2 and CRONOS2



The fuel element modelling in the diffusion code is also characterized by the number of depleting regions: 6 depleting regions in the homogeneous case whereas in the heterogeneous case, the number of depleting regions can vary from 12 to 24. The number of points in the prismatic block for the flux calculation also depends on the fuel element model (homogeneous or heterogeneous). The fuel element cross-sections used in CRONOS2 are computed by APOLLO2

in a 2D fuel element model, using the methods of characteristics (MOC) [5,6]. This calculation allows treating simultaneously the self-shielding of the resonant nuclides and the double heterogeneity feature of the fuel compacts. In order to be consistent with the reference 2D core calculations, the fuel element burnup calculations are carried out considering a 99 groups energy mesh instead of the 172 gr energy mesh used as a matter of routine in NEPHTIS.

Besides, the reference core burnup calculations performed in APOLLO2 are the same as the one described in section 2.1. For the core burnup calculations, the flux is computed in each mesh (Figure 2) whereas the concentrations are evaluated considering 48 depleted fuel compacts in each standard fuel elements. The choice of these 48 fuel compacts results from an optimisation taking into account the flux heterogeneity in the core.

2.3. Description of the "fine depletion model" in CRONOS2 code

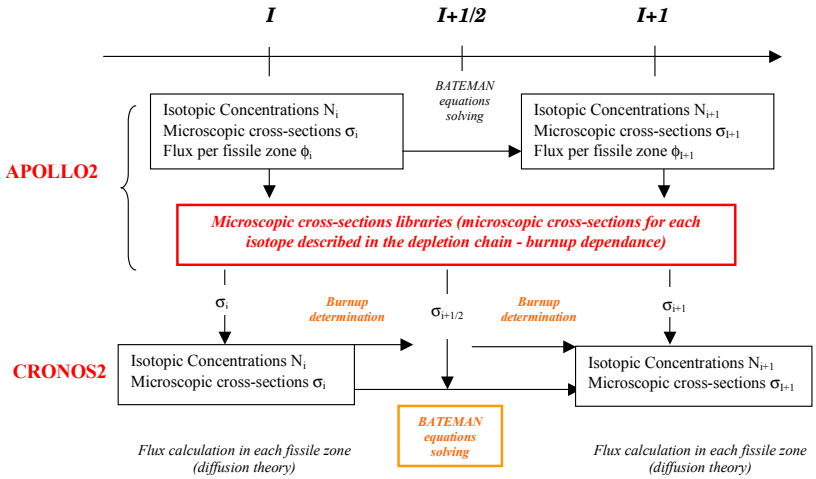
The core burnup calculations in NEPHTIS rely on a microscopic depletion model and a simplified depletion chain (20 heavy nuclides and 8 fissions products). At each time step, the isotopes concentrations are evaluated considering microscopic cross-sections (Figure 3) and by solving the Bateman equations in each mesh and for each isotope of the depletion chain according to the following formulation:

$$\frac{dC(t)}{dt} = A(t,\varphi,\sigma_{micr})\times C(t)$$

$C(t)$ Concentrations vector for each isotope present in the depletion chain at a time step t

A Depletion matrix depending on the time step, the microscopic cross-sections and the mesh-averaged flux

Figure 3: Description of the depletion calculation process in CRONOS2



The problem consists in calculating the isotopic concentrations at $t_0+\Delta t$ knowing the reactor state at t_0. During the depletion step from t_0 to $t_0+\Delta t$, the flux is kept constant: it represents the solution of the stationary diffusion equation. The microscopic cross-sections are also considered as constant. Furthermore, it should be stressed that the depletion model in CRONOS2 doesn't use up to now a predictor-corrector method as in APOLLO2. As a consequence, the depletion process in CRONOS2 remains strongly dependant to the time step chosen by the user.

3. Description of the studied configurations

As illustrated in Figure 4 and listed in Table I, various core configurations were treated for the analysis. For both first configurations "Nominal" and "B_4C+" (for this last configuration, the burnable poison loading is increased by a factor 5), a homogeneous core loading (case-a) and a relatively high burnup have been considered (one through core depletion till 125 GWd/t). For batch-wise core configuration called "Three batches", three various isotopic compositions corresponding to fuel elements at 0, 50 and 100 GWd/t were loaded into the core as shown in Figure 4 (case-b). Finally, in the last configuration called "Three enrichments" (case-c), three enrichments (10, 12 and 15 %) were used to load the core. The core burnup calculations were also performed till high burnup.

Figure 4: Description of the various core configurations used for the core depletion analysis

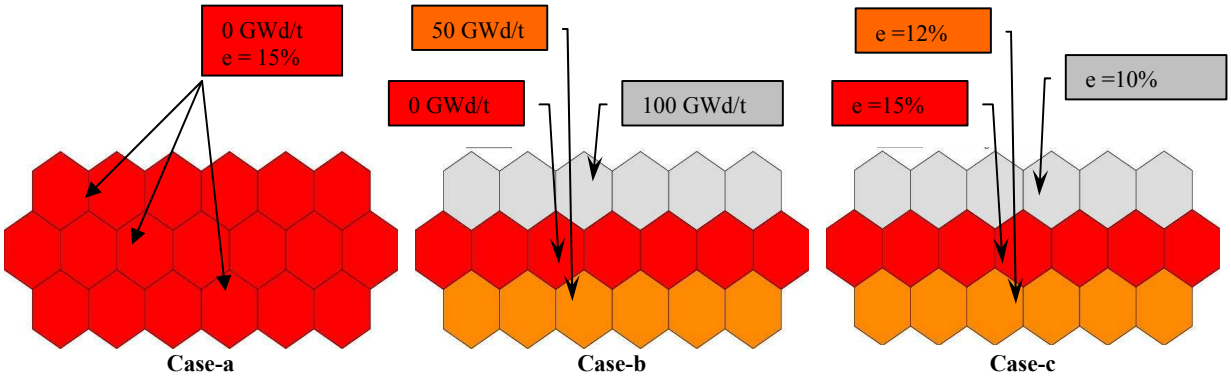


Table I: Description of the various core configurations used for the core depletion analysis

Name of the various configurations	Core geometry	Description
Nominal	Case (a)	Uniform core loading – e = 15% - Cold state
B_4C +	Case (a)	Uniform core loading – e = 15% - Cold state – $M_{B4C} = M_{nominal} \times 5$
Three batches	Case (b)	Three batches core loading – Burnup = 0, 50 & 100GWd/t - Cold state
Three enrichments	Case (c)	Three enrichment core loading – e = 15, 12 & 10% U^{235} - Cold state

4. Core static analysis: validation of the modelling in the transport code APOLLO2

4.1. Description of the problem

The 2D core calculations with APOLLO2 are considered as a reference for the validation of the NEPHTIS calculation scheme, a preliminary analysis was performed in order to evaluate the biases associated with this reference. All the cases listed in Table I were compared with the Monte-Carlo code TRIPOLI4 at the core beginning of life or beginning of cycle in the "Three batches" case. The core $k_{effective}$, the ratio [production/absorption] in the active zone, the average fuel element fission and absorption rates maps and the pin-by-pin fission rates map were analysed.

4.2. Results and discussion

The results are gathered in Table II for all the configurations. It turns out that the core $k_{effective}$ in APOLLO2 is estimated within ± 350 pcm. In addition, the ratio P/A in the active zone is quite well predicted by APOLLO2, the maximum discrepancy being 66 pcm. This is confirmed by the 4 factors formula provided in the Table II as we don't observe any compensation in the

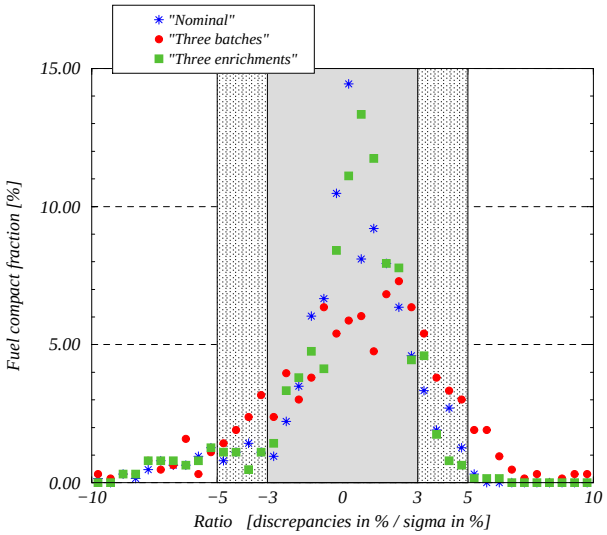
decomposition. Concerning the fission and absorption rates distribution in the fuel element, the discrepancies remains in the range of ± 1,1% (σ less than 0,1%). Finally, whatever the core configuration, the discrepancies on the pin-by-pin fission rates observed between APOLLO2 and TRIPOLI4 are in the range of ± 4,1% (σ=1%). It is important to note that this inter-comparison between APOLLO2 and TRIPOLI4 results from the analysis of more than 630 fuel compacts.

Table II also gathers the fuel compacts fraction for which the discrepancies are in the range ± 3σ (± 1%) and ± 10σ (± 3%). It is noteworthy that for all the analysed configurations, more than 99 % of the fuel compact fission rates are estimated within ± 3%. Moreover, the distribution of these discrepancies is centred on 0 as shown Figure 5.

Table II: 2D core calculations with APOLLO2 – Comparison with Monte-Carlo code TRIPOLI4

	Nominal		B_4C		Three batches		Three enrichments	
		Δ in pcm		Δ in pcm		Δ in pcm		Δ in pcm
Core keffective	1,42844	-241	1,23644	-285	1,27742	-342	1,38917	-269
Ratio P/A in active zone	1,57609	11	1,35642	-34	1,41639	-66	1,53951	11
4 factors formula								
ε	1,13256	2	1,15480	1	1,11348	-13	1,11576	-5
p	0,74479	-56	0,72755	-37	0,73012	-78	0,75427	-47
f	0,91946	68	0,79469	4	0,94986	24	0,90599	66
η	2,03213	-3	2,03156	-2	1,83419	1	2,01912	-3
Average fuel element fission rate map		Δ in %		Δ in %		Δ in %		Δ in %
Max Δ in %		0,90		0,73		1,10		0,65
Min Δ in %		-0,20		-0,25		-0,19		0,00
Average fuel element absorption rate map								
Max Δ in %		-0,83		0,65		1,09		0,58
Min Δ in %		-0,83		-0,69		-0,85		-0,83
Pin by pin fission rate map								
Max |Δ| in %		3,68		2,69		4,10		3,00
% of fuel pins in the range [-1% / +1%]		80,48		91,59		62,06		82,22
% of fuel pins in the range [-3% / +3%]		99,54		100,00		99,05		100,00

Figure 5: Distribution of the pin-by-pin discrepancies



5. Core burnup calculations: validation of the core depletion calculation with NEPHTIS

5.1. Analysis of the core reactivity

Table III gathers the discrepancies on the core $k_{effective}$ obtained with APOLLO2 and NEPHTIS for the various 2D core configurations presented previously and according to the different level of refinement of the models. One can notice that in "Nominal" configuration, the discrepancies between APOLLO2 and CRONOS2 are within ± 310 pcm whatever the core burnup is. The fuel element modelling in the diffusion code and the number of depleting regions have both a small impact on the core $k_{effective}$ in this configuration. However, the analysis of the "B_4C+" configuration (the reactivity effect due to the increase of B_4C loading is equal to 15000 pcm at the core beginning of life) shows that the homogeneous model of the fuel element leads to an underestimation of the burnable poison captures. Indeed, the poison compacts, located in the external region of the fuel element, are homogenised on the prismatic block for the core diffusion calculation. The reactivity underestimation strongly decreases with the B_4C consumption during core depletion. By introducing a heterogeneous fuel element model, the discrepancies are strongly reduced (± 300 pcm). For the last two configurations (*three batches* and *three enrichments* loadings), the core $k_{effective}$ is quite well predicted by NEPHTIS. Discrepancies lower than 240 pcm and 340 pcm can be observed respectively for both configurations.

Table III: Discrepancies in pcm between APOLLO2 and NEPHTIS – Min and Max Core $k_{effective}$ observed all along the cycle

Δk_{eff} in pcm	**Nominal**		**B_4C+**		**Three batches**		**Three enrichments**	
Homogeneous fuel element	Max	308	Max	*1201*	Max	*237*	Max	*313*
6 depleting zones/fuel element	Min	-197	Min	*-780*	Min	*11*	Min	*-147*
Heterogeneous fuel element	Max	76	Max	*291*	Max	*163*	Max	*336*
12 depleting zones/fuel element	Min	-159	Min	*-160*	Min	*-12*	Min	*-78*
Heterogeneous fuel element	Max	63	Max	*276*	Max	*105*	Max	*334*
24 depleting zones/fuel element	Min	-159	Min	*-160*	Min	*-45*	Min	*-92*

5.2. Analysis of the concentrations (core & fuel rings average concentrations)

In the Table IV are gathered the discrepancies calculated on the average core concentrations and for a selected number of isotopes. For the configurations "Nominal", "B_4C+" and "Three enrichments", the discrepancies were evaluated all along the core cycle, from 0 GWd/t to 125 GWd/t (110 GWd/t for the third case). Only the maximum observed discrepancies during the cycle are given in the Table IV. For the "Three batches" configuration, these discrepancies were evaluated all along an equivalent fuel cycle length of 50 GWd/t.

Whatever the fuel element model adopted in the diffusion calculations, accurate results have been obtained with NEPHTIS when it is compared to the reference modelling with APOLLO2. The maximum discrepancy reaches 8 % for the Pu^{242}. Like the others isotopes such as Np^{237}, Pu^{239} and Pu^{240}, it should be stressed that this maximum discrepancies are obtained during the first days of irradiation (till 500 MWd/t) where their concentrations remains very small. After this short transient period, the concentrations of the major isotopes (U^{235}, U^{238}, Np^{237}, Pu^{239}, Pu^{240} & Pu^{241}) are quite well estimated. For the configuration "Nominal", the U^{235} loading is divided by more than a factor 6 between the beginning and the end of the core life (0 to 125 GWd/t). Whatever the fuel element model in the diffusion code is, the concentrations of U^{235} is estimated within ± 2,5%.

More representative of the core depletion reliability in NEPHTIS are the concentrations calculated at the end of the core depletion. The results for the "Nominal", "Three enrichments" and "Three batches" configurations are gathered Table V, Table VI and Table VII. For the first two configurations, the discrepancies are calculated at the core end of life (125 GWd/t for "Nominal" and 110 GWd/t for "Three enrichments"). In the third case, the discrepancies are calculated at the core end of cycle (average core burnup equal to 100 GWd/t). It turns out that the discrepancies are higher in the inner and outer rings where the neutron spectrum transient is the most important. However, considering the first two cases (one-through core depletion calculations), it can be said that the concentrations in each core ring are calculated within ±4% for U^{238}, Np^{237}, Pu^{239} to Pu^{242} and Am^{241}. For U^{235}, the discrepancies are within ±5,3%. The highest discrepancy is observed in the inner ring where the U^{235} concentration is divided by a factor 9 between the beginning and the core end of life. The discrepancy is lower in the central ring where the average neutron spectrum is much closer to the fundamental mode spectrum computed by APOLLO2 during the cross-sections generation in infinite medium and in a 2D fuel element configuration. The major trends issued from the one-through core depletion calculations are strongly softened when analysing the more realistic configuration "Three batches". The discrepancies are calculated for the core-averaged concentrations but also for each batch loaded into the core. It is noteworthy that in this configuration, most of the concentrations are estimated with a very good accuracy (discrepancies within ± 3 %).

Table IV: Discrepancies in % between APOLLO2 and NEPHTIS observed during the core depletion - Average core concentrations

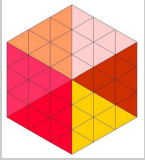
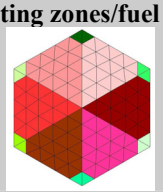
ΔConcentrations in %	Nominal		B_4C+		Three batches		Three enrichments	
Homogeneous fuel element 6 depleting zones/fuel element 	U^{235}	*±2,22*	U^{235}	*±2,89*	U^{235}	*±0,65*	U^{235}	*±2,68*
	U^{238}	*±0,01*	U^{238}	*±0,01*	U^{238}	*±0,02*	U^{238}	*±0,01*
	Np^{237}	*±4,47*	Np^{237}	*±6,93*	Np^{237}	*±0,66*	Np^{237}	*±4,36*
	Pu^{239}	*±2,89*	Pu^{239}	*±2,73*	Pu^{239}	*±2,37*	Pu^{239}	*±2,73*
	Pu^{240}	*±4,61*	Pu^{240}	*±2,84*	Pu^{240}	*±1,78*	Pu^{240}	*±4,47*
	Pu^{241}	*±4,38*	Pu^{241}	*±2,14*	Pu^{241}	*±1,53*	Pu^{241}	*±4,40*
	Pu^{242}	*±6,31*	Pu^{242}	*±2,50*	Pu^{242}	*±1,06*	Pu^{242}	*±6,25*
	Am^{241}	*±3,54*	Am^{241}	*±2,89*	Am^{241}	*±1,16*	Am^{241}	*±3,47*
Heterogeneous fuel element 12 depleting zones/fuel element 	U^{235}	*±2,12*	U^{235}	*±2,99*	U^{235}	*±0,62*	U^{235}	*±2,98*
	U^{238}	*±0,03*	U^{238}	*±0,01*	U^{238}	*±0,02*	U^{238}	*±0,01*
	Np^{237}	*±3,46*	Np^{237}	*±4,74*	Np^{237}	*±0,43*	Np^{237}	*±3,45*
	Pu^{239}	*±2,68*	Pu^{239}	*±2,59*	Pu^{239}	*±2,10*	Pu^{239}	*±2,47*
	Pu^{240}	*±5,61*	Pu^{240}	*±4,23*	Pu^{240}	*±1,89*	Pu^{240}	*±5,29*
	Pu^{241}	*±6,06*	Pu^{241}	*±4,54*	Pu^{241}	*±1,83*	Pu^{241}	*±5,81*
	Pu^{242}	*±7,99*	Pu^{242}	*±6,14*	Pu^{242}	*±1,05*	Pu^{242}	*±7,61*
	Am^{241}	*±5,18*	Am^{241}	*±3,36*	Am^{241}	*±0,99*	Am^{241}	*±4,84*
Heterogeneous fuel element 24 depleting zones/fuel element 	U^{235}	*±2,35*	U^{235}	*±3,21*	U^{235}	*±0,63*	U^{235}	*±3,21*
	U^{238}	*±0,03*	U^{238}	*±0,01*	U^{238}	*±0,03*	U^{238}	*±0,02*
	Np^{237}	*±3,47*	Np^{237}	*±4,75*	Np^{237}	*±0,38*	Np^{237}	*±3,46*
	Pu^{239}	*±2,41*	Pu^{239}	*±2,32*	Pu^{239}	*±1,95*	Pu^{239}	*±2,24*
	Pu^{240}	*±5,58*	Pu^{240}	*±4,20*	Pu^{240}	*±1,87*	Pu^{240}	*±5,25*
	Pu^{241}	*±6,06*	Pu^{241}	*±4,55*	Pu^{241}	*±1,95*	Pu^{241}	*±5,80*
	Pu^{242}	*±8,11*	Pu^{242}	*±6,23*	Pu^{242}	*±1,06*	Pu^{242}	*±7,63*
	Am^{241}	*±5,17*	Am^{241}	*±3,37*	Am^{241}	*±0,98*	Am^{241}	*±4,83*

Table V: "Nominal" configuration –Discrepancies in % calculated on average core and rings concentrations at the core end of life (average core burnup = 125 GWd/t)

		U^{235}	U^{238}	Np^{237}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Am^{241}
Homogeneous fuel element 6 depleting zones	**Core average**	**2.22**	**0.01**	**-1.16**	**-2.89**	**1.69**	**1.66**	**1.72**	**-0.78**
	Outer ring	3.59	0.01	-1.64	-3.45	2.39	2.34	2.10	-0.23
	Central ring	0.02	0.01	-0.64	-2.77	0.76	0.66	1.96	-1.74
	Inner ring	4.50	0.01	-1.34	-2.39	2.07	2.48	1.10	0.17
Heterogeneous fuel element 12 depleting zones	**Core average**	**2.12**	**-0.02**	**-0.78**	**-2.68**	**1.87**	**2.02**	**2.20**	**-0.50**
	Outer ring	3.97	-0.01	-1.33	-3.11	2.64	2.81	2.40	0.19
	Central ring	-0.57	-0.03	-0.13	-2.68	0.85	0.95	2.71	-1.57
	Inner ring	4.65	-0.01	-1.05	-2.17	2.30	2.86	1.43	0.48
Heterogeneous fuel element 24 depleting zones	**Core average**	**2.35**	**-0.03**	**-0.61**	**-2.41**	**1.93**	**2.37**	**2.39**	**-0.18**
	Outer ring	4.38	-0.02	-1.23	-2.81	2.69	3.18	2.56	0.57
	Central ring	-0.70	-0.05	0.20	-2.43	0.91	1.27	3.05	-1.31
	Inner ring	5.31	-0.02	-1.01	-1.89	2.36	3.22	1.51	0.84

Table VI: "Three enrichments" configuration –Discrepancies in % calculated on average core and rings concentrations at the core end of life (average core burnup = 110 GWd/t)

		U^{235}	U^{238}	Np^{237}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Am^{241}
Homogeneous fuel element 6 depleting zones	**Core average**	**2.68**	**0.01**	**-1.26**	**-2.72**	**1.26**	**1.47**	**1.19**	**-0.88**
	Outer ring	3.87	0.01	-1.62	-3.15	1.69	1.78	1.43	-0.61
	Central ring	1.67	0.01	-1.08	-2.97	0.91	1.26	1.65	-1.41
	Inner ring	4.05	0.01	-1.12	-1.78	1.22	1.45	0.46	-0.29
Heterogeneous fuel element 12 depleting zones	**Core average**	**2.98**	**0.01**	**-1.05**	**-2.44**	**1.38**	**1.78**	**1.29**	**-0.40**
	Outer ring	4.48	0.01	-1.46	-2.81	1.86	2.12	1.42	-0.08
	Central ring	1.84	-0.01	-0.80	-2.65	0.99	1.64	1.88	-0.88
	Inner ring	4.22	0.01	-1.01	-1.65	1.33	1.60	0.51	0.08
Heterogeneous fuel element 24 depleting zones	**Core average**	**3.21**	**0.00**	**-0.91**	**-2.20**	**1.42**	**2.09**	**1.43**	**-0.09**
	Outer ring	4.84	0.01	-1.39	-2.58	1.89	2.44	1.55	0.24
	Central ring	1.93	-0.02	-0.53	-2.33	1.04	2.00	2.08	-0.55
	Inner ring	4.68	0.01	-1.00	-1.51	1.35	1.82	0.60	0.31

Table VII: "Three batches" configuration –Discrepancies in % calculated on average core and rings concentrations at the core end of cycle (average core burnup = 100 GWd/t)

		U^{235}	U^{238}	Np^{237}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Am^{241}
Homogeneous fuel element 6 depleting zones	**Core average**	**0.65**	**-0.02**	**-0.66**	**-2.37**	**1.35**	**1.49**	**1.06**	**-1.16**
	First batch (50 GWd/t)	0.63	-0.02	-0.70	-3.54	1.81	2.06	2.47	-1.16
	Second batch (0 GWd/t)	0.57	0.00	-1.59	-1.71	2.08	1.19	1.61	-0.22
	Third batch (100 GWd/t)	1.12	-0.03	-0.38	-1.73	0.46	1.08	0.36	-1.30
Heterogeneous fuel element 12 depleting zones	**Core average**	**0.62**	**-0.02**	**-0.43**	**-2.10**	**1.58**	**1.82**	**1.05**	**-0.90**
	First batch (50 GWd/t)	0.96	-0.03	-0.55	-3.17	1.95	2.29	2.25	-0.90
	Second batch (0 GWd/t)	0.31	-0.01	-0.70	-1.44	2.61	2.24	3.22	1.01
	Third batch (100 GWd/t)	1.27	-0.03	-0.28	-1.58	0.62	1.18	0.33	-1.18
Heterogeneous fuel element 24 depleting zones	**Core average**	**0.63**	**-0.03**	**-0.38**	**-1.95**	**1.57**	**1.95**	**1.06**	**-0.85**
	First batch (50 GWd/t)	1.03	-0.03	-0.52	-2.99	1.91	2.40	2.24	-0.84
	Second batch (0 GWd/t)	0.28	-0.02	-0.49	-1.30	2.70	2.51	3.50	1.22
	Third batch (100 GWd/t)	1.29	-0.03	-0.27	-1.47	0.59	1.27	0.34	-1.17

5.3. Average fuel element power map

In this section, the fuel block-averaged power distribution in the core has been analysed. The results are gathered in Table VIII. The discrepancies observed on the fuel block-averaged power

map are very small compared to the reference calculations performed with APOLLO2. For all the configurations and whatever the average core burnup is, the discrepancies do not exceed ± 2,3 %.

Table VIII: Discrepancies in % between APOLLO2 and NEPHTIS – Fuel element-averaged Maximum Discrepancies in % calculated on average core and rings concentrations during core depletion power map

ΔFuel element power %	**Nominal**		**B_4C+**		**Three batches**		**Three enrichments**	
Homogeneous fuel element	Max	*0,78*	Max	*1,44*	Max	*1,79*	Max	*0,79*
6 depleting zones/fuel element	Min	*-0,05*	Min	*-0,24*	Min	*0,0*	Min	*-0,03*
Heterogeneous fuel element	Max	*1,86*	Max	*1,94*	Max	*2,32*	Max	*1,64*
12 depleting zones/fuel element	Min	*-0,02*	Min	*-0,11*	Min	*0,0*	Min	*-0,23*
Heterogeneous fuel element	Max	*1,36*	Max	*1,38*	Max	*1,83*	Max	*1,09*
24 depleting zones/fuel element	Min	*-0,13*	Min	*-0,20*	Min	*0,0*	Min	*0,0*

6. Conclusion

NEPHTIS is a neutronic calculation scheme for HTGR that is being developed at CEA in collaboration of AREVA-NP and EDF. Intensive phases of validation against reference or best-estimate calculations have been carried out and are still in process today. The present study focuses on the validation of the core burnup simulations that can be done with NEPHTIS. A fully detailed 2D core model has been implanted in the APOLLO2 transport code and served in a second phase as a best estimate to validate NEPHTIS.

As a first step, the 2D core reference model has been compared to the Monte Carlo code TRIPOLI4 for different core static configurations. These same core configurations have been used in a second step to performed several comparisons between APOLLO2 and NEPHTIS henceforth in the case of core burnup calculations. Static comparison of core reactivity, reaction rates and pin-by-pin power distributions indicates that the 2D APOLLO2 core model can be considered with confidence to validate the core burnup calculations performed with NEPHTIS.

In the second phase, reactivity, nuclei concentrations and power distribution from NEPHTIS have been compared to the reference 2D core model all along the core cycle length. It turns out that the evolution of the core reactivity and the isotopic concentrations are well predicted by NEPHTIS. The core $k_{effective}$ is calculated within ± 350 pcm. At the end of the core irradiation, the U^{235} consumption is calculated within ± 0,7 % while the plutonium mass discharged from the core is calculated within ± 1 %. As far as the core power distributions are concerned, small discrepancies (< 2.3 %) can be observed on the fuel block-averaged power distribution in the core. Analysis is also under progress in order to evaluate the 2D core power peak calculated in the diffusion code CRONOS2. Preliminary results showed that the local power is predicted within ± 6 %.

7. Acknowledgements

This study was performed at CEA in the framework of a coordinated project between CEA, EDF and AREVA-NP. The authors wish to thank these partners for financially supporting this work.

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