HORUS3D/N neutronics calculation tool dedicated to JHR design and safety studies - development, validation, biases and uncertainties quantification

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HORUS3D/N NEUTRONICS CALCULATION TOOL DEDICATED TO JHR DESIGN AND SAFETY STUDIES - DEVELOPMENT, VALIDATION, BIASES AND UNCERTAINTIES QUANTIFICATION

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ABSTRACT

The international Jules Horowitz Material Testing Reactor (JHR) is under construction at CEA Cadarache research center, in southern France. Its first criticality is foreseen by the end of the decade.

In order to perform JHR design and safety studies, a specific neutronics calculation tool, HORUS3D/N, based on deterministic codes and the European nuclear data library JEFF3.1.1, was developed. The purpose of this neutronics calculation tool is to predict JHR neutronics parameters: reactivity, power distribution, control rod reactivity worth,...

The calculation scheme relies on a two-level approach, with in the first level, a 2D flux calculation on restricted geometries with a fine energy meshing, and a cross section collapsing into a reduced energy meshing with the APOLLO2 lattice code. These collapsed cross sections are introduced into a full 3D core calculation with the CRONOS2 diffusion code in the second level.

The HORUS3D/N development followed the Verification & Validation – Uncertainty Quantification (V&V-UQ) process. This validation step aims at quantifying all the biases and uncertainties associated with HORUS3D/N calculations. These biases and uncertainties originate from both the nuclear data and the deterministic calculation scheme, for JHR calculations at beginning of life or during depletion (in particular for the JHR core at equilibrium).

The biases and uncertainties due to nuclear data are quantified by comparing the Monte Carlo reference TRIPOLI-4® calculations using the JEFF3.1.1 nuclear data library, with experimental data.

The biases and uncertainties due to the HORUS3D/N calculation scheme are assessed by comparing HORUS3D/N deterministic calculations with reference route calculations:

- 2D and 3D continuous-energy Monte Carlo TRIPOLI-4® calculations, for the JHR beginning of life core calculations,
- 2D APOLLO2-MOC deterministic calculations, using the Method Of Characteristics flux solver for the JHR core calculations during depletion.

Both reference routes are described with a heterogeneous geometry. They use the same JEFF3.1.1 nuclear data library as that of HORUS3D/N.

This paper describes the very latest developments implemented in the HORUS3D/N neutronics calculation tool and on the reference route considering depletion. These new developments take into account the APOLLO2.8/REL2005/CEA2005 package recommendations already applied for light water reactor studies. Moreover, the spatial meshing of the HORUS3D/N reference route was refined and optimized.

This paper also provides a synthesis of the biases and uncertainties associated with the different neutronics parameters calculated with this new version of the HORUS3D/N calculation scheme, for JHR safety studies.

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1 Introduction

The Jules Horowitz Reactor (JHR) [1] is the future Material Testing Reactor under construction in France. It will be a major research infrastructure in Europe designed to support existing power plant operations and lifetime extension, as well as future reactor design. Its objectives are to test the new structural material and fuel behavior under irradiation for the development of the GEN-III and GEN-IV reactors and also to demonstrate the satisfactory stainless steel behavior for current French Pressurized Water Reactor (PWR) lifetime extension. The JHR will also supply 25% to 50% of the European demand for radio-isotopes, mainly ^{99}Mo, for medical applications [2], and n-doped silicon for high power electronics.
The JHR first criticality is planned for the end of the decade.
The design and safety studies have been carried out using the neutronics calculation tool, HORUS3D/N, developed since the 2000s to meet the specific needs of JHR [3].
In this paper, after a brief description of the JHR, the HORUS3D/N calculation package will be presented. It will then focus on the very latest developments implemented in HORUS3D/N. These developments followed the Verification & Validation – Uncertainty Quantification (V&V-UQ) process, which aims at quantifying the biases and uncertainties associated with neutron calculations. At the end, the paper will provide a synthesis of the biases and uncertainties associated with the different neutronics parameters calculated using the new version of HORUS3D/N for JHR safety studies.

2 The Jules Horowitz Reactor

The JHR is a tank-in-pool type reactor using light water as its coolant and moderator. The maximum thermal power is 100 MW.
The core (600 mm. fuel active height) can contain 34 to 37 fuel elements, inserted in an aluminum alloy rack. When one of the 37 cells of the rack is free of a fuel element, an experimental device can be inserted. Up to 20 experimental devices can be loaded in the core or in the reflector and irradiated at the same time.
In order to obtain a high power density and thus reach a high fast neutron flux level (~5×10^{14} n/cm^2/s, E≥0.907 MeV), the fuel elements (see Fig.1) consist of 3 sets of curved plates assembled with aluminum stiffeners. The plates are cladded with Al-Fe-Ni. A hafnium control rod, connected to an aluminum follower (the follower is an aluminum tube replacing the absorber part of the control rod when it is withdrawn), or an experimental device can be loaded in the central hole. A boron insert is positioned 1 cm above the active height in each plate to prevent departure from nucleate boiling at the top of the core water channels.

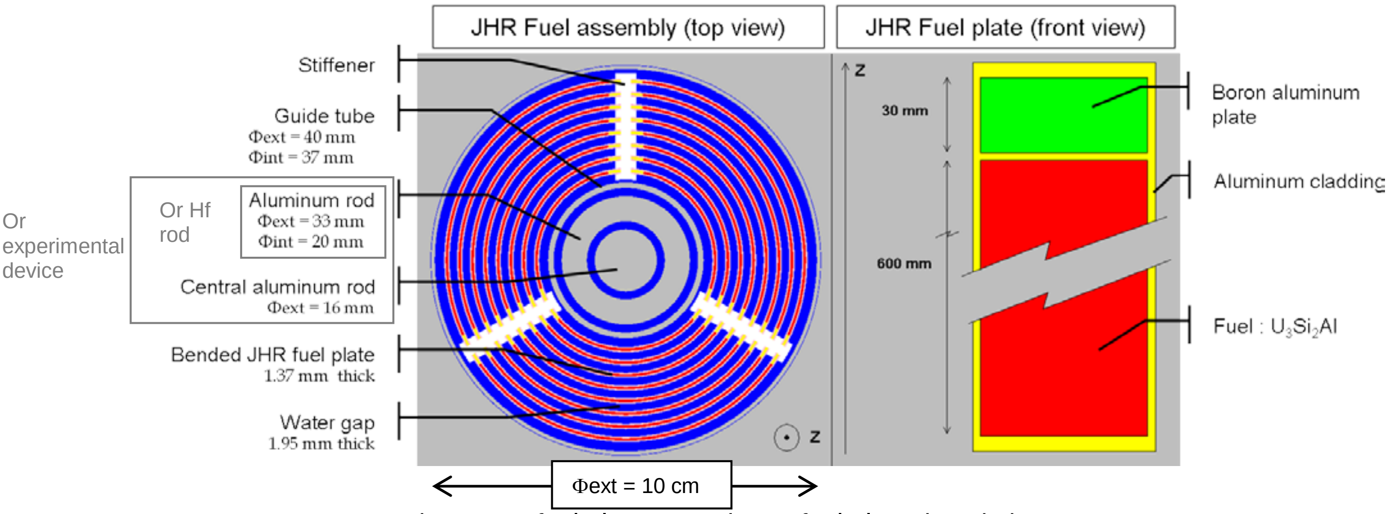


Fig.1: JHR fuel element and JHR fuel plate description

The JHR will start with a standard density low enriched U_3Si_2 fuel (e% ^{235}U = 19.75%, density 4.8 g.cm^{-3}), and with a maximum thermal power of 100MW.
The core will operate with a cold fuel (fuel temperature~100°C) and a slightly pressurized light water (pressure = 8 bars; temperature = 35°C).
The core area is surrounded by a reflector which optimizes the core cycle length and provides intense thermal fluxes in this area (~5×10^{14} n/cm^2/s, E≤0.625 eV). The reflector area is made of beryllium blocks. Experiments can be performed either in the core itself, as seen above, or in reflector static locations (Fig.2) but also on displacement systems as an effective way to investigate transient regimes occurring in incidental or accidental situations.
This provides a flexible experimental capability that can create up to 16 dpa/year - in comparison to the 2-3 dpa/year produced in industrial Light Water Reactors (LWR) - for in-core material experiments (with 275 full power operation days per year) and 600W.cm^{-1} for in reflector simple 1% ^{235}U enriched fuel experiments.

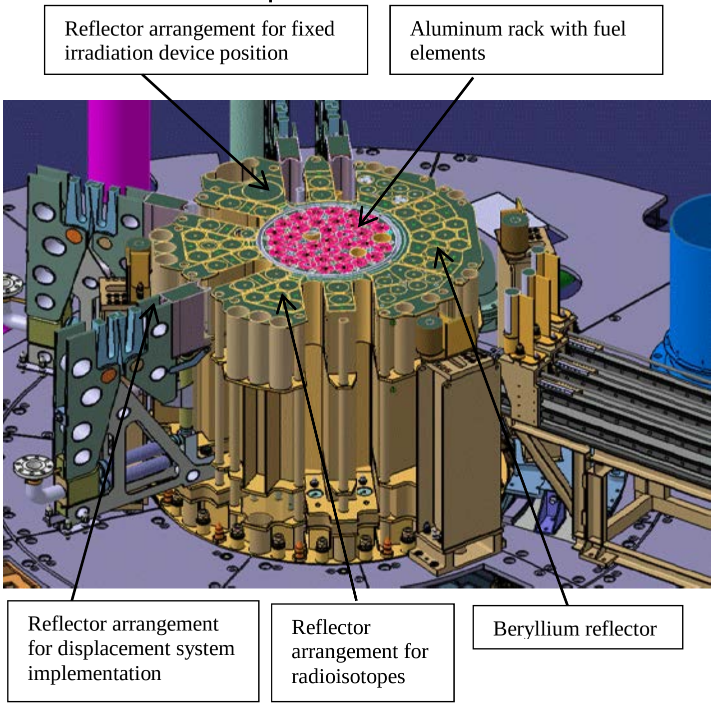


Fig.2: JHR description

3 The HORUS3D/N neutronics calculation package

The JHR innovative design led to the development of a specific neutronics tool, HORUS3D/N. The industrial route of this neutronics calculation tool is based on an APOLLO2 [4]/CRONOS2 [5] deterministic calculation scheme and the JEFF3.1.1 [6] European nuclear data library. It is a two-step calculation route (see Fig.4) with:

- ***for the first calculation step:*** several APOLLO2 two-dimensional (2D) fuel assembly calculations (one per component loaded in the center of the assembly) with fine energy-meshing to obtain self-shielded and depleted cross sections collapsed into 6 energy groups. The 1/6th assembly symmetry is used for the calculation. This first step provides libraries, tabulated versus burnup, for each kind of component present in the JHR,
- ***for the second calculation step:*** a 3D full core diffusion calculation on a hexagonal spatial meshing [3]. Despite the apparently irregular arrangement of the fuel element in the core, the assembly pattern has a hexagonal macro-symmetry (Fig.3). With the iso-parametric finite element method in the CRONOS2 code, each hexagonal mesh cell can be considered as a “Super Finite Element” (SFE). These SFEs need a conform mesh of arbitrary triangles, which form the basic finite elements. The fuel elements are meshed as dodecagons. The reflector region is modelled with a series of particular SFEs, allowing for an accurate modeling of radial and azimuthal heterogeneities.

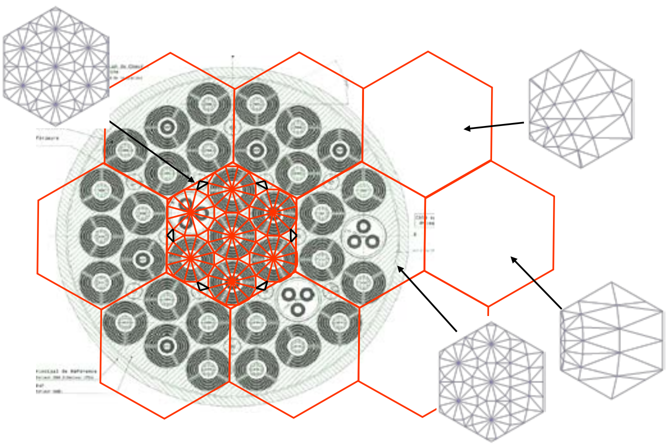


Fig.3: Division of the core by the hexagonal macro-symmetry and attribution of SFEs
for the CRONOS calculation

The HORUS3D/N development follows the Verification & Validation – Uncertainty Quantification (V&V-UQ) process [9]. This validation step aims at quantifying all the biases and associated uncertainties of HORUS3D/N calculations. These biases and uncertainties originate from both the nuclear data and the deterministic calculation scheme, for JHR calculations at beginning of life or during depletion (in particular for the JHR core at equilibrium).
The biases and uncertainties due to nuclear data are quantified by comparing Monte Carlo reference TRIPOLI-4® [13] calculations using the JEFF3.1.1 nuclear data library, with experimental data.
The biases and uncertainties due to the HORUS3D/N calculation scheme are assessed by comparing HORUS3D/N deterministic calculations with reference route calculations (Fig.4):

- 2D and 3D continuous-energy Monte Carlo TRIPOLI-4® calculations, for the JHR beginning of life core calculations,
- 2D APOLLO2-MOC deterministic calculations [7], [8], for the JHR depleted core calculations.

Both reference routes are described with a heterogeneous geometry and use transport solver. They use the same JEFF3.1.1 nuclear data library as HORUS3D/N.

The very latest developments concern the APOLLO2 first step of the HORUS3D/N industrial route, and the reference route for depletion (see Fig.4).

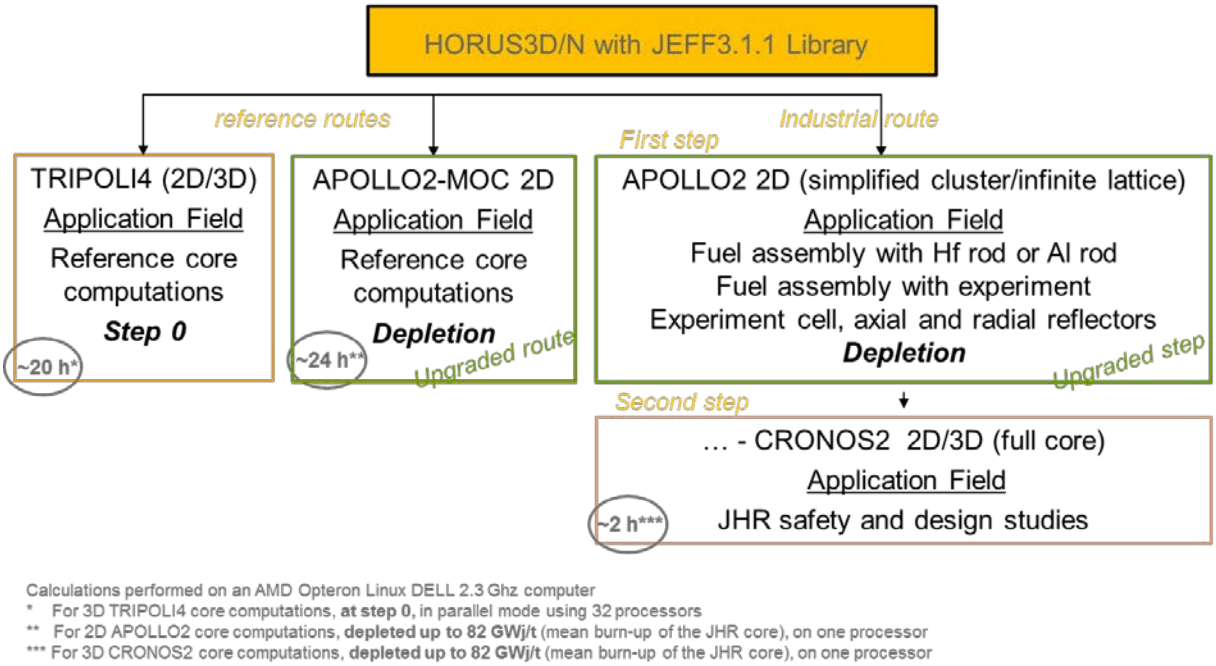


Fig.4: HORUS3D/N package calculation routes and upgraded routes

The following chapter will focus on these very latest developments.

4 HORUS3D/N package developments

Different developments were performed in HORUS3D/N last year: the reflector geometry is now updated in consistency with the JHR design evolution, the material balance with the main impurities is now considered, and, in the industrial route, new features are now available.
The main developments are presented hereafter. They take into account the APOLLO2.8/REL2005/CEA2005 package recommendations developed by CEA for light water reactor studies [10]. Moreover, the spatial meshing of the HORUS3D/N APOLLO2 core reference route was refined and optimized.

4.1 Industrial route developments

4.1.1 Self-shielding and flux computations

As mentioned above, these developments concern the first step of the industrial route, i.e. the APOLLO2 libraries[3] calculations for CRONOS2 (see Fig.4). The 2D calculation scheme for the different clusters (fuel assembly with Al rod, fuel assembly with Hf rod, fuel with experiments - Fig.1, and experiments in cell) and the radial reflector modelling, was improved by taking into account the APOLLO2.8/REL2005/CEA2005 package recommendations. The main developments for the fuel clusters are the following:

- concerning the self-shielding computations:
  - the use of the SHEM-281 group energy mesh on 1 D cylindrical simplified geometry,
  - for the U_3Si_2-Al fuel: the resonant mixture self-shielding treatment for ^{235}U, ^{238}U, ^{239}Pu and ^{240}Pu, is used in the 33-200 eV intermediate range, in order to rigorously account for resonance mutual shielding of these major actinides above 23 eV. Below 23 eV, the 281-group energy mesh (SHEM) is fine enough to avoid resonance self-shielding approximations,
  - for the Hafnium absorber: the resonant mixture self-shielding treatment for ^{177}Hf, ^{179}Hf, ^{176}Hf, ^{178}Hf, ^{180}Hf, is used up to 1keV in order to rigorously account for resonance mutual shielding of these isotopes in this energy range.

[3] Multi-group self-shielded cross sections for different fuel temperatures, moderator densities and fuel burn-ups, collapsed into 6 energy groups in the case of the JHR.

- concerning the flux computations:
  - the spatial meshing of the fuel assembly is performed with 24 angular sectors, i.e. 4 angular sectors on 1/6th of the assembly and 205 calculation regions (see Fig.5), allowing for a better assessment of the azimuthal thermal flux gradient near the stiffeners,
  - the computations are performed using the APOLLO2 Method Of Characteristics (MOC) flux solver with the SHEM-281 group energy mesh (no collapsing), at time-step zero and in depletion,
  - the calculations are based on fine tracking values: Tracking step: ΔR=0.04cm, radial direction number in [0, π]: NΦ=24, polar direction number in [0, $\pi/2$]: NΨ=3 (Bickley quadrature), associated with a P3 anisotropy scattering order,
  - neutron leakage: homogeneous B1 model with research of critical buckling.

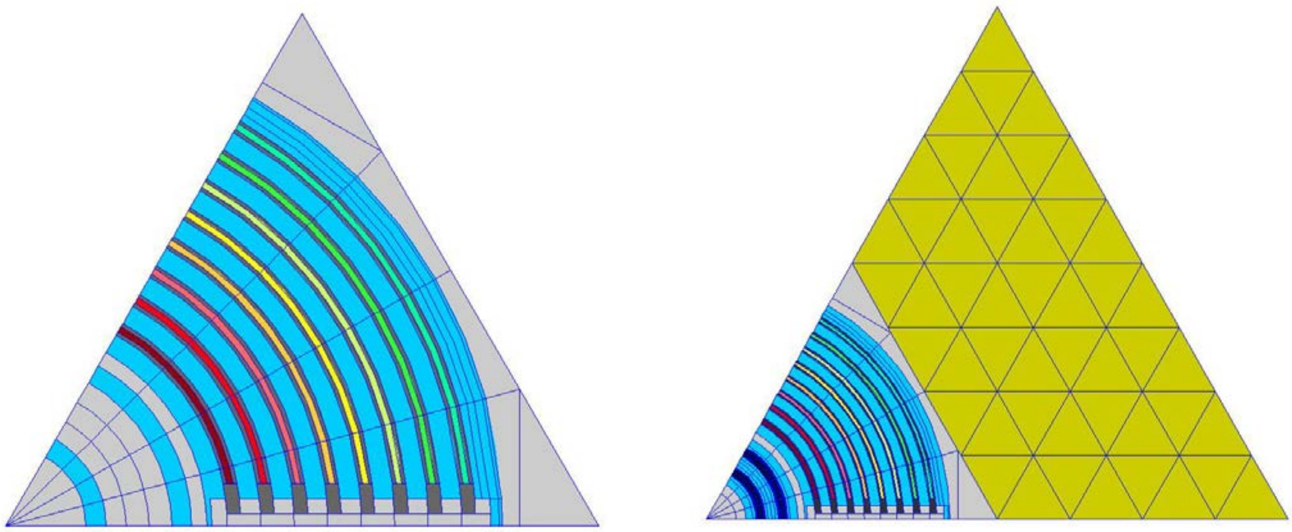


Fig.5: Flux computation geometry with APOLLO2 TDT-MOC flux solver:
1/6th of the fuel assembly with Al rod follower at the center of the assembly (205 calculation regions) (left hand side)
and 1/6th of the fuel assembly with hafnium rod with its homogenized environment in green (right hand side)

Table 1 summarizes the main developments performed on the HORUS3D/N v4.2 industrial route, in comparison with the previous versions (HORUS3D/N v4.1/v4.0). These new developments induced the adaptation of about 70 APOLLO2 procedures developed in the GIBIANE language.

Table 1: industrial route - APOLLO2 computation options - fuel clusters and reflector modellings

		HORUS3D/N v4.2 (new version)	**HORUS3D/N v4.1/v4.0** (previous versions)
APOLLO2	version	APOLLO2.8-4	APOLLO2.8-3
Library	version	JEFF3.1.1 (CEAV5.1.2, processed for APOLLO2)	JEFF3.1.1 (CEA2005V4.1.2, processed for APOLLO2)
Self-shielding	energy mesh	SHEM - 281 groups	XMAS - 172 groups
	method	Livolant-Jeanpierre + resonant mixture	Livolant-Jeanpierre + resonant mixture
	geometry	1D Cylindrical for most of the cases	
Flux calculation	energy mesh (collapsed cross sections)	**No collapsing (281 g)** *Except for:* *- axial reflector: 6 g* *- radial reflector: 22 g (t0 only)**	**6 g (collapsed from Pij 1D calculation)** *Except for:* *- fuel assembly+Hf rod: 172g* *- radial reflector: 20 g (t0 only)*
	geometry	1/6th of the fuel assembly with or without environment, "RZ" assembly for the axial reflector	
	spatial mesh	**24 angular sectors**	**6 angular sectors**
	solver	**MOC (2D)** *Except for:* *- axial reflector: SN*	**Pij (2D)** *Except for:* *- axial reflector: SN*
	Anisotropic scattering	**P3**	**P0-corrected**
	tracking	cyclic	cyclic
	Fine tracking values	- Tracking step: $\Delta R = 0.04$ cm - radial direction number in $[0, \pi]$: $N\Phi = 24$ - polar direction number in $[0, \pi/2]$: $N\Psi = 3$ - polar quadrature: "Bickley"	- Tracking step: $\Delta R = 0.05$ cm - radial direction number in $[0, \pi]$: $N\Phi = 24$ - polar direction number in $[0, \pi/2]$: $N\Psi = 2$ - polar quadrature: "Bickley"
	neutron leakage: homogeneous B1 model	critical buckling	geometrical buckling
Results		*self-shielded and depleted cross sections collapsed into 6 energy groups (input data for CRONOS2)*	

(*): obtained from the 2D core computations (see § 4.2), with homogenized fuel assemblies.

The number of flux calculation regions (205 for 1/6th of the assembly), and the order of anisotropic neutron scattering (P3) were optimized, i.e. a validation step (comparison of the computations with Monte Carlo TRIPOLI-4® calculations at step 0) performed on the 2 main fuel clusters (fuel assembly with Al rod, fuel assembly with Hf rod) showed that they correspond to the most computation time accuracy compromise:

- the computation region number of 205 is sufficient; finer meshing doesn't yield significant accuracy gains,
- the P3 scattering is necessary, in particular to evaluate the Hf absorption rate better; the computation time remains acceptable (~40 s with P3 to be compared to ~20 s with P0-corrected order).

4.1.1 Validation of the first step of the HORUS3D/N industrial route

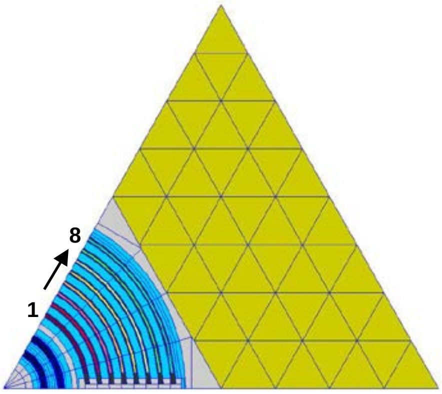
An important validation step was performed on the APOLLO2 assembly scheme with the calculation options presented in Table 1. This validation step was carried out on the 2 main fuel clusters: the fuel assembly with Al rod and the fuel assembly with Hf rod.

It consisted in comparing the APOLLO2 results with the Monte Carlo TRIPOLI-4® computations at step 0 with the same JEFF3.1.1 library.

Different computations were compared: reactivity, fission rate per fuel plate, hafnium rod efficiency. The results are the following:

- the reactivity is overestimated by ~+30 pcm for the fuel assembly with Al rod,
- the hafnium rod efficiency is overestimated by +1.1%,
- the discrepancy of the fission rate per fuel plate is less than 0.4% (see Table 2).

Table 2: Fuel assembly with Hf rod – biases on the fission rate per fuel plate



APOLLO2 modelling

Fuel plate	TRIPOLI-4®	std (%) MC unc.	(A2-T4)/T4 (%)	
			P0c	P3
1	0.503	0.008	**-0.6%**	0.1%
2	0.628	0.007	**-0.5%**	-0.1%
3	0.759	0.007	0.0%	0.3%
4	0.896	0.006	0.1%	0.3%
5	1.040	0.006	0.2%	0.2%
6	1.196	0.005	-0.1%	-0.1%
7	1.375	0.005	0.1%	0.1%
8	1.604	0.005	0.1%	-0.4%

These very good results validate the new APOLLO2 assembly scheme.

4.2 Reference route in depletion developments

4.2.1 Self-shielding and flux computations

The developments of the APOLLO2-MOC reference route (see Fig.3), follow, as APOLLO2 in the industrial route (see 4.1) the same APOLLO2.8/REL2005/CEA2005 package recommendations.
Table 3 summarizes the main developments performed on this route.

Table 3: reference route - APOLLO2-MOC computation options – 2D core

		HORUS3D/N v4.2 (new version)	**HORUS3D/N v4.1/v4.0** (previous versions)
APOLLO2	version	APOLLO2.8-4	APOLLO2.8-3
Library	version	JEFF3.1.1 (CEAV5.1.2)	JEFF3.1.1 (CEA2005V4.1.2)
Self-shielding	energy mesh	SHEM - 281 groups	XMAS - 172 groups
	method	Livolant-Jeanpierre + resonant mixture	Livolant-Jeanpierre + resonant mixture
	geometry	1D Cylindrical for most of the cases	
Flux calculation	energy mesh (collapsed cross sections)	**22 g** (collapsed from Pij 1D calculation)	**20 g** (collapsed from Pij 1D calculation)
	geometry	2D core	
	spatial mesh	Assembly: **12 angular sectors** Reflector: **new optimized spatial mesh**	Assembly: **6 angular sectors**
	solver	**MOC**	**MOC**
	Anisotropic scattering	**P3**	**P0 corrected**
	tracking	Non cycling	cyclic
	Fine tracking values	- Tracking step: ΔR= 0.04 cm - radial direction number in [0, π] : $N\Phi$ = 24 - polar direction number in [0, π/2] : $N\Psi$ = 3 - polar quadrature: "Bickley"	- Tracking step: ΔR= 0.05 cm - radial direction number in [0, π] : $N\Phi$ = 24 - polar direction number in [0, π/2] : $N\Psi$ = 2 - polar quadrature: "Bickley"

…/…

Table 3: reference route - APOLLO2-MOC computation options – 2D core (continued)

		HORUS3D/N v4.2 (new version)	**HORUS3D/N v4.1/v4.0** (previous versions)
Flux calculation	Leakage	Axial buckling No axial leakage when compared with TRIPOLI4 or CRONOS2	
Results		*Reactivity, power distribution,…* *in depletion*	

The spatial meshing of the reflector (16506 calculation regions), the assembly spatial meshing (12 angular sectors) and the anisotropic scattering order (P3) were optimized, i.e. a validation step (comparison of the computations with Monte Carlo TRIPOLI-4® calculations[4] at step 0) showed that they correspond to the most computation time accuracy compromise:

- the assembly spatial meshing with 12 angular sectors is sufficient to evaluate the azimuthal thermal flux,
- P3 anisotropic scattering enables us to reduce the reactivity discrepancy ($\Delta\rho$= -11 pcm with P3, $\Delta\rho$= -92 pcm with P0-corrected); the computation time remains acceptable (22 min. to be compared to 11 min. with P0-corrected order) (see Table 4).

Table 4: APOLLO2-MOC/TRIPOLI4 discrepancies - loaded core (37 fuel assemblies), no experiments in the core nor in the reflector, no Hafnium control rods, at JHR begin of life

	HORUS3D/N v4.2	
	P0-c	P3
Reactivity		
$\Delta\rho$ (pcm)	-92	-11
Plate power distribution		
mean deviation (%)	+1.1	+1.1
min. deviation (%)	-2.6	-2.9
max. deviation (%)	+2.9	+3.0
Computation time (Step 0)	11min.	22min.

The following paragraph focuses on the work performed to optimize the spatial meshing of the reflector, considering the REL2005 recommendation.

4.2.2 Reflector spatial meshing optimization

Before HORUS3D/Nv4.1, for APOLLO2-MOC calculations, the spatial meshing of the core and of the reflector was performed with the pre-processing user interface SILENE. The spatial meshing generation was a time-intensive task (duration of several weeks), with a serious risk of error.

Therefore, the decision was made to introduce a more modern and high performance pre-processing user interface into HORUS3D/N: the SALOME platform [14], in order to:

- generate a spatial meshing in a few minutes, and thus follow the evolution of JHR design easily,
- have the same geometric model between Monte Carlo and deterministic schemes, and thereby limit the risk of error and the computation biases,
- have a greater flexibility and thus refine areas of interest.

Up to now, only the reflector zone has been concerned with these new developments. HORUS3D/Nv4.1 was an intermediate version used to test the feasibility of the SALOME integration.

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[4] Monte Carlo TRIPOLI-4® Computations are performed with 4.10^8 particles (corresponding to a standard deviation on k_{eff} of 5 pcm).

In HORUS3D/Nv4.2, thanks to SALOME, the spatial meshing of the reflector was upgraded in order to:

- follow the APOLLO2.8/REL2005/CEA2005 package recommendations (see Fig.6), i.e. refine the radial mesh near the core in order to respect the thermal neutron flux gradient:

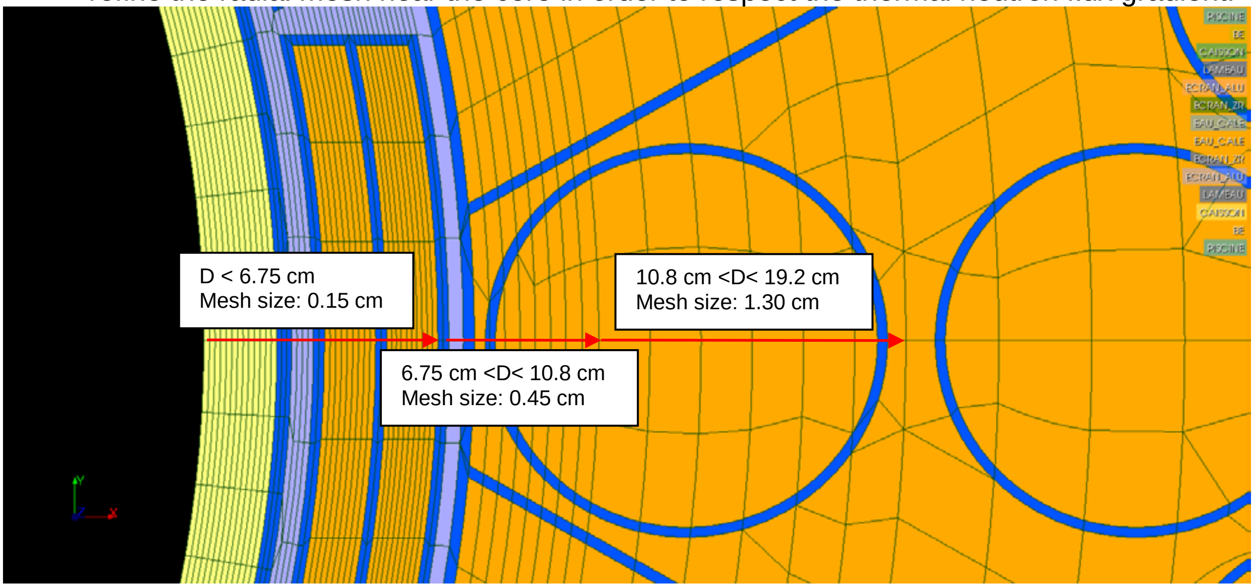

Fig.6: reflector meshing with SALOME in compliance with APOLLO2.8/REL2005/CEA2005 package recommendations

- define a specific meshing for each experiment (see Fig.7) without changing the meshing of the rest of the reflector:

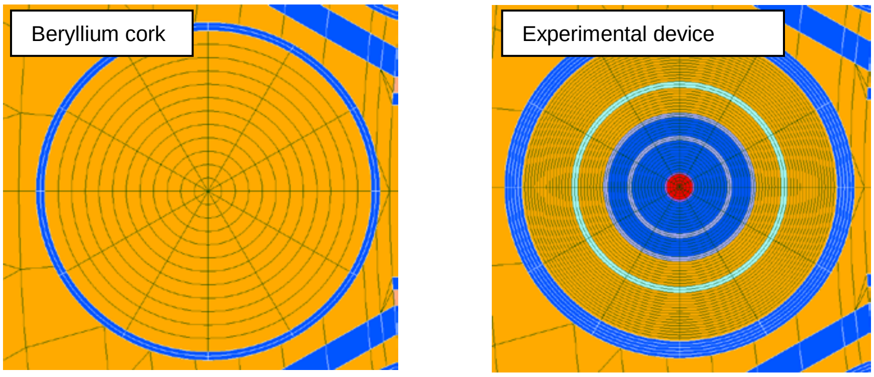

Fig.7: specific meshing with SALOME – Beryllium cork (left hand side) – experimental device (right hand side)

- optimize the mesh number (i.e. define the meshing which corresponds to the most computation time accuracy compromise).

Table 5 presents the mesh number of the two last versions of HORUS3D/N (see Fig.8). One can notice that the mesh number of the reflector is equivalent between the 2 versions. Thus, this new meshing doesn't increase the computation time, but it is optimized (refine meshing in the areas of interest) and generated much more quickly: a few minutes with SALOME, in comparison to 3 to 4 weeks with SILENE.

Table 5: mesh number of HORUS3D/N v4.2 and v4.0 versions - loaded core (37 fuel assemblies), no experiments in the core nor in the reflector

	HORUS3D/N v4.2 (reflector meshing with SALOME)	HORUS3D/N v4.0 (meshing with SILENE)
Core	25686*	16140*
Reflector	16506	13349
Total	42192	29489

(*): HORUS3D/N v4.2: 12 angular sectors for each assembly; HORUS3D/N v4.0: 6 angular sectors for each assembly.

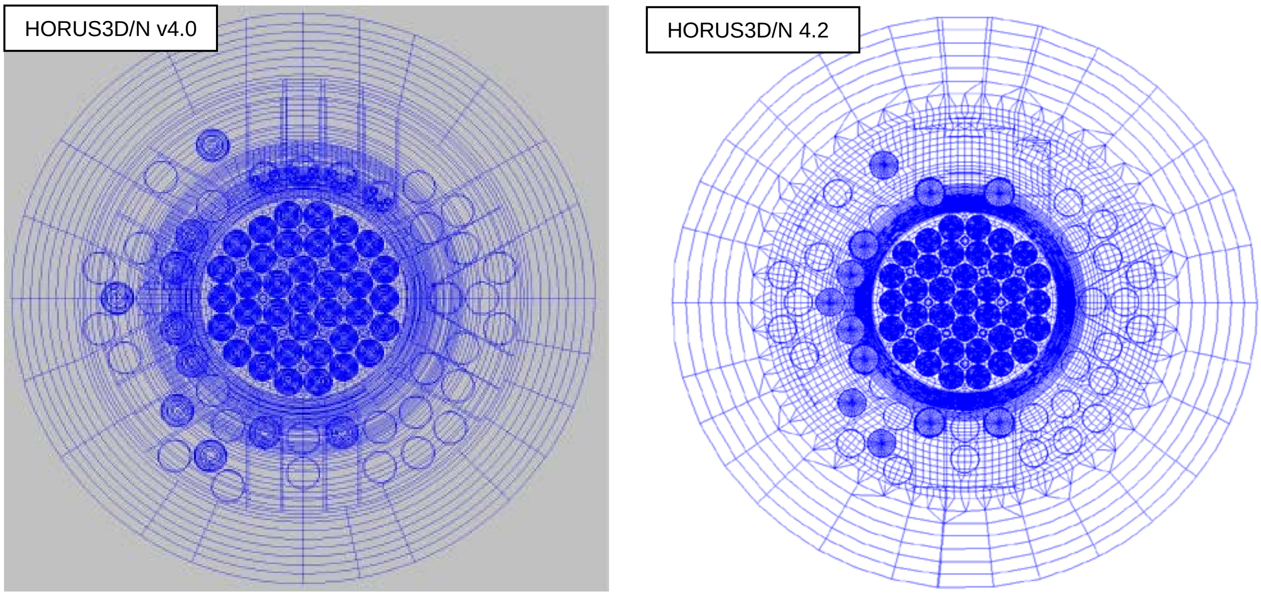

Fig.8: core and reflector meshing for v4.0 and v4.2 HORUS3D/N versions

4.2.3 Validation of the reference route in depletion

An important validation step was performed on the 2D APOLLO2-MOC core scheme of HORUS3D/N v4.2 (with the optimized meshing – see § 4.2.2, and the calculation options as presented in Table 3).
It consisted in comparing the 2D APOLLO2-MOC results versus the 2D Monte Carlo TRIPOLI-4®[5] at step 0 with the same JEFF3.1.1 library.
Different configurations were studied increasing successively the core perturbation:

- 37 Fuel Elements, without experiments, without Hafnium rod (“37FE” configuration),
- 34 Fuel Elements, maximal core experimental loading (7 Fuel elements with experiments +3 cells loaded with experiments), without Hafnium rod (“34FE” configuration),
- 34 Fuel Elements, maximal core experimental loading, with 10 Hafnium rods (“34FE_10Hf” configuration),

the reflector being loaded or not with the 12 experiments.

The results were compared to those of the previous version, the 2D APOLLO2-MOC core scheme of HORUS3D/N v4.0.

Table 6 and Table 7 summarize the discrepancy between the 2 versions when compared to the Monte-Carlo TRIPOLI-4® code, for the plate power distribution and the reactivity, respectively.
Fig.9 gives an example for the plate power distribution computation.

Table 6: Plate power distribution at JHR beginning of life - APOLLO2-MOC v4.2 and v4.0/TRIPOLI-4® discrepancies

		HORUS3D/N v4.2			HORUS3D/N v4.0		
REFLECTOR	CONFIG	mean deviation (%)	max. deviation (%)	min. deviation (%)	mean deviation (%)	max. deviation (%)	min. deviation (%)
Without experiments	*37FE*	**1.1%**	3.0%	-2.9%	**1.9%**	4.2%	-3.5%
	34FE	**1.2%**	2.7%	-4.4%	**1.9%**	4.6%	-6.0%
	34FE_10Hf	**1.5%**	3.3%	-5.4%	**2.2%**	4.8%	-6.6%
With experiments	*37FE*	**1.1%**	3.1%	-2.3%	**2.1%**	4.8%	-3.6%
	34FE	**1.2%**	2.3%	-4.6%	**2.1%**	4.7%	-6.2%
	34FE_10Hf	**1.6%**	3.3%	-5.4%	**2.5%**	5.4%	-6.8%

[5] Monte Carlo TRIPOLI-4® Computations are performed with a total number of 4.10^8 neutron histories (corresponding to a standard deviation on $k_{effectif}$ of 5 pcm).

Table 7: Reactivity at JHR beginning of life - APOLLO2-MOC v4.2 and v4.0/ TRIPOLI-4® discrepancies

		HORUS3D/N v4.2	HORUS3D/N v4.0
REFLECTOR	CONFIG	Δρ (pcm)	Δρ (pcm)
Without experiments	*37FE*	-11	-33
	34FE	61	67
	34FE_10Hf	-209	-72
With experiments	*37FE*	-8	-46
	34FE	66	62
	34FE_10Hf	-207	-85
Computation time (Step 0)		~20 min.	~10 min.

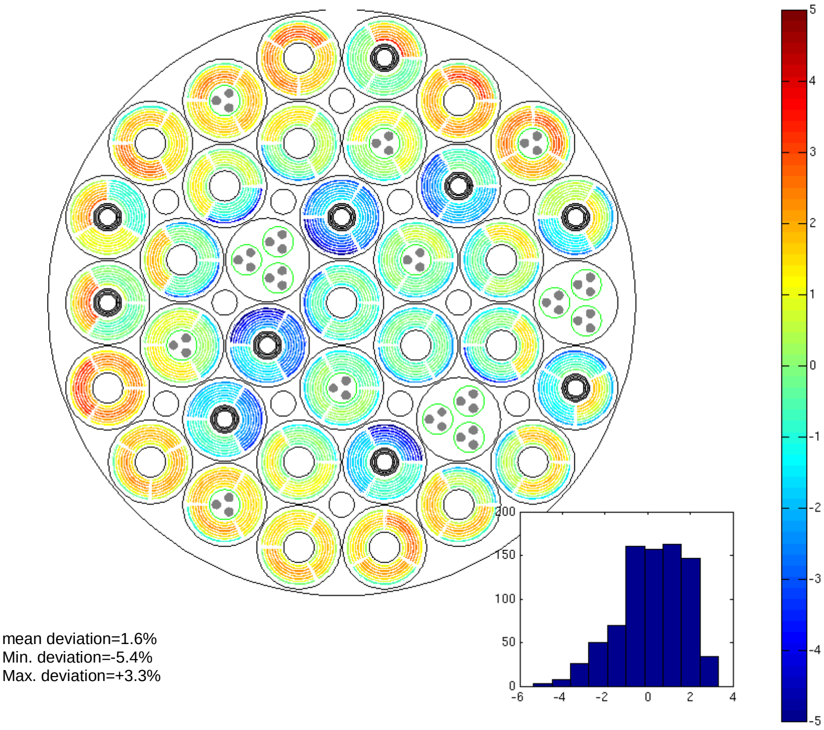

Fig.9: Plate power distribution at JHR beginning of life - APOLLO2-MOC v4.2/ TRIPOLI-4® discrepancies (in %) - 34 Fuel Elements, maximal core experimental load, 10 Hafnium rods (“34FE_10Hf” configuration), maximal reflector experimental load

Regarding the plate power distribution, APOLLO2-MOC v4.2 was improved significantly in comparison to the previous version. The mean deviation is strongly reduced: dropping from 2.5% in the v4.0 version to 1.6% in the v4.2 version in the most disturbed configuration (see Table 6).
Regarding the reactivity, APOLLO2-MOC v4.2 computations, when compared to TRIPOLI-4®, slightly underestimate the reactivity in the less disturbed configurations (-11 pcm) (see Table 7). The 10 Hafnium rods reactivity worth is overestimated by 4%.
The computation time remains acceptable (20 min. at step 0, in comparison to 10 min. for the previous version) (see Table 7).
These very good results validate the 2D APOLLO2-MOC reference core scheme of HORUS3D/N v4.2.

The development of the HORUS3D/N industrial route (see Fig.4) followed the Verification & Validation – Uncertainty Quantification (V&V-UQ) process. First, it was submitted to a Verification step including non-regression tests, and then to a Validation process in order to Quantify the biases and Uncertainties to be applied to each parameter computed with the calculation route.
The following chapter briefly presents this validation process and focuses on the main results of this step: the biases and uncertainties quantification.

5 HORUS3D/N industrial route global validation

The HORUS3D/N simulations are used to predict neutronics parameters with quantifiable confidence and across the JHR application domain. The V&V-UQ process aims at determining to what degree a calculation tool is an accurate representation of the "real world", i.e. it aims at quantifying the biases and uncertainties associated with the HORUS3D/N computations. These biases and uncertainties have two origins:

- the nuclear data which are physical parameters input and which describe all the interactions between neutrons with matter,
- the models, and more generally, all the approximations used in the APOLLO2/CRONOS2 calculation scheme (approximation of the real geometry, energy cutting, resonance self-shielding, depletion, flux solver, etc.).

5.1 Nuclear data validation

The biases and uncertainties due to nuclear data are quantified by the comparison between Monte Carlo reference TRIPOLI-4® calculations and an integral experiment.
In order to provide JHR representative measurement data the AMMON program was launched between late 2010 and early 2013 in the EOLE zero-power critical mock-up (see [9] for details). The AMMON experiment consists of an experimental zone dedicated to the analysis of the JHR neutron and photon physics surrounded by a driver zone. The experimental zone, for the reference configuration, contains 7 JHR fresh fuel standard assemblies-like (see § 2) inserted in an aluminum alloy hexagonal rack (30 cm side length). The driver zone for the reference configuration consists of 622 standard Pressurized Water Reactor (PWR) fuel pins (3.7% ^{235}U enriched UO_2), with Zircaloy-4 cladding and stainless steel overcladding. The hexagonal lattice pitch of the driver pins was optimized in order to reproduce, as well as possible, the same neutron spectrum as the one of the experimental zone. 5 configurations were studied (see Fig.10):

- a reference configuration with 7 JHR fresh fuel assemblies,
- a configuration with a hafnium control rod totally or half inserted in the middle assembly,
- a configuration with a beryllium block replacing the middle assembly,
- a configuration with water in the middle of the middle assembly (withdrawn Hf rod follower),
- a configuration with water replacing the middle assemblies.

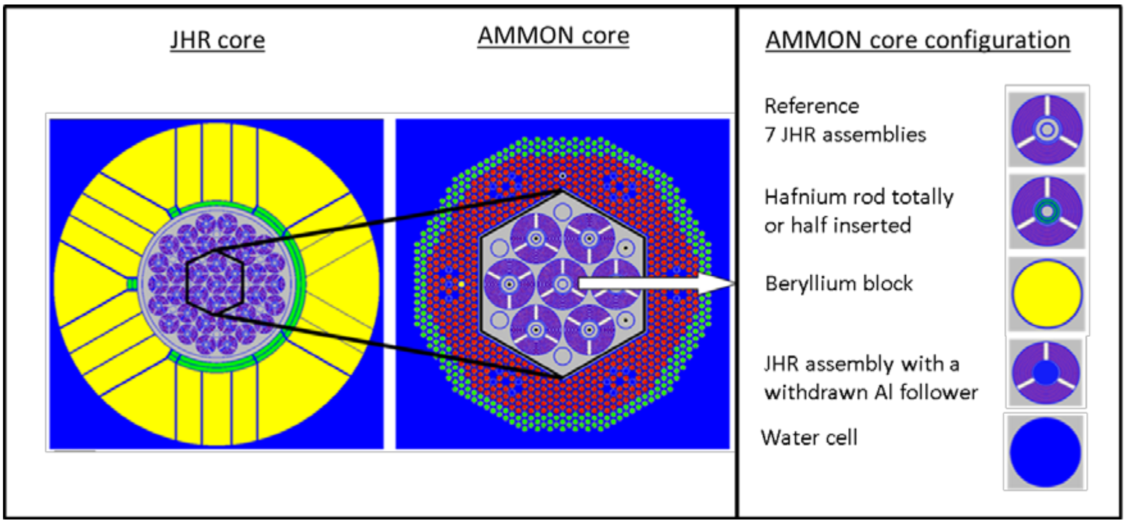

Fig.10: configurations of the AMMON experiment

The interpretation of the AMMON experiments with reference TRIPOLI-4® calculations using the JEFF3.1.1 nuclear data library, allowed us to quantify the biases and uncertainties originating from the nuclear data[6]. These results were transposed from the AMMON experiment to the real

[6] Few physical assumptions are made in TRIPOLI-4® that is why the biases are supposed to come only from nuclear data.

JHR core with the representativity methodology [11], [12], for the JHR-Beginning Of Life but also for the JHR in equilibrium. Indeed, a specific study showed that the ^{239}Pu (produced in the U_3Si_2-Al fuel thanks to ^{238}U radiative capture) contribution in assembly fission rates remains limited (<10%) compared to the ^{235}U contribution during the JHR life (the JHR neutron spectrum can be considered as constant). Thus, even if the AMMON experiments were performed on fresh JHR fuel, the results can also be transposed to the JHR in equilibrium.
The biases and uncertainties on the different neutronics parameters computed with HORUS3D/N originating from the nuclear data are summarized in [9]. They are not recalled here. Only the results of the global validation step are presented in chapter *6.*

The biases and uncertainties on the different neutronics parameters computed with HORUS3D/N, due to nuclear data and to the calculation scheme (see § 5.2) are summarized in chapter 6.

5.2 HORUS3D/N scheme validation

An important HORUS3D/N scheme validation step was carried out during late 2014. It consisted in assessing the biases and uncertainties due to the scheme itself (geometry approximation, energy cutting, flux solver,…) by comparing HORUS3D/N industrial route computations with reference routes calculations (see chapter 3, especially Fig.4):

- 2D and 3D continuous-energy Monte Carlo TRIPOLI-4® calculations, for the JHR beginning of life core calculations,
- 2D APOLLO2-MOC deterministic calculations, using the Method Of Characteristics flux solver, for the JHR core calculations during depletion.

The validation studies will be completed in 2015 with the use of TRIPOLI-4® in its new depletion mode, for the comparison with the HORUS3D/N calculations.

The scheme application domain matches the JHR operation domain, i.e.:
. Concerning the reactor configuration:

- fuel assembly: 34 to 37 fuel assemblies with or without Hafnium rods,
- maximal core experimental load: 7 fuel elements with experiments + 3 cells loaded with experiments
- maximal reflector experimental load: 12 experiments

. Concerning the time step:

- beginning of cycle (no xenon, samarium at saturation)
- Xenon equilibrium
- Mid cycle
- End of cycle.

Over 100 validation cases were performed to cover the JHR operation domain and to ensure statistical representativeness.
The detail of this study is not presented in this paper. Only the results of the global validation step are presented hereafter.

The biases and uncertainties on the different neutronics parameters computed with HORUS3D/N, due to the calculation scheme and to nuclear data (see § 5.1) are summarized in chapter 6.

6 HORUS3D/N performances: biases and uncertainties quantification

The results of the validation steps presented in chapter 5 were combined as follows for each JHR relevant parameter computed with the HORUS3D/N industrial route:

- Biases: $$\mathrm{Biases_{Global}} = \mathrm{Biases_{Scheme}} + \mathrm{Biases_{ND}} \quad (1)$$
- Uncertainties: $$\sigma_{Global} = \sqrt{(\sigma_{Scheme})^2 + (\sigma_{ND})^2} \quad (2)$$

With:
$Biases_{scheme}$: Biases of HORUS3D/N due to the calculation scheme, see § 5.2,
$Biases_{ND}$: Biases of HORUS3D/N due to Nuclear data see § 5.1,
σ_{scheme}: uncertainties of HORUS3D/N due to the calculation scheme, see § 5.2,
σ_{ND}: uncertainties of HORUS3D/N due to Nuclear data, see § 5.1.

Table 8 summarizes the results of the global validation of HORUS3D/N v4.2.

Table 8: HORUS3D/N v4.2 biases and uncertainties assessment

		Biases and uncertainties (2σ)	
		Step 0	**Depletion**
Reactivity of the critical core at nominal and cold conditions	Without control rod	-71 pcm ± 650 pcm	-233 pcm ± 827 pcm
	With control rods	-366 pcm ± 811 pcm	-663 pcm ± 911 pcm
Initial core reactivity (with 8 IA)		-862 pcm ± 640 pcm	-
Xenon equilibrium antireactivity		-	+0% ± 3.2%
Xenon antireactivity at the peak		-	+0% ± 16.9%
Samarium antireactivity		-	+0% ± 2.5%
Integral rod worth		+5.9% ± 4.7%	+6.4% ± 3.6%
Differential rod worth		+4.3% ± 3.2%	+8.9% ± 3.2%
In core experiment reactivity worth		-1.5% ± 6.0%	-3.4% ± 6.1%
In reflector experiment reactivity worth		-72 pcm ± 39 pcm	-92 pcm ± 31 pcm
Hot assembly power		+0% ± 5.4%	+0% ± 5.4%
Hot plate power		-2.6% ± 4.6%	-2.6% ± 4.6%
Burnup distribution – Assembly level		-	+0% ± 4.1%

7 Conclusion

The HORUS3D/N neutronics calculation tool, dedicated to JHR design and safety studies was upgraded in 2014 in order to take into account the APOLLO2.8/REL2005/CEA2005 package recommendations already applied for light reactor studies: HORUS3D/N v4.2 was thus released by the end of 2014. An important validation step was carried out to quantify the biases and uncertainties to be associated with each neutronics parameter computed with the new scheme. Thanks to the AMMON experiments, and to the improvement of the scheme, the performances were improved, allowing a better assessment of the JHR safety margins. Consequently, a complete validation file of the JHR neutronics calculation tool is obtained.
The development of a new neutronics deterministic calculation tool dedicated to JHR operation and loading studies will begin by the end of 2015. The objective of the tool is to deal with time constraint (a JHR loading will have to be fully calculated in a few days) and user experience (the studies will be performed routinely by JHR operators). The new HORUS3D/N v4.2 tool will serve as a starting point for these new developments.

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