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NEW MODELLING OF LWR ASSEMBLIES USING THE APOLLO2 CODE PACKAGE

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ABSTRACT

The recent package APOLLO2.8-MOC/CEA2005-SHEM developed by CEA is undergoing a large validation program. First works of development and validation of a new optimized calculation scheme called *REL2005* - based on the Method of Characteristics - are presented in this paper. The comparison of APOLLO2.8/*REL2005* results to reference Monte Carlo TRIPOLI4 ones on specific PWR benchmarks emphasizes the ability of the deterministic tool to calculate UOX assemblies poisoned by gadolinium within 200 pcm accuracy on multiplication factor. Validation against the CAMELEON mock-up experiment confirms this good performance: pin-by-pin power is always predicted within 2% accuracy. Comparisons against reference deterministic depletion calculations show also good agreements: Keff and pin-by-pin power are respectively predicted within 150 pcm and 1% accuracy up to 60 MWd/kg.

Key Words: PWR, Gadolinium, CAMELEON, APOLLO2, Method of Characteristics, SHEM

1. INTRODUCTION

Developments recently implemented in the CEA neutronics APOLLO2.8 code [1,3] now allow 2D-exact heterogeneous deterministic calculations of Light Water Reactors assemblies with reasonable computing times. Those developments are:

- new SHEM 281-group energy mesh defined to avoid resonance self-shielding approximations below 23 eV [2],
- multi-domain DP_N acceleration techniques for the Method Of Characteristics (MOC) [3].

Two recent papers [4-5] presented some numerical elements of validation for fresh BWR fuel assemblies. Comparisons showed good agreement with reference TRIPOLI4 continuous-energy Monte Carlo calculations [6] (same nuclear data processed with NJOY [7] from the JEFF3.1 evaluation at 300 K were used for the two codes).

However, the 281-group MOC calculation needed to be optimized to reach computing times acceptable for depletion assembly calculations. A large program of numerical and experimental validations has started up with CEA to define a new calculation scheme based on these new tools and evaluate its performances. This new scheme, called "*REL2005*", benefits from all the knowledge of the previous one "*CEA-97*" [8], in particular the same rigorous methodology of validation is used [9].

First works, presented in this paper, concern the optimization and validation of UOX PWR assemblies' calculations and especially UOX assemblies poisoned with gadolinium. In the next section, the new *REL2005* calculation scheme based on the APOLLO2.8-MOC/CEA2005-SHEM tools is described. The third section deals with time 0 optimization works of this scheme, achieved against reference TRIPOLI4 3D continuous-energy Monte Carlo calculations. Section four presents experimental validation with the French CAMELEON experiments analysis and section five deals with depletion validation against a reference 281-group APOLLO2-MOC calculation; the strong improvements brought by the new SHEM-281 group energy structure on reactivity loss will be highlighted.

2. THE *REL2005* SCHEME

Despites improvements in the acceleration techniques for the MOC [3], a direct 281-group assembly calculation is too time consuming for generating a multi-parameters cross section library for core depletion calculations (it would take several days on one processor, APOLLO2 being not parallelized). More than a factor 10 has to be gained on time consumption. If we want to keep the MOC to describe local heterogeneities and have a good spatial calculation, the main way is to reduce the number of energy groups even if optimizations have to be done on other items like space mesh, track density and scattering order of anisotropy.

In order to reduce the number of groups, a preliminary calculation must be introduced, which rests on a transport solver much less costly than the MOC but accurate enough to provide realistic self-shielded cross sections and local spectra. The optimized *REL2005* assembly scheme is therefore based on a two-level approach that we can summarize like a fine-in-energy but rather rough-in-space calculation followed by a rather rough-in-energy but fine-in-space calculation. The main difficulty is to find the balance between both that preserves the quality of the final results. Some details of the *REL2005* scheme are now given (see also Fig. 1); validations of most of the choices will be presented in the next chapter.

1) In the first step, the neutron energy spectrum is calculated in the 2D assembly geometry, using a Pij multicell model : the UP1 Interface Current method based on linearly anisotropic interface fluxes. The fuel pellets are split into 4 (UOX) or 6 ($UO_2Gd_2O_3$) rings in order to give an accurate representation of absorption of U238 and even isotopes of gadolinium inside the pins. Local spectrum calculation is performed in the SHEM 281-group structure, instead of the previous European XMAS-172g mesh [10]. Above the refined energy mesh, i.e E>23 eV, self-shielding formalism based on the "Background Matrix" is used. With the calculated fluxes, cross sections are collapsed without any spatial homogenization according to an optimized 26-group energy mesh, which avoids the energetic equivalence procedure.

2) In a second step, a heterogeneous 26-group flux calculation is performed on the "exact" 2D geometry using the unstructured-meshes allowed by the MOC solver.

3) If depletion calculation is needed, one evolution step is carried out on the second-level media with fluxes calculated by the MOC and new nuclide concentrations are obtained in each ring of each pin. 281-group Pij-multicell calculation is performed again to get the new spectrum and to collapse again cross sections into the 26-group mesh.

This procedure is iterated up to the last burn-up step. Self-shielding calculations are repeated at the following steps: 4, 8, 12, 24, 36, 48…MWd/kg.

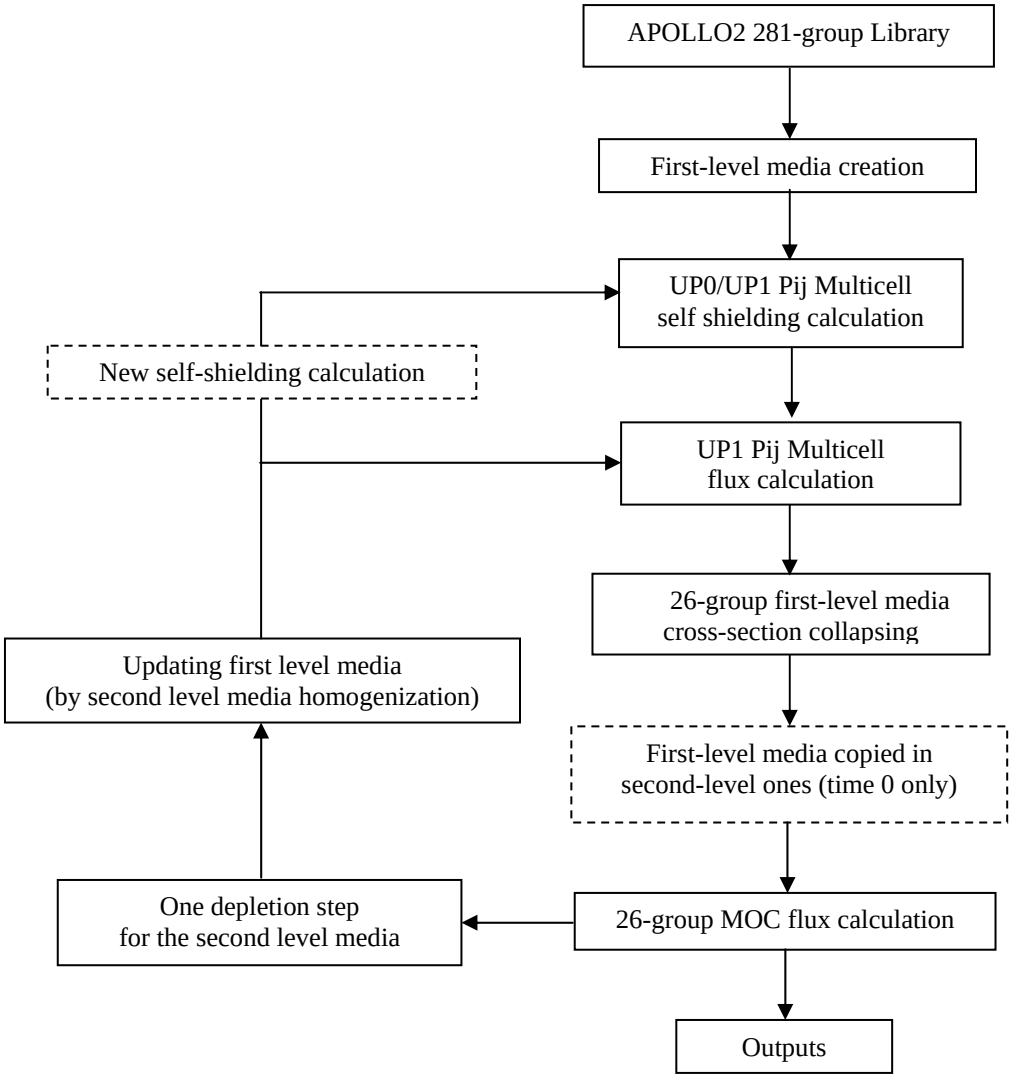

Figure 1. New APOLLO2.8 LWR calculation scheme "*REL2005*"

3. *REL2005* SCHEME OPTIMIZATION

3.1 Benchmarks

Three PWR-representative UOX assembly Benchmarks have been studied:

- a UOX 17x17 with a 4% uniform enrichment and 25 water holes,
- a first UOX assembly (named “Gd_A”) with 12 pins poisoned with gadolinium and largely spread on the assembly (in black color on Fig. 2),
- a second gadolinium assembly (named “Gd_F”) where poisoned pins are placed closer around the center with a stronger shadow effect, four of them facing water holes.

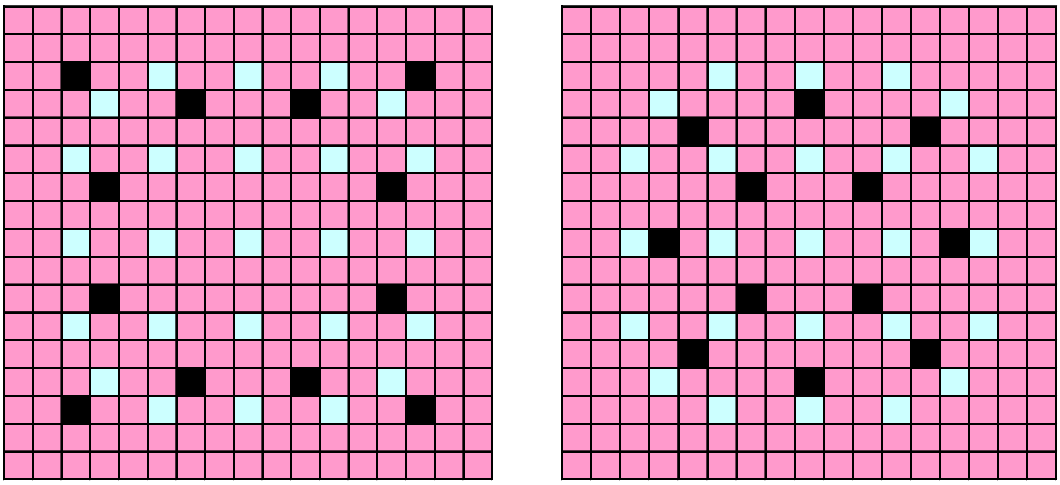

Figure 2. UO2-Gd2O3 PWR assembly benchmarks: Gd_A and Gd_F

Common parameters are: lattice pitch=1.26 cm, assembly pitch=21,42 cm, moderator temperature=300°C, pressure=150 bars.

3.2 Reference calculations

As mentioned before, two reference calculations have been carried out for the 3 benchmarks:

- T4 : TRIPOLI4 Monte-Carlo calculation performed with a simulation of 100 million neutron histories leading to a standard deviation of 12 pcm on Kinfinity and 0,1 % on pin absorption rates,
- A2ref : 281-group deterministic APOLLO2-MOC calculation with the fine mesh presented on Fig. 3. associated with very tight trajectories (36 radial track directions in $[0, \pi]$ with tracks spaced by 0.01 cm, 8 azimuthal directions in $[0, \pi/2]$ with a Gaussian quadrature). The scattering anisotropy is taken into account by a P5 expansion of the scattering law.

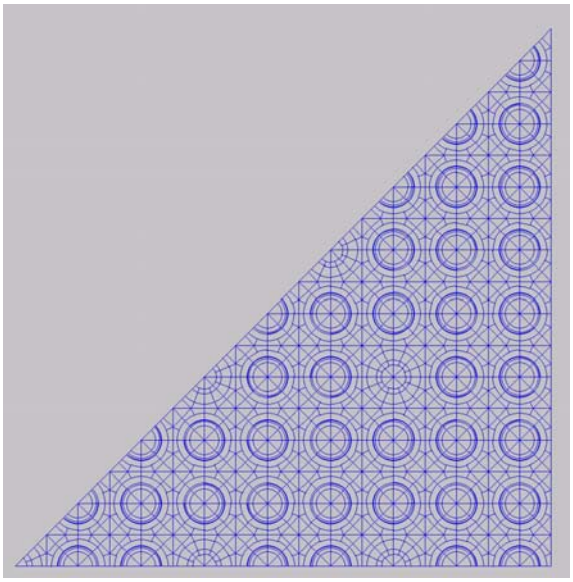

Figure 3. Fine mesh for reference MOC calculations

Table I shows a good agreement between reference deterministic calculations and Monte Carlo ones. Discrepancies on Keff are less than 150 pcm and discrepancies on gadolinium worth are about 1%. The radial distribution of absorption and fission rates is well calculated: in UOX-pins, absorption and power peaks are underestimated by less than 0,4%; in Gd-pins, they are overestimated by 0.8 % in coherence with the gadolinium worth.

Table I. Reference APOLLO2.8-MOC against Monte Carlo TRIPOLI4 calculations

	Benchmark	TRIPOLI4	A2ref/T4
Keff (ΔGd worth)	UOX	1.40507±11pcm	-40 pcm
	GD_A	1.24932±11pcm	-144 pcm (1.2%)
	GD_F	1.25093±15pcm	-133 pcm (1.0%)
Peak (quadratic) error on UOX-pins Absorption Rates	UOX		-0.2% (0.1%)
	GD_A		-0.3% (0.2%)
	GD_F		-0.4% (0.3%)
Peak (average) error on Gd-pins Abs. rates	GD_A		0.7% (0.6%)
	GD_F		0.8% (0.6%)

3.3 Anisotropy and polar quadrature

A delicate issue lies in choosing the discretization in the polar direction (angles and weights) because of the link with the anisotropy development order. In the case of isotropic scattering, by analogy with the collision probabilities method, optimisation is obtained in using a Bickley-

Naylor quadrature to minimise error on the integral occurring in the Bickley-Naylor functions Ki_n. Generally, a Bickley-Naylor quadrature can be compared to a Gauss-Legendre one with 3 to 4 times $N\psi$ angles in terms of accuracy [11] with the same ratio for time consuming.

When anisotropic scattering is considered, it has been shown [12] that the Bickley option leads to a poor integration of the Legendre polynomials and a slow convergence of high order anisotropic moments of the flux, which may have repercussions on the overall neutron conservation. However, this effect is not always relevant for a low anisotropy order and we have experimented on PWR assemblies that a linear (P1) representation combined with a Bickley-Naylor with $N\psi=2$ gives accurate results (Table II). With only 2 azimuthal directions a factor 3 is gained on time consumption (however, on chapter 4, we will see that for 2D-core calculations, a P3 expansion with $N\psi=3$ is needed for accurate leakage calculation).

Table II. P1/P5 anisotropy and polar quadrature effects

	Bench.	A2ref/T4	A2 with P1 anisotropy & Gauss quad. ($N\psi=8$)/T4	A2 with P1anisotropy & Bick quad. ($N\psi=2$)/T4
ΔKeff (ΔGd worth)	UOX	-40 pcm	-65 pcm	-60 pcm
	GD_A	-144 pcm (1.2%)	-194 pcm (1.5%)	-162 pcm(1.2%)
	GD_F	-133 pcm (1.0%)	-185 pcm (1.4%)	-153 pcm (1.0%)
Peak (quadratic) error on UOX-pins Absorbtion Rates	UOX	-0.2% (0.1%)	-0.2% (0.1%)	-0.2% (0.1%)
	GD_A	-0.3% (0.2%)	-0.3% (0.2%)	-0.3% (0.2%)
	GD_F	-0.4% (0.3%)	-0.4% (0.3%)	-0.4% (0.3%)
Peak (average) error on Gd-pins Abs. rates	GD_A	0.7% (0.6%)	0.7% (0.6%)	0.6% (0.6%)
	GD_F	0.8% (0.6%)	0.9% (0.6%)	0.8% (0.6%)

3.4 Cross-section collapsing

The previous 'CEA-97' scheme [11] soon proposed a 20-group broad energy structure for 2D Sn transport PWR core calculations: cross sections were collapsed from the 172-group XMAS library on this 20-group structure and homogenized on each cell. In that case, SPH equivalence procedure was needed to preserve reaction rates obtained with the fine-group structure and cell-heterogeneous calculation.

Using the method of characteristics instead of the Sn method in the second level allows now describing the exact heterogeneities of the cells. Cross sections in the broad structure are generated from the fine-group Pij-multicell flux calculation performed on the self-shielding geometry. In each first-level medium, they are collapsed with the local fine-group fluxes, without any spatial homogenization.

For UOX assemblies, first tests with 20-group MOC calculations showed good agreements on reactivity and spatial reaction rate distributions without SPH equivalence procedure. However, for MOX assemblies, discrepancies on reactivity were too high. Using the APOLLO2-SPH equivalence procedure for MOX improved reactivity but spatial reaction rate distribution was worse. So, we have tried to improve the 20-group energy structure to avoid the equivalence procedure for MOX. The detailed analysis of the different energetic and isotopic contributions to the neutronic balance of a MOX cell has shown that the main discrepancies was coming from the lack of discretization in the 1.06 eV ^{240}Pu resonance. The group including this resonance in the 20-group structure has been divided into 7, leading to a new 26-group energy structure adopted for both UOX and MOX calculations.

With this 26-group mesh, the two-level MOC calculations are in good agreement with the single-level (281-group) ones (see Table III) and computation time is divided by a factor of 10.

Table III. Energy collapsing: 26/281 groups effects

	Bench.	A2ref/T4	A2 with P1 anisotropy & Bick quad. (Nψ=2)/T4	
		281 groups		26 groups
ΔKeff (ΔGd worth)	UOX	-40 pcm	-60 pcm	-76 pcm
	GD_A	-144 pcm (1.2%)	-162 pcm(1.2%)	-188 pcm (1.3%)
	GD_F	-133 pcm (1.0%)	-153 pcm (1.0%)	-175 pcm (1.1%)
Peak (quadratic) error on UOX-pins Absorption Rates	UOX	-0.2% (0.1%)	-0.2% (0.1%)	-0.3% (0.1 %)
	GD_A	-0.3% (0.2%)	-0.3% (0.2%)	-0.3% (0.2%)
	GD_F	-0.4% (0.3%)	-0.4% (0.3%)	-0.4% (0.3%)
Peak (average) error on Gd-pins Absorption Rates	GD_A	0.7% (0.6%)	0.6% (0.6%)	0.7% (0.6%)
	GD_F	0.8% (0.6%)	0.8% (0.6%)	0.8% (0.6%)

3.5 MOC spatial mesh and radial tracking parameters

The last optimization deals with the spatial radial mesh and the radial parameters for tracking (number of trajectory directions Nϕ in [0,π] and spacing between trajectories Δr).

In APOLLO2.8, the MOC rests on a flat source approximation so meshing must be done in order to follow the spatial thermal flux shape (energy domain where flux gradients are the strongest). A PWR assembly lattice is not far from an infinite cell lattice, so the selected mesh (Fig. 4) and MOC trajectories (Nϕ=24, Δr=0,1 cm) have been first optimized on a single cell with specular reflective boundary conditions and then comforted on assemblies.

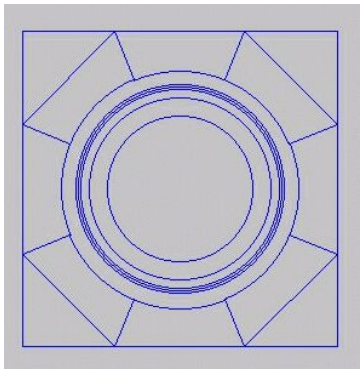

Figure 4. Optimized "windmill mesh"

When applying these parameters to assemblies' calculations, results stay good despites water holes presence that increases macroscopic flux gradients and anisotropic scattering (see Table IV). The whole of the options of this calculation corresponds to that retained for the optimized *REL2005* scheme.

Table IV. *REL2005* performances on Gd worth calculations

	Bench.	**A2ref[(a)]/T4**	**A2-*REL2005*[(b)]/T4**
		281 groups	**26 groups**
ΔKeff (ΔGd worth)	UOX	-40 pcm	-76 pcm
	GD_A	-144 pcm (1.2%)	-204 pcm (1.5%)-
	GD_F	-133 pcm (1.1%)	193 pcm (1.3%)
Peak (quadratic) error on UOX-pins Absorbtion Rates	UOX	-0.2% (0.1%)	-0.4% (0.2 %)
	GD_A	-0.3% (0.2%)	-0.4% (0.3%)
	GD_F	-0.4% (0.3%)	-0.6% (0.3%)
Peak (average) error on Gd-pins Abs. rates	GD_A	0.7% (0.6%)	0.9% (0.8%)
	GD_F	0.8% (0.6%)	1.2% (0.7%)

(a) Ref: P5 anisotropy, 281 groups, refined mesh, tracking parameters: Δr=0.01, Nϕ=36, Nψ=8, Gauss. quad.
(b) *REL2005*: P1 anisotropy, 26 groups, windmill mesh, tracking parameters: Δr=0.1, Nϕ=24, Nψ=2, Bick. quad.

Finally, the *REL2005*-APOLLO2.8-MOC scheme biases against TRIPOLI4 results are satisfactory, not very far from those of the reference deterministic APOLLO2 calculation:

- reactivity is underestimated by 200 pcm at most (150 pcm for A2ref),
- absorption in UOX fuel pins is underestimated by 0.6% (0.4%) at most,
- and absorption in UO_2-Gd_2O_3 pins is overestimed by 1.2% (0.8%) at most.

4. TIME 0 EXPERIMENTAL VALIDATION

The CAMELEON program proceeded in the EOLE facility at CEA-Cadarache (France) from 1982 to 1984 [13]. A PWR mock-up was built in the EOLE vessel and devoted to experimental measurements of main neutronic parameters (reactivity, material buckling, poisons and absorbers worth, power maps).

We focus on three experiments called Ref-25TG, 8-12D1-A and 8-12D3-A. The "reference" Ref-25TG configuration simulates in its center a 3.5% enriched-UOX PWR 17x17 assembly with 25 water holes. For the other configurations (Fig. 5 and 6), 12 fuel pins have been replaced by 12 poisoned pins (8% weight Gd_2O_3 mixed with $UnatO_2$) in two different ways closed with those studied in the numerical validation (Gd_A and Gd_F).

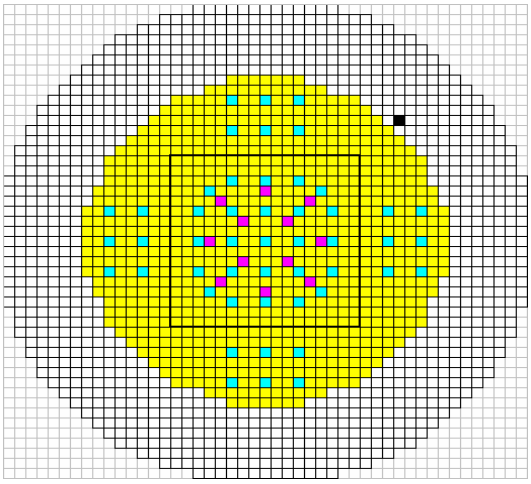

Figure 5. Configuration 8-12D1-A

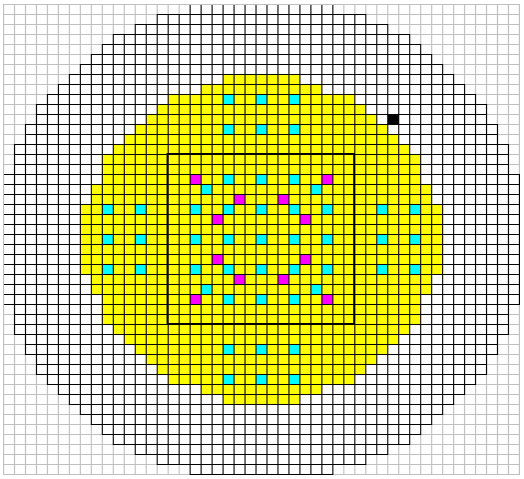

Figure 6. Configuration 8-12D3-A

4.1. Anisotropy and polar quadrature for core calculations

For core calculations, the $N\psi=2$ Bickley-Naylor polar quadrature optimized on assemblies gives large discrepancies on Keff values: more than 200 pcm on the Ref-25TG configuration, even when anisotropy is limited to the P1 expansion (see Table V where reference calculations use a $N\psi=8$ Gaussian polar quadrature). A $N\psi=3$ Bickley-Naylor quadrature allows to reduce these discrepancies at about 30 pcm.

It can also be noticed that the P1/P3 effect is greater than 100 pcm; a P1 anisotropic scattering is not accurate enough for lattice migration area and water reflector treatment in core calculations. A P3 expansion is recommended (P3/P5 effect is less than 20 pcm).

Table V. P1/P3 anisotropy and polar quadrature effects on CAMELEON Ref-25TG core

Polar Quadrature	Bickley				Gauss	
Scattering anisotropy	P1		P3		P1	P3
Nψ	2	3	2	3	8	
Critical Keff	1.00589	1.00309	1.00661	1.00439	1.00342	1.00460
Keff(Bick)-Keff(Gauss)	247 pcm	-33 pcm	201 pcm	-21 pcm		
P1/P3 effect	72 pcm	130 pcm			118 pcm	

4.2. Gadolinium worth

Gadolinium worth for the 8-12D1-A and 8-12D3-A configurations has been measured from the Ref-25TG configuration by equivalence with soluble boron. Comparisons with calculated values (Table VI) show a notable improvement with the new product CEA2005-SHEM/APOLLO2.8-MOC/*REL2005*[1] against the previous scheme. This improvement comes for:

- 0.5% from the new cross section library CEA2005 with the 281 energy group structure,
- 2% from the new *REL2005* scheme using the MOC solver.

With the reference MOC options, results are improved only by 0.5% (in coherence with the results of Table IV). About 1% of the 5,3% overestimation is coming from multigroup discetization (cf. numerical validation against TRIPOLI4, also in Table IV), the remaining 4% is consistent with the experimental uncertainty on the boron concentration measurements: ±2%(1σ).

Table VI. CAMELEON critical Keff and Gd worth

	Library	CEA93/JEF2.2	CEA2005/JEFF3.1		
	Group number	172 XMAS	281 SHEM		
	Solver	APOLLO2-Sn	APOLLO2-MOC		
	scheme	CEA97 (S8 20 groups P1)		REL2005 (26 groups P3)	Reference (281 groups P3)
Configuration	Boron concentration (ppm)	Critical Keff			
Ref 25TG	602,3	1,00877	1,00603	1,00631	1,00529
8-12D1-A	324,1	1,00537	1,00287	1,00401	1,00316
8-12D3-A	324,1	1,00537	1,00286	1,00391	1,00311

Configuration	Gd efficiency (pcm)	(C-E)/E %			
8-12D1-A	-4181	8,0%	7,5%	5,5%	5,0%
8-12D3-A	-4047	8,3%	7,8%	5,9%	5,3%

[1] Library/solver/*scheme*, CEA2005 is based on the JEFF3.1 evaluations with the 281-group SHEM structure, CEA93 on the JEF2.2 with the 172-group XMAS structure

4.3. Fission rate distribution

On the fission rate distribution (for symmetry reasons, measures have only been made on the up and right corner of the central assembly), the *REL2005* results are as good as the reference MOC ones. Table VII gives comparisons for the 8-12D1 worst configuration:

- on (quadratic) average, discrepancies on fission rates are under 1% compared to an experimental uncertainty of ±1%(1σ),
- the maximum error is only -2%.

Table VII. Prediction of the radial power map in the CAMELEON 8-12D1 core

(C-E)/E	max(+)	max(-)	σ
	1,3%	-2,0%	0,92%

							0,935 1,2%	
GT			GT			1,008 1,0%		
Gd					GT			
				Gd	1,023 -0,4%			
GT			GT	0,964 1,0%		GT		
		Gd	0,952 0,4%					
1,072 -0,7%	0,993 -0,5%	0,926 -0,2%	1,004 1,1%		0,943 -2,0%	1,057 -1,3%		
GT	1,052 1,3%	1,026 0,4%	GT	0,951 -0,2%	Gd	GT	1,073 -0,4%	

26-group calculation

(C-E)/E	max(+)	max(-)	σ
	1,4%	-1,9%	0,91%

							0,935 0,7%	
GT			GT			1,008 0,7%		
Gd					GT			
				Gd	1,023 -0,4%			
GT			GT	0,964 1,2%		GT		
		Gd	0,952 0,4%					
1,072 -0,5%	0,993 -0,5%	0,926 -0,2%	1,004 1,2%		0,943 -1,9%	1,057 -1,4%		
GT	1,052 1,4%	1,026 0,7%	GT	0,951 -0,2%	Gd	GT	1,073 -0,4%	

281-group calculation

5. DEPLETION VALIDATION

5.1 Numerical validation

Validation of the optimized *REL2005* scheme for UOX assemblies' depletion calculations has been performed against reference MOC ones. Three parameters have been compared:

- reactivity with burnup,
- nuclides concentrations at 60 MWd/t,
- power distribution on standard UOX fuel pins and gadolinium poisoned pins.

Results are only given for the Gd_F benchmark, which is the more difficult case, but trends are the same for the Gd_A and UOX cases.

5.1.1 Reactivity and Gd worth

With the MOC options defined for fresh fuel, the *REL2005* calculation is close to the reference one: Keff underestimation is smaller than 150 pcm all along the [0, 60 MWd/t] burnup range (see Fig. 7)

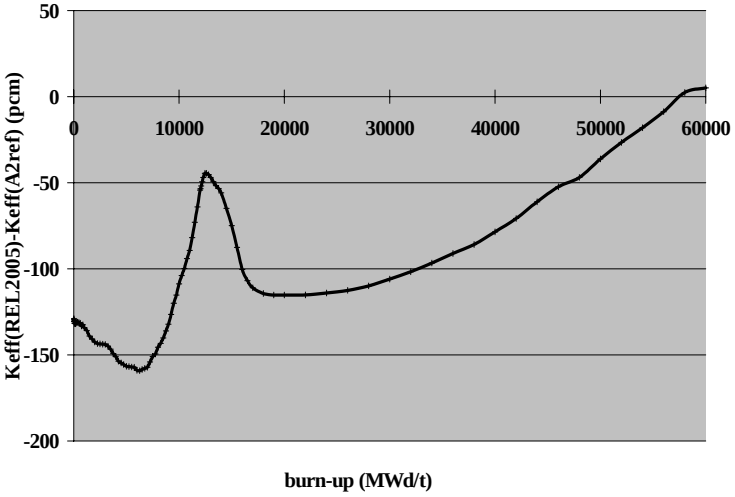

Figure 7. Reactivity biases on Gd-F benchmark

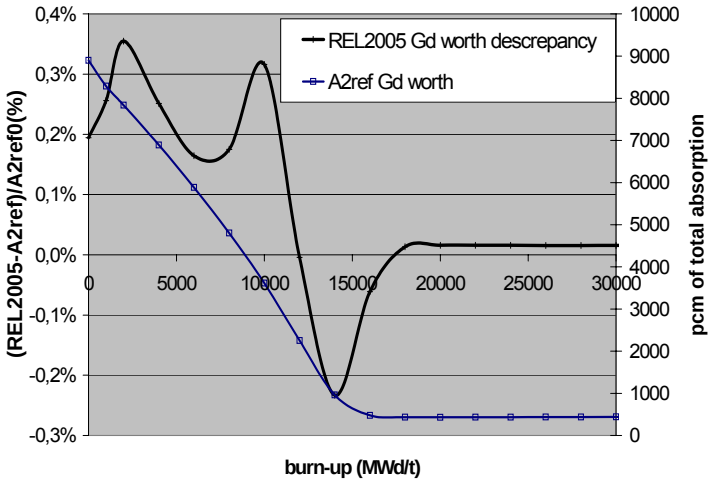

Figure8. Gd worth biases on Gd-F bench.

The 6 rings discretization of the Gd pin in the REL 2005 scheme (11 rings for the reference calculation) allow to obtain for all depletion steps a better than 0.4% precision on the gadolinium worth (Fig. 8).

5.1.2 Nuclide inventory

Maximum discrepancies on actinides occur at 60 MWd/kg. With only 0.8% discrepancy on major actinides and 1.2% on minor ones, agreement is rather good (Table VIII).

Table VIII. Actinide concentration discrepancies at 60 MWd/kg : 26 vs. 281-group A2-MOC

Nuclides	(*REL2005*- Ref.)/Ref.	Nuclides	(*REL2005*- Ref.)/Ref.
U234	-0.6 %	Pu242	0.0 %
U235	0.7 %	Am241	1.0 %
U236	0.0 %	Am242	1.2 %
U238	0.0 %	Am243	-0.1 %
Np237	0.6 %	Cm242	0.3 %
Pu238	0.8 %	Cm243	0.7 %
Pu239	0.8 %	Cm244	-0.3 %
Pu240	0.4 %	Cm245	1.0 %

5.1.3 Power map

During depletion, the 0.6% maximum discrepancy on poisoned pins occurs at 14 MWd/t at the reactivity peak (Table IX). For standard fuel pins, this maximum is observed at 60 MWd/t with a bias of only 0.5%.

Table IX : Gd-F assembly - power distribution at 14 MWd/kg : 26 vs. 281-group A2-MOC

REL2005 value (REL2005-A2ref)/A2ref) %								
								1,007 -0,2
							0,980 0,0	0,994 0,0
						1,006 -0,1	0,987 0,1	0,994 0,1
					0,004 -0,5	1,050 0,0	1,001 0,1	1,001 0,0
				0,526 -0,5	1,097 -0,3	1,068 -0,1	1,018 0,0	1,008 -0,1
			0,004 -0,4	1,096 -0,1	1,083 0,0	0,004 -0,5	1,046 0,0	1,016 0,0
		0,504 0,2	1,086 0,1	1,051 0,0	1,044 0,0	1,060 0,0	1,022 0,0	1,015 0,0
	1,045 0,0	1,054 0,1	1,076 0,1	1,050 0,0	1,055 0,0	1,066 0,1	1,024 0,0	1,016 0,0
0,004 -0,5	1,070 0,1	1,071 0,0	0,004 -0,4	1,088 0,1	0,531 0,6	0,004 -0,4	1,049 0,0	1,019 -0,1

5.2 SHEM improvements of reactivity loss – UOX assembly benchmark

In this section, we underline the improvements brought by the new 281-group SHEM energy structure in comparison with the European XMAS 172-group one.

The principle of construction of SHEM have already been exposed [3] [5] : below 23 eV, a fine mesh has been optimized to avoid self-shielding models for the whole resonances of major and minor Actinides, main Fission Products and LWR absorbers. A consequence is that resonance overlapping is explicitly treated in this energy range.

Improvements on void reactivity prediction have soon been presented [4] but other neutronics parameters are also concerned. Indeed, using SHEM instead XMAS causes a tremendous effect on reactivity loss with depletion. Fig. 9 shows the difference in reactivity in the range [0, 60 MWd/kg] for the UOX assembly (trends are the same for poisoned assemblies). Keff values are very close for fresh fuel, but they deviate quickly to reach +650 pcm at 60 MWd/kg.

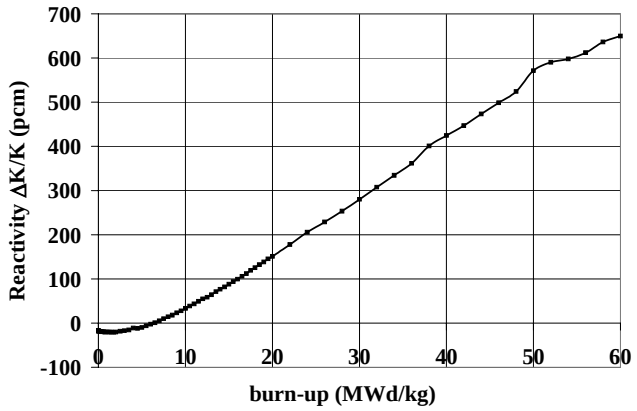

Figure 9: SHEM/XMAS effect (UOX assembly depletionbenchmark)

Balance analysis (Table X) indicates that this effect arises from less resonant absorption of Minor Actinides and Fission Products, particularly due to resonance overlapping between ^{150}Sm and ^{238}U : ^{150}Sm poisoning is reduced by 30% with SHEM (+90 pcm on reactivity at 60 MWd/kg) due to the correct treatment of its 20,65 eV resonance almost superimposed with the ^{238}U 20,8 eV resonance (see Fig.10).

Table X : SHEM/XMAS discrepancies (UOX assembly benchmark) : main contributions at 60 MWd/kg

ISOTOPE	Concent.	|Abs. Rate discrepancy| > 10 pcm [(a)]			1 group cross section
	(S-X)/X (%)	XMAS (pcm)	S-X (pcm)	(S-X)/X (%)	(S-X)/X (%)
H2O	0.0	3309	-22	-0.7	-0.1
B10	0.0	3566	-27	-0.7	-0.2
ZR91	0.0	496	-17	-3.5	-3.0
U236	-0.1	971	-19	-2.0	-1.4
AM243	0.0	464	-8	-1.7	-1.1
CM244	-2.4	96	2	2.1	5.4
MO95	0.4	321	-18	-5.5	-5.3
TC99	0.6	647	-20	-3.0	-3.0
XE131	4.9	794	-41	-5.2	-9.2
CS133	-1.0	871	25	2.9	4.6
PM147	7.2	449	-16	-3.6	-9.6
SM149	-0.7	619	-10	-1.6	-0.3
SM150	6.6	309	-70	-22.6	-27.0
SM151	-12.9	512	-70	-13.6	-0.2
SM152	-8.6	596	-59	-9.8	-0.8
EU153	-7.0	530	-37	-7.0	0.6
EU154	-5.7	483	-32	-6.7	-0.4
EU155	-5.3	507	-30	-6.0	-0.2
Total		15540	-468		

(a) Source normalised at 100000 neutrons

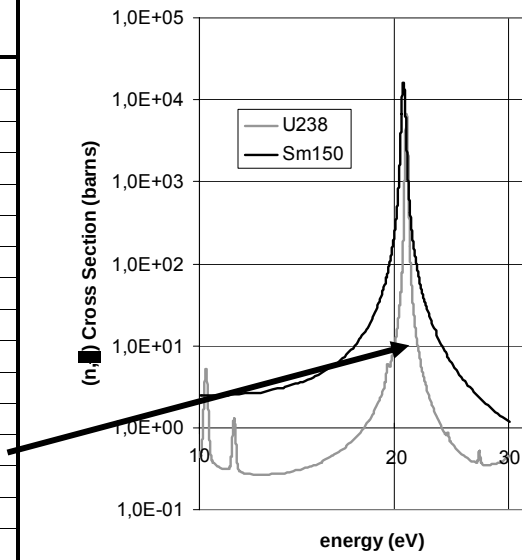

Figure 10. ^{150}Sm/^{238}U resonances overlap around 21 eV

6. CONCLUSIONS

Thanks to recent developments of the method of characteristics in unstructured mesh, APOLLO2.8 has now a powerful 2D transport method usable for most water reactor applications, from R&D studies to routine industrial calculations. In addition, the new SHEM 281-group energy structure implemented in the CEA2005 LWR applications library, based on the JEFF3.1 file, improves resonant reaction calculations in avoiding self-shielding approximations below 23 eV.

On these bases, the "optimized" *REL2005* scheme using a two-level approach has been derived for LWR applications to reach reasonable computing time for assembly depletion calculations with a small loss of precision against MOC single-level reference calculations. For UOX PWR fresh fuel assemblies including gadolinium pins, the target accuracies: 200 pcm on reactivity and

1% on pin-by-pin power distribution are reached against the TRIPOLI4 continuous-energy Monte Carlo code. These good performances have been confirmed against CAMELEON experimental results. Reactivity loss with depletion is strongly improved with SHEM compared to XMAS due to a fine description of F.P. resonances and to F.P./^{238}U mutual-shielding handling. Against MOC single-level reference calculation, biases on major actinide build-ups are lower than 0.8% accuracy. Next validation step will involve P.I.Es analysis.

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