Qualification of APOLLO2 BWR calculation scheme on the BASALA mock-up

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Abstract

A new neutronic APOLLO2/MOC/SHEM/CEA2005 calculation scheme for BWR applications has been developed by the French "Commissariat à l'Energie Atomique". This scheme is based on the latest calculation methodology (accurate mutual and self-shielding formalism, MOC treatment of the transport equation) and the recent JEFF3.1 nuclear data library.

This paper presents the experimental validation of this new calculation scheme on the BASALA BWR mock-up

The BASALA programme is devoted to the measurements of the physical parameters of high moderation 100% MOX BWR cores, in hot and cold conditions. The experimental validation of the calculation scheme deals with core reactivity, fission rate maps, reactivity worth of void and absorbers (cruciform control blades and Gd pins), as well as temperature coefficient.

Results of the analysis using APOLLO2/MOC/SHEM/CEA2005 show an overestimation of the core reactivity by 600 pcm for BASALA-Hot and 750 pcm for BASALA-Cold.

Reactivity worth of gadolinium poison pins and hafnium or B_4C control blades are predicted by APOLLO2 calculation within 2% accuracy. Furthermore, the radial power map is well predicted for every core configuration, including Void configuration and Hf / B_4C configurations: fission rates in the central assembly are calculated within the ±2% experimental uncertainty for the reference cores. The C/E bias on the isothermal Moderator Temperature Coefficient, using the CEA2005 library based on JEFF3.1 file, amounts to -1.7±0.3 pcm/°C on the range 10°C-80°C.

KEYWORDS: BWR, APOLLO2, JEFF3.1, SHEM, BASALA, EOLE

1 Introduction

For these last 15 years, the APOLLO2 [1] code has benefited from a large work of experimental validation for Light Water Reactors (LWRs), and more particularly on PWR spectra. An extension of the qualification has been achieved for BWR spectra, with the analysis of the BASALA experiment. The difficulty of calculating this type of LWRs lies on the presence of void and strong heterogeneities in the geometry: several enrichments axially and radially in the assembly, the presence of burnable poisons such as UO_2-Gd_2O_3 pins, large central water rod and peripheral water blade.

The BASALA experimental programme [2] was devoted to the measurements of the physical parameters of high moderation 100% MOX BWR cores, within the framework of an international cooperation between JNES (formally NUPEC, Japan), CEA and COGEMA (France). It was implemented in the EOLE facility at CEA Cadarache. This programme comprised two types of core simulations with Hot (BASALA-H) and Cold (BASALA-C) conditions.

The former tool [3] ('CEA97' optimized scheme based on the one hand on XMAS-172 group energy mesh and a space-dependent self-shielding correction and on the other hand on a Sn method in the APOLLO2 code) was not well suited for BWR flux gradient calculation. Therefore, a new calculation scheme based on the SHEM fine mesh (to reduce drastically mutual and self-shielding errors), and the exact 2D heterogeneous MOC method, has been developed for BWR applications [4].
After a brief description of the BASALA experiment, this paper describes the APOLLO2 calculation scheme and the results of the analysis of this experiment.

2 BASALA experiment

The BASALA programme comprises two types of core simulations (Table 1): Cold (BASALA-C) and Hot (BASALA-H) conditions. The BASALA-C core simulates a 0% void fraction, i.e. the conditions at the entry of an Advanced Boiling Water Reactor (ABWR). The BASALA-H core simulates a 42% void fraction, corresponding to the partially vaporized water that can be found at the middle height of a fuel pin in an ABWR. The void fraction for each type of core is obtained with the variation of the dimension of the lattice and the assembly pitches.

For each type of core, a reference configuration and specific configurations (with poisons or void) are performed. A total of 6 configurations are analyzed in this paper:

- BASALA-H: hot reference conditions (REF), burnable poison – 2 assemblies with 8 UO_2-Gd_2O_3 pins (8GD), high void conditions (VOID);
- BASALA-C: cold reference conditions (REF), B_4C control cross (B4C), hafnium control cross (HF).

Table 1: BASALA core configurations

BASALA-H	BASALA-C
lattice pitch=1.13 cm, assembly pitch=11.41 cm, H/HM~5 Representative of: T~287°C, P~70bars, Rvoid~42%	lattice pitch=1.35 cm, assembly pitch=13.55 cm, H/HM~9 Representative of: T~20°C, P~1bars, Rvoid~0%
Reference core (REF) Burnable poison - 2×8 Gd (8GD) High void condition (VOID)	Reference core (REF) B_4C control cross configuration (B4C) Hf control cross configuration (HF)

The BASALA core is composed of 4 central test 9×9 assemblies, which are zoned and loaded with 4 Pu-content pins increasing from 3.0% up to 8.7%; the main measurements are performed in these assemblies. To mock-up industrial ABWR assemblies, the 2 central large water rods are replaced by seven water full guide-tubes. The central zone is surrounded by 9x9 assemblies built with 7%Pu MOX pins. Negative reactivity worth, such as Gd pins or control blades, are measured against feeder pins loaded at the core periphery (MOX 7%Pu in BASALA-C, UOX 3.7% ^{235}U pins in BASALA-H).
The BASALA-H and BASALA-C reference cores (REF) are described on Figures 1 and 2.

The main characteristics of the 4 other cores are given below:

- BASALA-H/8GD core: 2 assemblies on the NE-SW diagonal of the BASALA-H/REF core are replaced by 2 assemblies containing 8 UO_2-Gd_2O_3 pins (2.55% Gd content – 4.95% U235 enrichment), on the periphery of the assembly (see Figure 3).
- BASALA-H/VOID core: the pin overclads of the 4 central assemblies are thicker than in the reference core to simulate a 72% void fraction, that corresponds to a ABWR

core upper zone;

- BASALA-C/B4C and HF core: a cross-shaped control blade in natural hafnium and in natural B4C is inserted in the water gap between the 4 central assemblies.

Figure 1: BASALA-H/REF core **Figure 2: BASALA-C/REF core**

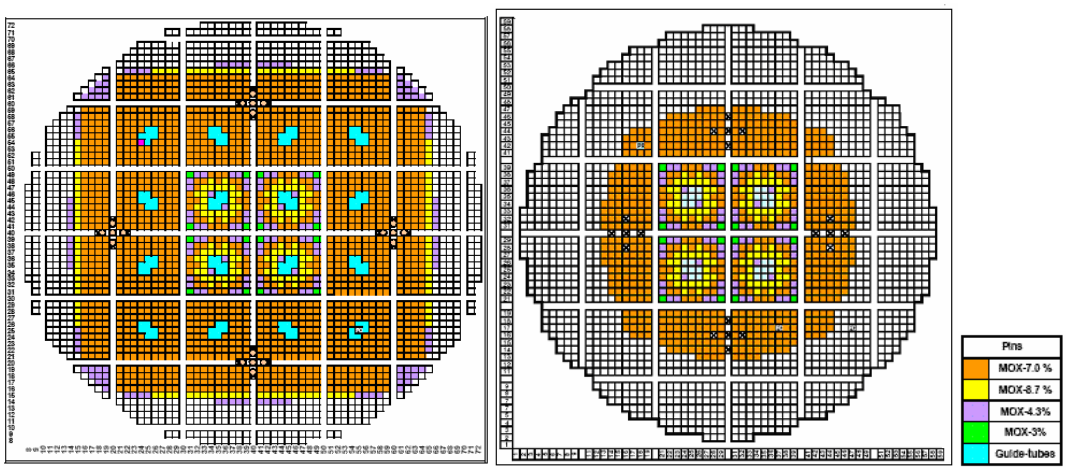
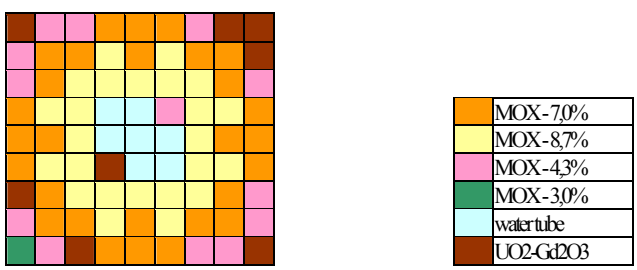


Figure 3: Description of the BASALA-H assembly containing 8 UO_2-Gd_2O_2 pins



3 Calculation route

3.1 General outline

The new APOLLO2 calculation route is developed mainly for BWR applications. It is based on the latest tools available at CEA in term of methodology and in term of nuclear data:

- the resolution of the transport equation by the Method of Characteristics (MOC) [5], implemented in the APOLLO2 code: it enables both a treatment of the scattering anisotropy and an heterogeneous description of the geometry, with a reasonable CPU time;
- the universal 281-group mesh (SHEM) [6]: it makes the resonance treatment more accurate by simplifying the self-shielding strategy since no self-shielding is needed under 23 eV;
- the APOLLO2 nuclear data library CEA2005 processed by NJOY from the Joint European File JEFF3.1: the JEF2.2 evaluations of main actinides and absorbing FPs have been improved in order to account for CEA trends derived from exhautive PWR type experiments.

3.2 Calculation scheme

This new calculation scheme is a two-level scheme, which can be split into 4 steps:

- a space-dependent self shielding strategy for cross sections, with a discretization of the fuel pins in 4 rings to treat with accuracy the U238 resonant absorption; the Pij calculation for the determination of the background section is performed in UP1 multicell approximation (the angular interface fluxes are linearly anisotropic) for U238 and in UP0-ROTH×4 (isotropic angular interface fluxes) for the other isotopes;
- a flux calculation in the accurate Pij-UP1 interface current method, using the 281-group structure;
- from neutron spectrum obtained in the previous step, a cross-section energy collapsing to 26 groups is carried out: this 26-group structure is well suited for UOX and MOX assemblies, with a refined meshing for the ^{240}Pu resonance at 1.06 eV [7];
- a flux calculation in MOC in the 26-group structure. A uniform spatial quadrature (Δr=0.04 cm) and a uniform azimuthal quadrature with $N\varphi$=24 is used for the x-y integration. A Gauss-Legendre quadrature with $N\psi$=9 is retained for the polar integration. Concerning the scattering anisotropy, a third-order Legendre polynomials expansion is required.

The bias of this calculation scheme has been calibrated against reference Monte Carlo TRIPOLI4 [8] calculations, for all types of BASALA assemblies [4] [7].

The core calculation is a X-Y APOLLO2 calculation, on a 1/8 symmetrical geometry (except for BASALAH/8GD where a 1/2 symmetrical geometry is required). The axial leakage is simulated through the measured axial buckling.

4 Results of experiment analysis

4.1 Core reactivity

The core reactivity (with the pilot rod extracted) is accurately measured through the critical fuel loading. The results of the APOLLO2/MOC/SHEM/CEA2005 analysis are shown in Table 2.

Table 2: Calc/Exp Comparison of the core residual reactivity (pcm)

	HOT			COLD		
	REF	**VOID**	**8GD**	**REF**	**B4C**	**HF**
Experiment	67±3	38±2	86±3	38±2	43±2	49±2
APOLLO2	670	582	655	799	822	720
C-E	603	545	569	761	779	671

The experimental reactivity is measured with the divergence technique that is based on the measurement of the doubling time of the flux level, linked to the reactivity by Nordheim equation: the uncertainty associated to this measurement gathers the statistical uncertainty on doubling time and the systematic uncertainty due to the delayed neutron fraction βeff.
The APOLLO2 calculation overestimates reactivity of 100% MOX cores: from 600 pcm in the BASALA-H under-moderated core up to 750 pcm in the BASALA-C over-moderated core, using the JEFF3.1 library. We can notice that this overestimation is 100 pcm higher than

the one obtained in JEF2-based calculation. This MOX reactivity overestimation was already pointed out in LWR regular MOX cores, such as EPICURE, MISTRAL2 and MISTRAL3 in EOLE [9].

In order to check that this reactivity overestimation is not linked to deterministic modeling biases, APOLLO2/MOC core calculation was compared to reference Monte Carlo TRIPOLI4 calculation. First, in a theoretical case of 2D core calculation with no leakage, the APOLLO2 reactivity is only 80 pcm higher than the reactivity calculated by TRIPOLI4 (BASALA-H/REF core case). The actual TRIPOLI4 3D core calculation also gives consistent result with the APOLLO2 calculation using axial buckling [10]: the agreement lies within the 20 pcm statistical uncertainty.

The residual reactivity has been calculated using both SHEM-281 and XMAS-172 group mesh (see Table 3) to highlight the improvement of the void and absorber worth calculation, as detailed in the next paragraph.

Table 3: APOLLO2/MOC Calculation of core residual reactivity (pcm)

	HOT			COLD		
	REF	**VOID**	**8GD**	**REF**	**B4C**	**HF**
Experiment	67±3	38±2	86±3	38±2	43±2	49±2
JEFF3.1-SHEM	670	582	655	799	822	720
JEFF3.1-XMAS	655	557	640	811	830	684

4.2 Absorber and void reactivity worth

The residual reactivity on the critical cores containing absorbers and assemblies with high void fraction enables to estimate the bias on the reactivity worth summarized in Table 4.

Table 4: Calc/Exp comparison on reactivity Worth

	HOT		COLD	
	VOID	**8GD**	**B4C**	**HF**
Experimental Worth	-1300 pcm	-2000 pcm	-9700 pcm	-9200 pcm
(C-E)/E - JEFF3.1-SHEM	+4,5±0,5%	+1,7±0,5%	-0,2±0,4%	+1,0±0,4%
(C-E)/E - JEFF3.1-XMAS	+5,3±0,5%	+1,7±0,5%	-0,1±0,4%	+1,5±0,4%

The uncertainty (1σ) associated to the (C-E)/E is a quadratic combination of the measurement uncertainties on residual reactivity and on reactivity worth (derived from ASM measurement) and of the uncertainty linked to the added feeder pins. This last uncertainty component, is evaluated as the discrepancy between APOLLO2 core calculations using either JEF2.2 or JEFF3.1 data for the feeder zone.
Absorber reactivity worth is satisfactory predicted with APOLLO2/MOC/SHEM/JEFF3.1. B_4C and hafnium control blade efficiencies are predicted by APOLLO2 within 1% accuracy, and UO_2-Gd_2O_3 poisoning worth within 2% accuracy.
The use of the SHEM 281group mesh instead of the XMAS 172-group mesh improves the void and hafnium reactivity worth calculation because of the refined mesh under 23 eV that describes the resonances of each isotope with accuracy: for the hafnium, it concerns the description of the ^{179}Hf resonance at 5.7 eV, the ^{177}Hf resonance at 5.9 eV, and the ^{177}Hf/^{179}Hf

and ^{176}Hf/^{178}Hf resonance overlap respectively in the 5.8eV and 7.8eV range. For the calculation of the void configuration, it concerns the ^{238}U, two first resonances and the ^{235}U/^{238}U/^{240}Pu resonance overlaps at 6.7 eV and 20.9 eV.
However, the void reactivity worth is still overestimated by 4%. It is partially linked to the bad treatment of the ^{238}U/^{240}Pu/^{239}Pu resonance overlap at 66 eV; it should be improved by a mutual shielding treatment in a resonant mixture, in the 35 eV-200 eV range, that has been recently implemented in the APOLLO2 code [11].

4.3 Radial fission map

The radial map of the fission rates is obtained by integral gamma-spectrometry measurement directly on the fuel rods. In the case of mixed assemblies loaded with MOX fuel and UO_2-Gd_2O_3 pins, a special technique is performed to normalize the MOX and UO_2-Gd_2O_3 fission maps: it is the particular peak check measurement technique that consists in measuring the individual gamma peak from La140 (1596 keV).
The distribution of fission rates has been analyzed for each of the 6 configurations. It is normalized on the whole set of measured pins.

The XY APOLLO2 calculations reproduce accurately the experimental results on the whole core. No trend between the center and the periphery of the core can be really determinated (see Figures 4 and 7). The pin-by-pin fission rates are well predicted in the central assembly for reference, void and absorber configurations. The fission rates are systematically underestimated on the pins in the corner of the assembly. The peak of the distribution rates (in bold type in the Figures 4 and 7) is calculated at -0.4±1.0% (1σ) on the reference cores.
Concerning BASALA-H configurations, on the central assembly, the fission rates of MOX pins (Figures 4 to 6) are calculated within 2% accuracy, in agreement with the ±1% (1σ) experimental uncertainty. A slight trend to overestimate the fission rates in the center of the assembly of the REF configuration can be noticed, whereas the fission rates are underestimated in the pins near the water hole for the VOID and 8GD configurations.
The fission rates in the UO_2-Gd_2O_3 pins are systematically underestimated by 4.0% ±2% (1σ), with a small spread (±0.5%) in the BASALA/8GD configuration. The 2% uncertainty is bigger in the peak check measurement technique due to the uncertainty on La140 yields. Moreover, the fission reactions in the UO_2-Gd_2O_3 pins take place in the ^{235}U resonances, where nuclear data uncertainties are larger than in the thermal energy range.

Figure 4: (C-E)/E bias (%) on fission rate distribution in BASALA-H/REF

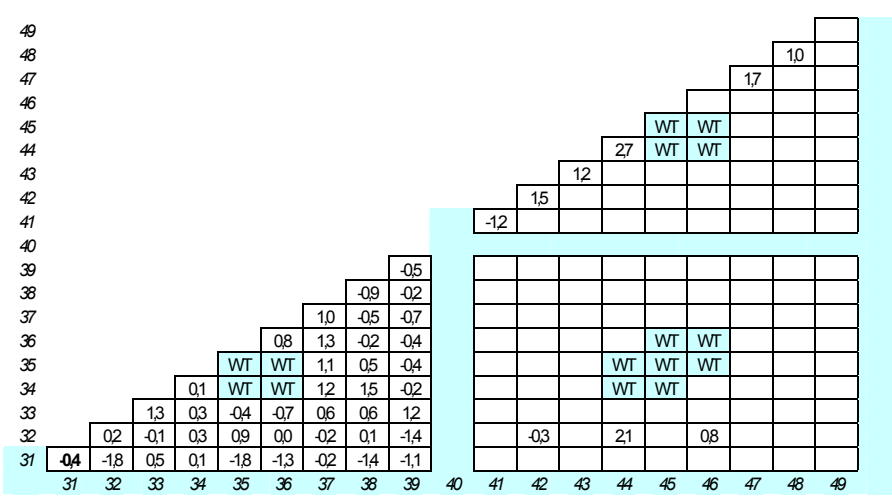


Figure 5: (C-E)/E (%) bias on fission rate distribution in BASALA-H/VOID central assembly

	31	32	33	34	35	36	37	38	39	40
39									-1,0	
38								0,1	-1,7	
37							-0,5	-0,5	-0,5	
36						-1,6	-2,0	-1,5	-0,8	
35					WT	WT	-1,8	0,2	0,4	
34				-1,2	WT	WT	-1,9	-1,0	0,0	
33			-0,5	-0,6	-0,7	-1,3	-0,8	-0,2	0,3	
32		0,1	-0,9	0,8	0,8	-0,6	0,4	1,4	0,2	
31	0,3	0,3	1,5	1,1	1,2	1,2	1,0	0,1	-0,4	

Figure 6: (C-E)/E (%) bias on fission rate distribution in BASALA-H/8GD central assembly

	41	42	43	44	45	46	47	48	49
49									Gd
48								-0,8	Gd
47							-1,0	-0,6	-0,3
46						-0,7	-1,6	-1,3	-0,4
45					WT	WT	-1,3	1,4	-0,5
44				Gd	WT	WT	-0,8	-0,3	0,7
43			1,4	0,1	-0,3	-0,4	0,6	1,1	0,7
42		0,9	1,0	-0,7	0,3	0,3	1,5	1,9	0,8
41	-1,8	1,3	Gd	-1,2	-0,3	0,6	0,7	0,9	Gd

Concerning BASALA-C configurations, fission rates in BASALA-C/REF pins are calculated within 2% accuracy, in agreement with the ±1% (1σ) experimental uncertainty (Figure 7). Fission rates in the central assembly are well predicted even in the MOX pins close to the B_4C and hafnium control blades (Figures 8 and 9). However, the calculation tends to overestimate the fission rates in front the absorber blade, meanwhile a slight underestimation is observed in the assembly corner.

Figure 7: (C-E)/E bias (%) on fission rate distribution in BASALA-C/REF

	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
42												-2,0					
41																	
40																	
39									-0,4								
38								-0,1	-0,6								
37							-0,7	0,1	0,0								
36						-1,0	0,8	-0,4	-0,5								
35					WT	WT	1,3	-0,3	0,2		0,3	-2,3	-0,7	-1,3			
34				0,5	WT	WT	0,9	0,4	0,8								
33			-0,9	0,3	0,2	-0,2	-0,3	0,7	-0,4								
32		1,0	-1,1	0,2	-0,9	-0,4	0,1	-0,7	0,3								
31	-0,2	0,0	0,0	1,9	-0,7	1,0	0,9	0,0	-0,4								

Figure 8: (C-E)/E bias (%) on fission rate distribution in BASALA-C/B4C central assembly

	31	32	33	34	35	36	37	38	39	40
39									-2,9	
38								-0,3	-2,3	
37							-0,4	-0,2	-0,5	
36						0,2	-0,5	-0,8	0,0	
35					WT	WT	0,0	1,5	-1,1	
34				0,0	WT	WT	0,1	1,2	-1,0	
33			-0,2	0,8	-0,4	-1,6	0,1	1,7	-0,5	
32		0,7	0,9	0,2	2,1	1,1	2,8	0,4	0,2	
31	-2,3	-1,7	0,6	1,3	0,8	2,0	2,5	2,9	-1,3	

Figure 9: (C-E)/E bias (%) on fission rate distribution in BASALA-C/HF central assembly

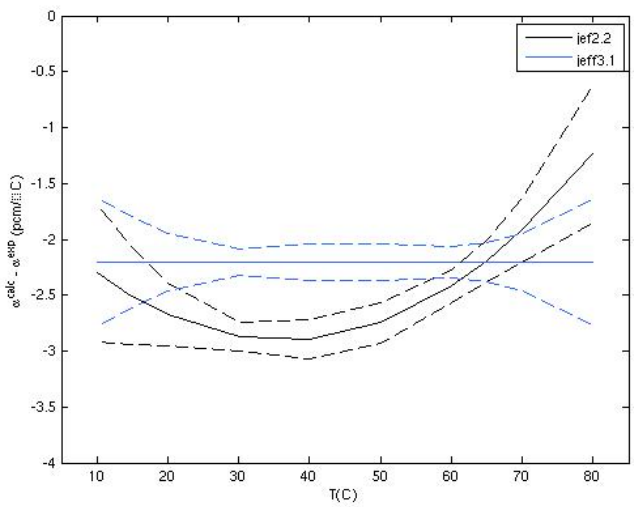
	31	32	33	34	35	36	37	38	39	40
39									-0,5	
38								-0,5	4,4	
37							-0,3	0,6	1,1	
36						-0,6	-0,4	-1,5	0,2	
35					WT	WT	-0,7	1,2	0,3	
34				-0,6	WT	WT	-0,2	0,8	-1,3	
33			-0,1	-0,1	-2,2	0,3	0,3	1,2	-0,3	
32		0,5	1,1	-0,3	1,5	1,1	1,3	0,2	-1,8	
31	-1,2	-1,0	1,0	1,2	2,4	1,6	0,7	-0,6	-1,4	

4.4 Isothermal temperature coefficient

The error on the isothermal temperature coefficient α calculated by APOLLO2/MOC has been calibrated in BASALA-C/REF configurations. Measurements have been performed by variation of the critical size, in the range from 10°C up to 80°C. Measurements have been carried out at least each 10°C. The analysis has been performed with the JEFF3.1 and JEF2.2 libraries to highlight the impact of the modification of $S(\alpha,\beta)$ matrix in the JEFF3.1 library on the isothermal temperature coefficient.

The discrepancy between calculation and experiment $\Delta\alpha$ is evaluated with the derivation of the fitting of the residual reactivity discrepancy $\Delta\rho_{exp/calc}$ by a polynomial. A third-order polynomial was required to fit $\Delta\rho_{exp/calc}$ in the JEF2.2 calculation, whereas a first-order polynomial was sufficient in the JEFF3.1 calculation. The Calculation-Experiment bias ($\Delta\alpha$ in pcm/°C) is plotted in Figure 10.

Figure 10: Calc / exp bias on BWR-MOX isothermal temperature coefficient



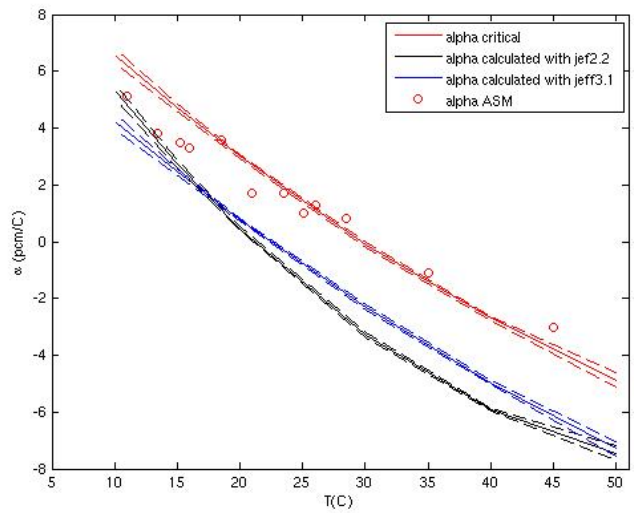
The uncertainties derived from the fitting are indicated in Figure 10 by dotted lines.

The error $\Delta\alpha$ calculated with JEF2.2 is not monotonous and goes through a minimum, -2.8 ± 0.3 pcm/°C, at 40°C; the average value is –2.4 pcm/°C. Around 20°C, the error is determined by the spectral shift component, whereas above 60°C it is mostly due to the water density component. Between 30°C and 60°C no effect is predominant. That is why 3 different slopes can be observed on Figure 10 (JEF2.2 results). This analysis is consistent with the interpretation results of the MISTRAL2 and MISTRAL3 MOX experiments [12].

The error $\Delta\alpha$ obtained with the JEFF3.1 library is quasi constant in the 10°C-80°C temperature range:-2.2 ±0.3 pcm/°C. The modification of the water thermal scattering section in the JEFF3.1 library mainly explains the modification of the error law; the neutron spectrum change modifies the number of neutrons absorbed in the ^{239}Pu 0.3 eV large resonance.

Moreover, the value of α can be accurately evaluated in the limited temperature range 10°C-50°C since the measurements are performed on a unique core configuration (the pilot rod is sufficient to compensate the reactivity loss due to temperature increase). The experimental and calculated residual reactivities have been fit by a third-order polynomial, and then this function has been differentiated to obtain $\alpha(T)$ (Figure 11). It has been verified that this experimental value was consistent with an independent α measurement by ASM method.

Figure 11: Isothermal moderator coefficient in the range 10°C-50°C



Note that the thermal expansion of fuel and structural materials (overclad and grid) is not taken into account in the calculation results presented above: a correction of +0.5 pcm/°C should be added to the calculated value α (both JEFF3.1 and JEF2.2 results), and consequently the C/E disagreement is decreased by 0.5 pcm/°C.

5 Conclusion

This paper has presented the analysis of 100% MOX BWR experiments performed wihin the framework of the BASALA programme, simulating hot conditions with BASALA-H (42% void) and cold conditions (0% void) with BASALA-C. Three configurations were analyzed for both types of cores: one reference core and two configurations containing absorbers or simulating high void fraction (72% void).

The core fission rate map is well predicted by APOLLO2/MOC/SHEM, within the ±2% experimental uncertainty for the reference cores. Radial power maps remain accurately calculated when inserting Hf or B4C control blades, as well as Gd burnable poison pins introduced in the central assemblies.

The MOX reactivity is overestimated in APOLLO2/JEFF3.1 calculations by 600 pcm for BASALA-H core and 750 pcm for BASALA-C core. Concerning absorber worth, UO_2-Gd_2O_3 poisoning, B_4C and hafnium control blade efficiency are satisfactorily predicted within 1% accuracy for B_4C and hafnium, and 2% for gadolinium. The hafnium resonant absorption has been improved by 0.5% using the 281 group-SHEM mesh and no self-shielding below 23 eV.

The bias on the void effect calculation is evaluated by 4.5% with APOLLO2/MOC/SHEM. It is already improved by 0.5% using the SHEM energy mesh; the residual bias could be decreased by the use of the new mixture self-shielding model in the $^{238}U/^{239}Pu/^{240}Pu$ resonance overlap at 66 eV.

The isothermal moderator temperature coefficient is better predicted with JEFF3.1 than with JEF2, by 0.6 pcm/°C in the temperature range 30°C-50°C. The C/E error on the temperature coefficient is quite constant in the range 10°C-80°C and amounts to –1.7 ± 0.3 pcm/°C.

6 Acknowledge

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7 References

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