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VALIDATION OF THE NEW CODE PACKAGE APOLLO2.8 FOR ACCURATE BWR CALCULATIONS

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ABSTRACT

This paper summarizes the Validation work performed to demonstrate the accuracy of the new APOLLO2.8/*SHEM-MOC* package based on JEFF3.1.1 nuclear data file for the prediction of BWR neutronics parameters. The Uncertainty Quantification derived from the experimental validation points out that design target-accuracies are met.

Key Words: **APOLLO2.8, BWR, VV-UQ, BASALA, FUBILA, GUNGREMMINGEN.**

1. INTRODUCTION

Target-accuracies are steadily decreasing for LWR calculations; moreover, fast and accurate BWR assembly calculations are requested by AREVA-NP for their industrial applications [1]. Therefore, a new version APOLLO2.8 based on the Method Of Characteristics was developed to allow enhanced LWR calculations in 2D-exact geometry [2]. This new version is well-suited to perform transport calculation of heterogeneous geometries, such as BWR assemblies (fuel rod enrichment zoning, UO_2-Gd_2O_3 burnable poisons, large water rods, channel box, liquid water blade). Moreover, a new energy mesh SHEM 281-group [3] was developed; this optimized multigroup structure using refined mesh below 23eV allows accurate resonant reaction rate prediction and resonance overlap handling both for actinides and fission products.

To reach the required target accuracies, a new nuclear data file JEFF3.1.1 [4] was issued in 2008, which accounts for the feedback from JEF2.2 qualification and trends derived from exhaustive PWR-type experiments. The processing of this JEFF3.1.1 supplied the recommended APOLLO2.8 library CEA2005v4.

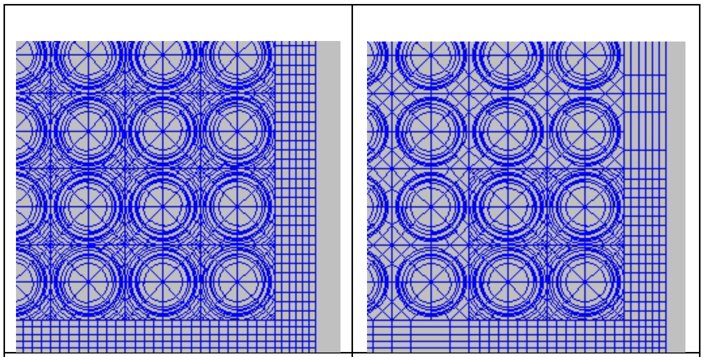
These recent advances in LWR calculation capabilities and relevant nuclear data evaluations allowed the definition of a 2005-2013 work program on the BWR Validation of the APOLLO2.8 package. This paper describes this VV-UQ work performed in the framework of the AREVA/CEA collaboration for the Convergence project.

2. VALIDATION OF REFERENCE *SHEM-MOC* AND OPTIMIZED *REL2005* SCHEMES

The Verification of the APOLLO2.8 code (no regression of the code compared to the previous recommended version APOLLO2.5), as well as the Validation of the new functionality MOC, was carried out using the Validation Machine MACH2 [5].

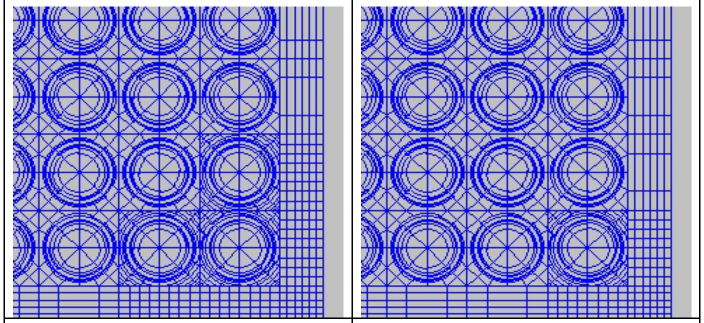
The APOLLO2.8 Reference Scheme for LWR assemblies is a two-step scheme [6]:
a) in the first step, the neutron energy spectrum is calculated in the 2D assembly geometry, using an accurate Pij multicell model: the UP1 Interface Current based on linearly anisotropic interface fluxes. Local spectrum calculation is performed in the optimized SHEM 281group structure. Above the refined energy mesh (i.e E>23eV), self-shielding formalism is used: a powerful space-dependent self-shielding based on the “Background Matrix” method is implemented, using Probability Tables for a more efficient quadrature in the Homogeneous/Heterogeneous equivalence.
b) in the second step, the exact-2D calculation is performed using the Method Of Characteristics.
In the Reference scheme *SHEM-MOC* this MOC assembly calculation is directly performed in the SHEM-281group mesh, meanwhile in the Optimized scheme *REL2005* the MOC calculation is carried out using collapsed cross sections from the first step in a 26-group mesh.

The numerical validation of the APOLLO2.8 BWR scheme, through a comparison to reference continuous-energy calculation TRIPOLI4, was carried out on various 9x9 assemblies. Figure 3 presents the corner discretization of the different geometries that were considered for the optimization study.



Ref. 1 (6338 regions)

Ref. 2 (4450 regions)



Ref. 3 (4354 regions)

Ref. 4 (4042 regions)

Figure 1. Corner discretization of BWR MOX assembly

Table 1 points out that *SHEM-MOC* Reference Scheme gives a small underestimation of the assembly multiplication factor (-157pcm) and a peak error lowered down to -0.6 %, compared to TRIPOLI4 reference results. The energy collapsing to the 26-group structure yields a slight bias by -30 pcm. Furthermore, results on geometry Ref. 1 indicates that the optimized tracking parameters are

$N\phi=24$ and $\Delta r=0.04$cm. To meet the challenging 1% target-accuracy on the pin-by-pin power map, the results on geometry Ref. 3 show that it is sufficient to discretized only the assembly corners.

Table 1. Results of the BWR MOX corner discretization study

Geometry Ref.	Group Number	$N\phi$	Δr	Keff (AP2/T4)	quadratic (peak) error on fission rate (%)
1	281	48	0,01	1,19074 (-157)	0,281 (-0,6)
	26	48	0,01	1,19027 (-191)	0,316 (-0,6)
	26	24	0,04	1,19036 (-185)	0,345 (-0,7)
2	26	24	0,04	1,19049 (-175)	0,414 (-0,8)
3	26	24	0,04	1,19050 (-174)	0,421 (-0,8)
4	26	24	0,04	1,19057 (-169)	0,470 (-1,2)

Concerning energy treatment, Table 2 shows the neutron balance in the challenging case 40%void, accordingly to Fermi's phenomenological breakdown: $K_\infty = \chi_{n,2n}\ \varepsilon_{U238}\ \varepsilon_{U235}\ p\ f\ \eta$. SHEM refined mesh allows accurate resonant rate calculations, meanwhile XMAS previous mesh produces large biases respectively on ε_{U235} fast/resonant fission factor and p resonance escape probability.

Table 2. Neutron balance breakdown and APOLLO2.8 biases in UOX-40%void

6 factors	TRIPOLI	XMAS (pcm)	SHEM (pcm)
$\chi_{n,2n}$	1.00158	3	3
ε_{U238}	1.09504	7	-9
ε_{U235}	1.34873	118	-13
p	0.48671	-398	19
f	0.96305	9	2
η	1.86758	0	1
K_∞	1.29493	-261	3

3. QUALIFICATION OF BWR NEUTRONICS PARAMETERS

The experimental validation of BWR neutronics parameters was carried out mainly on BASALA [7] and FUBILA [8] measurements in EOLE reactor: reactivity of BWR MOX assemblies, fuel zoning and pin-by-pin power maps, UO_2-Gd_2O_3 worth, 70% void effect corresponding to BWR upper core, Reactivity Temperature Coefficient, Efficiency Worth of B_4C and Hf control cross. The VENUS BWR experiment was analyzed to extend the validation to UOX cores [9].

3.1. Fresh fuel reactivity

Table 3 presents the Calculation-Experiment comparison on the K_{eff} of FUBILA critical cores. Table 4 confirms that APOLLO2.8 prediction of the reactivity of BWR UOX cores is satisfactory.

Table 3. C/E comparison of the reactivity of the FUBILA 100%MOX BWR cores in EOLE

Configuration	**9x9 REF**	**9x9 NORM**	**9x9 70%VOID**	**10x10**
K_{eff} *SHEM-MOC*	1.00464	1.00619	1.00706	1.00477
C-E ± δE (pcm)	407 ± 130	558 ± 110	622 ± 110	435 ± 120

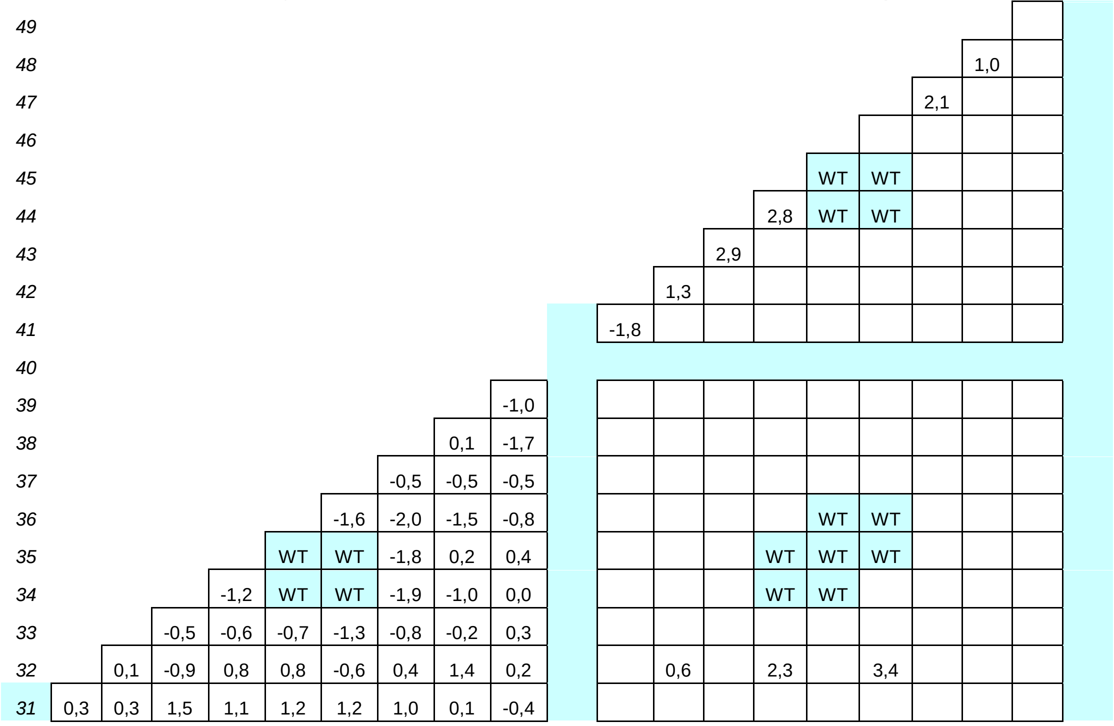
Table 4. C/E comparison of the reactivity of the VENUS-BWR UOX and mixed-loading cores

Configuration	**UOX**	**I-MOX**	**T-MOX**
K_{eff} *SHEM-MOC*	1.00095	0.99958	1.00087
C-E ± δE (pcm)	95 ± 270*	-42 ± 260*	87 ± 220*

*experimental uncertainty including axial leakage modeling and technological uncertainties

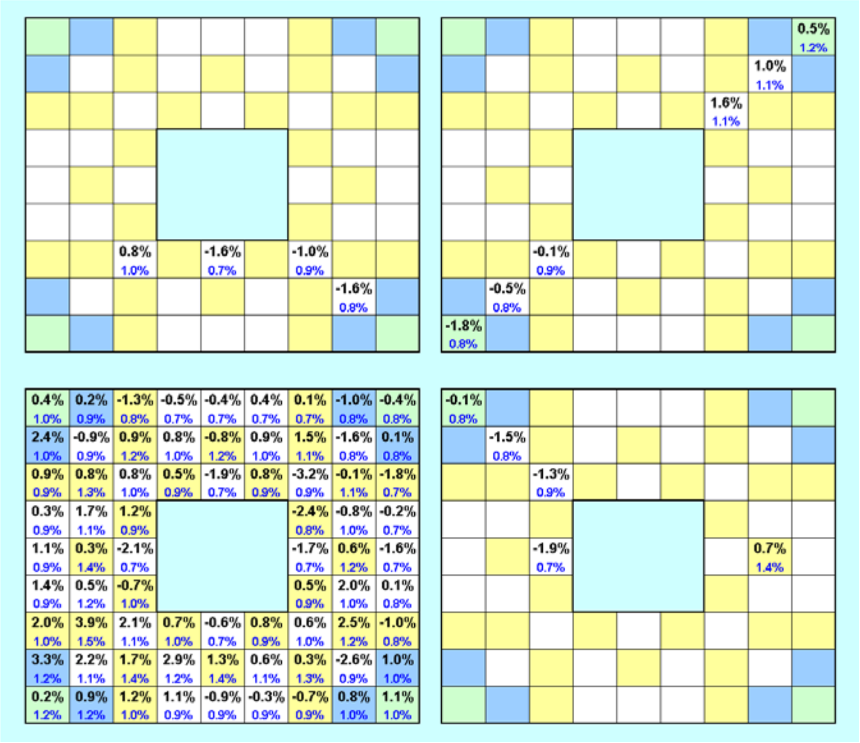
3.2. Pin-by-pin power map

Radial power maps in BASALA and FUBILA mock-ups are measured directly on the fuel rods by integral gamma-spectrometry. C/E comparisons on the fission rate distribution in BASALA-Hot/V (70%Void in central assembly) and FUBILA/NORM cores are plotted in Fig.2 and Fig.3.



49																		
48																	1,0	
47																2,1		
46																		
45														WT	WT			
44													2,8	WT	WT			
43												2,9						
42											1,3							
41										-1,8								
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					WT	WT			
35					WT	WT	-1,8	0,2	0,4				WT	WT	WT			
34				-1,2	WT	WT	-1,9	-1,0	0,0				WT	WT				
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		0,6		2,3		3,4			
31	0,3	0,3	1,5	1,1	1,2	1,2	1,0	0,1	-0,4									

Figure 2. (C-E)/E bias (%) on the fission rate in BASALA-Hot/VOID (1/8 core)



																	0.5% 1.2%
																1.0% 1.1%	
															1.6% 1.1%		
		0.8% 1.0%		-1.6% 0.7%		-1.0% 0.9%					-0.1% 0.9%						
							-1.6% 0.8%			-0.5% 0.8%							
									-1.8% 0.8%								
0.4% 1.0%	0.2% 0.9%	-1.3% 0.8%	-0.5% 0.7%	-0.4% 0.7%	0.4% 0.7%	0.1% 0.7%	-1.0% 0.8%	-0.4% 0.8%	-0.1% 0.8%								
2.4% 1.0%	-0.9% 0.9%	0.9% 1.2%	0.8% 1.0%	-0.8% 1.2%	0.9% 1.0%	1.5% 1.1%	-1.6% 0.8%	0.1% 0.8%		-1.5% 0.8%							
0.9% 0.9%	0.8% 1.3%	0.8% 1.0%	0.5% 0.9%	-1.9% 0.7%	0.8% 0.9%	-3.2% 0.9%	-0.1% 1.1%	-1.8% 0.7%			-1.3% 0.9%						
0.3% 0.9%	1.7% 1.1%	1.2% 0.9%				-2.4% 0.8%	-0.8% 1.0%	-0.2% 0.7%									
1.1% 0.9%	0.3% 1.4%	-2.1% 0.7%				-1.7% 0.7%	0.6% 1.2%	-1.6% 0.7%			-1.9% 0.7%					0.7% 1.4%	
1.4% 0.9%	0.5% 1.2%	-0.7% 1.0%				0.5% 0.9%	2.0% 1.0%	0.1% 0.8%									
2.0% 1.0%	3.9% 1.5%	2.1% 1.1%	0.7% 1.0%	-0.6% 0.7%	0.8% 0.9%	0.6% 1.0%	2.5% 1.2%	-1.0% 0.8%									
3.3% 1.2%	2.2% 1.1%	1.7% 1.4%	2.9% 1.2%	1.3% 1.4%	0.6% 1.1%	0.3% 1.3%	-2.6% 0.9%	1.0% 1.0%									
0.2% 1.2%	0.9% 1.2%	1.2% 1.0%	1.1% 0.9%	-0.9% 0.9%	-0.3% 0.9%	-0.7% 0.9%	0.8% 1.0%	1.1% 1.0%									

Figure 3. (C-E)/E bias and δE/E (1σ) on the fission rate in FUBILA/NORM (1/4 core)

3.3. Void coefficient

The void worth was measured both in BASALA and FUBILA experiments by inserting Al fuel over-clads or Al microrods in the 3x3 central BWR assemblies in order to simulate 40% void (BASALA-H and FUBILA/NORM) and 70% void fraction (BASALA-H/Void and FUBILA/Void).

Table 5. C/E comparison on the Void Fraction worth in BASALA and FUBILA experiments

	40% void		**70% void**	
	BASALA	FUBILA	BASALA	FUBILA
Void worth	-4000 pcm	-3200 pcm	- 1300 pcm	- 2460 pcm
(C-E)/E ± δE/E	2.5% ± 2.4%	-4.7% ± 3.0%	4.5% ± 3.0%	-2.6% ± 3.0%

3.4. Efficiency of control cross and Gd burnable poison

Table 6. C/E comparison on the reactivity worth of B_4C or Hf control cross and Gd poison

Configuration	**B_4C control cross**	**Hf control cross**	**UO_2-Gd_2O_3**
	BASALA-C		BASALA-H

Absorber Worth	-9700 pcm	-2000 pcm	-2000 pcm
(C-E)/E ± δE/E	-0.2% ± 0.4%	+1.0% ± 0.4%	-1.7% ± 0.7%

4. UNCERTAINTY QUANTIFICATION

The integral experiments, used to validate APOLLO2.8 for the calculation of BWR neutronics parameters, were selected because they are representative of actual BWR applications (c_K ~.0.95). Therefore, the Representativity theory allowed the Transposition [10] of C/E results to BWRs: APOLLO2.8/JEFF3.1.1 biases and associated uncertainties (1σ) are summarized in Table 7.

Table 7. Biases and Uncertainties of APOLLO2.8/*SHEM-MOC* calculation for BWR parameters

BWR parameter	UOX	MOX
Keff	+180 ± 250 pcm	+280 ± 260 pcm
Power Peak	-0.1% ± 0.7%	-0.3% ± 0.6%
$P^{ass}_{MOX} / P^{ass}_{UOX}$	+2.1% ± 1.7%	
Void coefficient	+0.8% ± 1.3%	+1.2% ± 1.5%
Temperature coefficient	-0.4 ± 0.5 pcm/°C	-0.7 ± 0.6 pcm/°C
B_4C control blade efficiency	-0.2% ± 0.5%	
Hf control blade efficiency	+0.7% ± 0.6%	
UO_2-Gd_2O_3 efficiency	+0.3% ± 1.2%	-1.2% ± 0.8%
Reactivity Loss with burnup	+0.4% ± 1.4%	+1.4% ± 2.2%

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