QUALIFICATION OF THE APOLLO2.5/CEA93.V6 CODE FOR UOX AND MOX FUELLED PWRS.

A. Santamarina, C. Chabert, A. Courcelle, O. Litaize and G. Willermoz,
CEA-Cadarache DEN / DER / SPRC
13108 Saint Paul-lez-Durance, France
alain.santamarina@cea.fr

D. Biron
EDF / SEPTEN

L. Daudin
Framatome-ANP

ABSTRACT

The recent code package APOLLO2.5/CEA93.V6 developed by CEA is currently implemented in the new PWR neutronics tools of Framatome-ANP and Electricité de France. The development of this neutronics tool was achieved within Quality Assurance process, using a rigorous methodology of Verification/Validation/Qualification. The average of the C/E errors among the various integral experiments allowed the "calibration" of the APOLLO2.5 product, as well as the associated uncertainty, for every PWR design parameter. The qualification extends up to 4.8% U235-enriched UO_2 fuel and 7% Pu MOX fuel. Concerning burnup range, the APOLLO2.5 qualification spans the 0 – 60 Gwd/t range for UOX fuel, and extends up to 45 Gwd/t for MOX fuel.

1. INTRODUCTION

The recent code package APOLLO2.5/CEA93.V6 developed by CEA [1] is currently implemented in the new PWR neutronics tools of Framatome-ANP and Electricité de France, SCIENCE.V2 [2] and N3C respectively. This code is also extensively used at CEA for design studies of large Thermal Reactors (PWR, BWR, VVER, naval propulsion reactors, HTR, CANDU, Graphite-moderated reactors), High Conversion Reactors, as well as Irradiation reactors and Safety experimental reactors.

The development of this industrial code package was achieved within Quality Assurance process. Therefore, a rigorous methodology of Verification/Validation/Qualification was developed and applied.

2. THE VALIDATION / QUALIFICATION PROCESS

The first step of this process verifies that numerical models and programming of each module are correct; this Verification is also based on the Test Machine which avoids non-regression in the new APOLLO2 Version.

The second step corresponds to the Validation of the APOLLO2 functionalities (Pij, resonance self-shielding, fine flux, depletion, accurate SPH homogenisation, Sn, etc.) as well as the '*CEA-97*' reference calculation route. This Validation is based on the comparison of APOLLO2.5/*CEA-97* calculation results against continuous-energy Monte Carlo TRIPOLI4 reference calculation. Both calculations use the same nuclear data JEF2.2. This Validation enables also the "calibration" of the recommended *CEA-97* Reference route : the calculation bias is determined for each LWR design parameter. This validation process is automated through the MACH2 Machine.

The Qualification is the third step, corresponding to the comparison of the results of the global package (code + reference calculation route + nuclear data library, i.e APOLLO2.5/*CEA-97*/CEA93.V6) against experimental results from integral measurements. A first set of experiments characterised by their fundamental measurements [3] is used to qualify the CEA93 nuclear data (processed from the JEF2.2 library) of the main isotopes; for instance, capture cross sections of the main poisoning Fission Products are qualified through reactivity worth measurement of separated FP samples by an oscillation technique in various spectra at the central cell of the Minerve zero power rector [4]. A second set of mock-up experiments is used to qualify the calculation of the whole LWR parameters; from this qualification process, based on several thousands of integral measurements; the total error of the APOLLO2.5 product is obtained for each design parameter, as well as the associated uncertainty.

These calculation errors and their confidence intervals, reported in the Qualification document, are used by CEA, EDF and Framatome as a part of the qualification of their own neutronics design calculation chains.

3. QUALIFICATION OF UOX AND MOX REACTIVITY

The lattice reactivity versus moderation ratio is mainly checked through Material Buckling values deduced from radial and axial flux measurements in french critical experiments. The slight reactivity overestimation for very tight UOX lattices shown in Table 1 is mainly linked to the low capture Resonance Integral of the U235 evaluation in JEF2.2 [5].

Table 1. Material Buckling Analysis of LWR-UOX lattices

Nom	Pitch (cm)	Rmod	Slowing Q	C_B (ppm)	$Keff^{AP2} - 1$	δkeff (1σ)
Cristo3	0,96	0,45	0,37	750	+ 1267 pcm	± 700 pcm
ZPR HiC SS clad	1,24	0,96	0,50	0	+ 98 pcm	± 500 pcm
UH1.2	1,26	1,25	0,51	569	+ 448 pcm	± 300 pcm
CAMELEON	1,26	1,80	0,57	610	+ 885 pcm	± 400 pcm
MISTRAL1	1,32	1,75	0,53	294,2	- 222 pcm	± 400 pcm
Cristo2 C_B = 832 ppm	1,58	3,56	0,76	832	- 162 pcm	± 400 pcm
Cristo2 C_B = 1550 ppm	1,58	3,56	0,86	1550	- 534 pcm	± 450 pcm
Cristo2 « wide »	1,71	4,40	0,79	672,5	- 4 pcm	± 400 pcm
Cristo1	1,86	5,46	0,89	750	+ 216 pcm	± 400 pcm

This slight overestimation of the reactivity of PWR-type lattice is confirmed by regular core experiments where Keff is accurately measured through the critical fuel loading or/and critical soluble boron concentration, mainly the CAMELEON [6] – ERASME [7] – EPICURE [8] – MISTRAL [9] experiments performed in the Eole reactor (Table 2).

Table 2. Reactivity of LWR regular cores

	APOLLO2.5	Experiment	C-E
EPICURE UH1.2	ρ = 596 pcm	ρ = 55 pcm	+ 541 pcm
MISTRAL1	ρ = 527 pcm	ρ = 109 pcm	+ 418 pcm
CAMELEON	ρ = 935 pcm	ρ = 110 pcm	+ 825 pcm

The qualification was extended to LWR-mockup benchmarks reported in the international ICSBEP data base. Table 3 indicates that the Keff value of these critical cores is overestimated by APOLLO2 : $Keff_{\mathbf{AP2}.5} - Keff_{exp} = + 140 \pm 200$ pcm ; the APOLLO2 results are consistent with the reference TRIPOLI4 3D continuous-energy Monte Carlo calculations.

Table 3. APOLLO2 and TRIPOLI4 Analysis of the ICSBEP LWR-mockup cores

Nom	Pitch (cm)	Rmod	clad	UOX pins	C_B(ppm)	exp unc(1σ)	$Keff_{AP2.5}$	$Keff_{TRI4}$
ZPR HiC13	Δ 1,17	0,43	Al	5091	0	± 640 pcm	0.99852	0.9968
ZPR HiC11	Δ 1,27	0,75	Al	1417	0	± 470 pcm	0.99987	0.9971
ZPR HiC10	□ 1,24	0,96	Al	950	0	± 410pcm	0.99909	0.9979
ZPR HiC8	□ 1,24	0,96	SS304	1766	0	± 370 pcm	1.00441	1.0032
ZPR HiC13	□ 1,35	1,37	Al	589	0	± 340 pcm	0.99890	0.9970
VVER 3.6%	Δ 1,10	0,89	Zr	1675	0	± 370 pcm	0.99844	0.9990
VVER 3.6%	Δ 1,27	1,66	Zr	721	0	± 300 pcm	1.00238	1.0025
VVER 3.6%	Δ 1,50	2,88	Zr	409	0	± 340 pcm	1.00193	1.0016
VVER 3.6%	Δ 1,50	2,88	Zr	985	700	± 420 pcm	1.00726	1.0070
VVER 4.4%	Δ 1,50	2,88	Zr	349	0	± 400 pcm	1.00147	1.0014
VVER 3.6%	Δ 1,90	5,51	Zr	313	0	± 300 pcm	1.00620	1.0041
KRITZ 2:1	□ 1,48	1,17	Zr	1936	218	± 380 pcm	1.00071	0.9954
KRITZ 2:13	□ 1,63	1,70	Zr	1600	452	± 250 pcm	1.00172	0.9969
VALDUC1	□ 1,26	1,82	Al	484	0	± 300 pcm	0.99853	0.9967
VALDUC2	□ 1,60	3,81	Al	272	0	± 300 pcm	1.00040	0.9986

The reactivity of LWR Pu-fuelled cores is also well predicted by APOLLO2.5/CEA93 for moderation ratios ranging from 0.51 (ERASME experiments corresponding to HCPWRs) up to 2.1 . For standard PWR-MOX lattices (excluding ERASME in Table 4), the average error is : C–E= +5 pcm ± 250 pcm (1σ).

Table 4. Material Buckling Analysis of MOX lattices

Experiment	Pitch (cm)	Rmod	Slowing Q	C_B (ppm)	Keff AP2 -1	δkeff (1σ)
ERASME/S	0,945	0,51	0,24	0	+ 345 pcm*	± 400 pcm
ERASME/R	1,035	0,90	0,36	0	+ 736 pcm*	± 400 pcm
EPICURE MH1.2	1,26	1,25	0,52	224	- 368 pcm	± 350 pcm
MISTRAL2	1,32	1,75	0,57	0	+ 73 pcm	± 350 pcm
ERASME/L Small	1,19	2,1	0,50	0	- 628 pcm	± 500 pcm
ERASME/L Large	1,19	2,1	0,53	1656	- 696 pcm	± 400 pcm
MISTRAL3	1,39	2,11	0,60	235	+ 308 pcm	± 300 pcm

4. RADIAL POWER MAPS

The qualification of local power peak prediction is based on EPICURE configurations. UH1.4 core is a 17x17 PWR mock-up which allowed the conclusion that APOLLO2 reference route predicts rod power within ± 0.7% spread, compared to the ± 0.6% (1σ) experimental uncertainty on fuel rod gamma spectrometry. The qualification of radial powermap in mixed loading PWR cores is obtained from the UMZONE mock-up : Figure 1 points out a satisfactory prediction in the various Pu zones of the central MOX assembly. However, a systematic overestimation of MOX power is raised relatively to surrounding UOX assemblies : + 1.8 % ± 0.7%. This overestimation is consistent with the ± 2% experimental uncertainty associated to the La140 peak check technique.

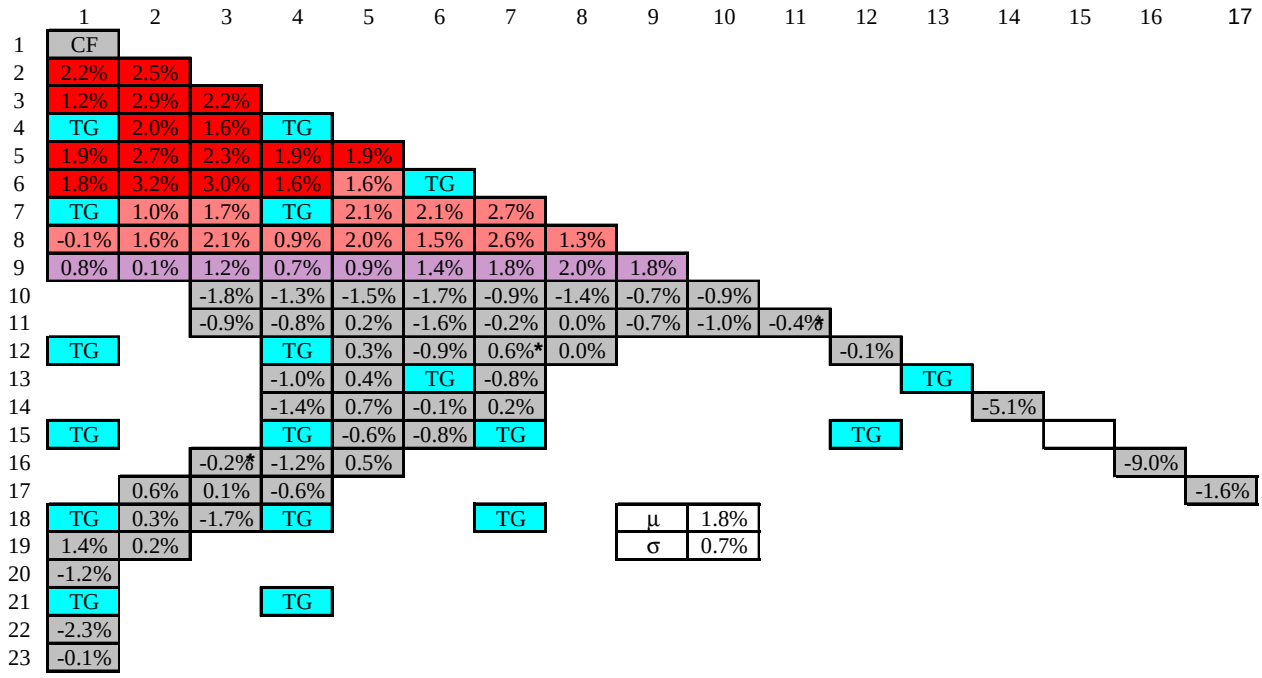

Figure 1. APOLLO2 prediction of the radial power map in the mixed loading UMZONE core

5. DEPLETION CALCULATION AND FUEL INVENTORY

The qualification is mainly based on Post Irradiation Experiments (PIE) carried out on spent 17x17 assemblies from various french PWRs. Bugey3 and Fessenheim2 assemblies allowed the qualification of 3.1% U235-enriched UOX fuel up to 60 Gwd/t, meanwhile P.I.E after 2, 3, 4 and 5 cycles in Gravelines enabled the extension of the qualification up to E_{U235} = 4.5% and Bu = 62 Gwd/t [10]. Table 5 summarises the C/E comparison on major actinides for the rod cuts at assembly mid-height.

Table 5. APOLLO2 analysis of isotopic ratios in PWR spent fuel

Fuel rod	**K08**	**K11**	**G07**	**G11**	**G10**	**K08**	**J09**	**J07**
Cycle	2	2	3	4	4	5	5	5
Asssembly Burnup (GWd/t)	26.9	26.9	38.4	50.8	49.8	60.0	60.0	60.0
U234/U238	-0.2	1.1	1.0	-3.9	0.9	1.3	0.9	3.1
U235/U238	0.4	2.3	2.5	4.33	2.1	-1.9	6.0	9.7
U236/U238	-4.1	-5.5	-4.6	-5.0	-4.3	-3.9	-4.1	-4.6
Np237/U238	-	-2.3	-3.7	-5.3	-	-	-	-6.4
Pu238/U238	-9.1	-15.3	-10.6	-10.7	-9.6	-9.5	-9.2	-11.7
Pu239/U238	-0.4	-1.0	0.4	1.7	0.2	-0.6	2.5	2.2
Pu240/U238	-1.5	-4.2	-2.1	-1.1	-0.7	-0.2	-0.8	-1.2
Pu241/U238	-3.5	-7.1	-4.1	-3.0	-2.9	-3.8	-1.2	-1.8
Pu242/U238	-7.0	-12.6	-9.2	-9.7	-7.5	-6.6	-7.4	-9.6

The depletion qualification of MOX assemblies extends currently up to 45 Mwd/t [11]. Chemical assay results demonstrated that APOLLO2.5 tool is able to predict the major actinide content within 3% accuracy, except Pu242 which is underestimated by -5 % ± 2% (Table 6).

Table 6. APOLLO2 analysis of isotopic ratios in SLB1 PWR MOX assembly

Fuel pin	P14	I13	I02	Q17	N13	P16	L14
Cycle	1	2	2	3	3	3	3
Zone	Interm.	Central	Interm.	Periph.	Interm.	Periph.	Central
Burnup (GWd/t)	12.9	28.4	28.5	37.7	41.5	42.0	45.0
U^{234}/U^{238}	-4.42	-11.52	-6.87	2.09	-4.87	-3.94	-9.41
U^{235}/U^{238}	1.13	1.89	2.92	5.79	4.70	2.04	4.28
U^{236}/U^{238}	-10.13	-7.10	-8.24	-5.63	-7.84	-5.18	-6.45
Pu^{238}/U^{238}	-8.10	-9.05	-8.56	-7.56	-6.17	-6.76	-8.57
Pu^{239}/U^{238}	0.57	3.98	1.54	-1.28	4.72	-0.23	4.13
Pu^{240}/U^{238}	-0.45	0.62	0.01	4.07	1.91	1.14	1.28
Pu^{241}/U^{238}	-2.20	-1.25	-3.22	-3.86	-1.42	-3.17	-1.83
Pu^{242}/U^{238}	-2.19	-3.37	-4.60	-5.73	-6.21	-4.87	-5.64

6. ABSORBER CLUSTER WORTH

The reactivity worth of various 24-Rod Control Clusters (Silver-Indium-Cadmium, B_4C nat, B_4C 90 % B10, Hf) was qualified in PWR UOX and MOX mock-up cores.

Table 7. C/E comparison on Control Cluster Efficiency in PWR-UOX mock-ups

		δΔρ	Exp unc.
UH1.4-ABS	B4C	+0.7%	±1% (1σ)
	S-I-C	+1.3%	±1% (1σ)
UH1.4	SS + S-I-C	+3.9%	±1.5% (1σ)
	Pyrex	+2.7%	±1.5% (1σ)

These satisfactory results are confirmed by fission rate measurements (integral γ-spectrometry on fuel pin), as shown in Figure 2.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	CF															
2	0.9%	0.7%														
3	-0.5%	-1.4%	-1.6%													
4	AIC	-2.7%	-0.9%	AIC												
5	-1.2%	-1.9%	-2.7%	-2.0%	-2.8%											
6	1.2%	-1.2%	-1.4%	-1.7%	-3.7%	AIC										
7	AIC	-0.5%	-0.2%	AIC	-1.6%	-0.5%	-1.0%									
8	-2.7%	-2.3%	-2.0%	-0.5%	-0.8%	-1.4%	-0.9%	0.4%								
9	-1.7%	-1.8%	-1.4%	-0.7%	-0.8%	-1.4%	-0.8%	-1.5%	-0.6%							
10			-1.7%	-2.0%	-0.7%	-0.8%	-0.3%	0.5%	-0.4%	0.3%*						
11				-1.7%	0.0%	0.0%	0.5%	-0.2%			-0.3%*					
12	TG			TG	-0.8%	-0.5%	1.1%					-0.2%				
13				-1.7%	-0.2%	TG							TG			
14				-1.6%	0.6%									0.2%		
15	TG			TG			TG					TG			-1.7%	
16			-0.3%	-1.8%												-3.0%
17		1.8%	0.1%													
18	CF	1.7%		TG			TG									
19	2.1%															
20	-0.9%															
21	TG			TG												
22	-1.9%															
23	-3.0%															

μ	-1.2%
σ	1.0%

* : points de normalisation

Figure 2. APOLLO2 prediction of radial power map in UH1.4 core with 24 Silver-In-Cd (S-I-C)

7. REACTIVITY COEFFICIENTS

The experimental qualification of the various PWR reactivity coefficients was carried out : Doppler coefficient [12], isothermal temperature coefficient up to 300°C in both UOX and MOX lattices, soluble boron coefficient, integral boron poisoning up to ΔC_B = 600 ppm, Void coefficient.
The Reactivity Temperature Coefficient (RTC) was qualified at room temperature conditions (5°C – 80°C) in the "homogeneous" cores MISTRAL1 for LWR-UOX and MISTRAL2 plus MISTRAL3 for LWR-MOX [3]. The RTC Calculation – Experiment comparison, plotted in Figure 3 for the MISTRAL1-UOX core, shows a satisfactory agreement : C-E error always lies within the ±0.3 pcm/°C experimental uncertainty margin throughout the 10°C – 70°C temperature range.

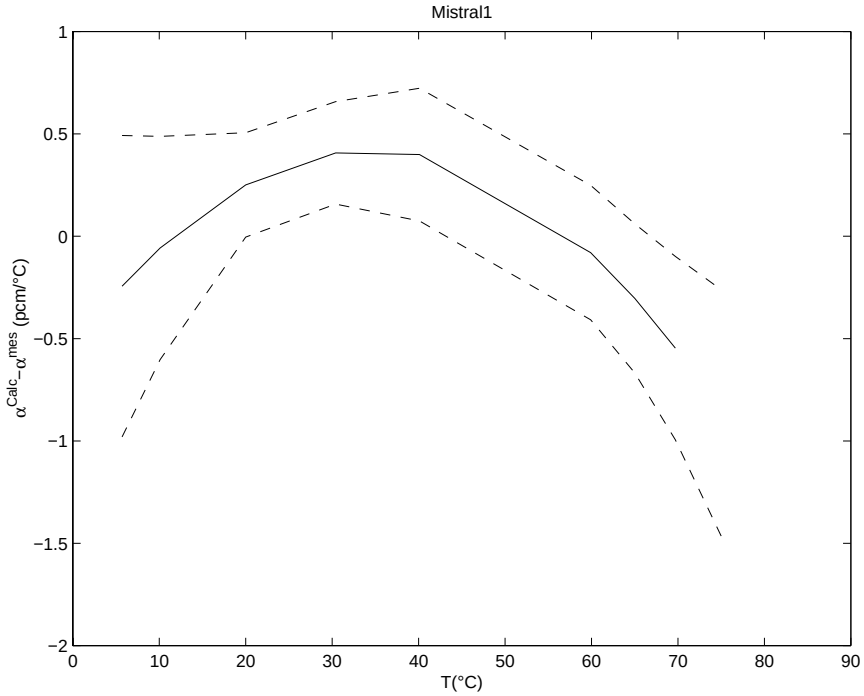

Figure 3. APOLLO2 –Experiment comparison on RTC in MISTRAL1-UOX core

The APOLLO2 qualification of the RTC in PWR nominal conditions was carried out in the Creole experiment [13]. A specific PWR pressurised loop was implemented at the centre of the EOLE critical facility. The RTC has been measured in UO_2 and UO_2-PuO_2 PWR type lattices. Both clean and Boron poisoned water moderated lattices were investigated for the temperature range starting from room temperature up to PWR power plant operating conditions (300°C). Starting from a core with a reactivity excess of 300 pcm, the moderator temperature in the loop was raised using an electrical heater; the resultant core reactivity change was measured by the doubling time technique every 10°C. A least-square polynomial fitting of the core reactivity, versus water temperature, was applied both to measurements and to APOLLO2 Sn-RZ calculations. After differentiation, the core RTC analytical forms were obtained : Figures 4 and 5 show the comparison of the calculated and measured differential

RTC in the UO_2 and the MOX configuration respectively. The experimental temperature dependence of the core RTC is quite well reproduced by APOLLO2. For the UO_2 clean lattice, the discrepancies are within the experimental uncertainties and consequently no significant error can be associated with calculation for the whole temperature range; whereas, for the MOX lattice there is a clear tendency to underestimate the absolute value of the core RTC for the temperature range beyond 250°C.
In addition to the measurements of the global reactivity temperature coefficient, the water expansion effects were also estimated in Creole experiment using Aluminium overclads.
The transposition from the Creole core to PWR situation was settled by using the relative reactivity worth of the experimental loop. The results for both temperature and water expansion effects are summarised in three temperature ranges in Table 8.

Table 8. APOLLO2 - Experiment comparison on RTC and water expansion component

$\Delta\alpha_{C-E}$ (in pcm/°C) RTC discrepancy ± uncertainty 1σ (water density component)					
UO_2 configuration			MOX configuration		
20°C - 90°C	90°C-250°C	250°C-300°C	20°C - 90°C	90°C-250°C	250°C-300°C
- 0.8 ± 1.5 (+0.3)	- 0.7 ± 1.7 (+0.7)	+ 0.7 ± 2.0 (+1.2)	- 0.7 ± 1.8 (+0.7)	+ 0.5 ± 2.0 (+1.5)	+ 3.0 ± 2.2 (+2.5)

The qualification of the soluble boron coefficient was mainly obtained from MISTRAL UOX and MOX cores where the boron worth was measured by changing the boron concentration by ±3 ppm. The APOLLO2 analysis is shown in Table 9 for the LWR-UOX core.

Table 9. Boron coefficient qualification in MISTRAL1-UOX core

$\alpha = dK_{eff}/dC_B$	Experiment (pcm/ppm)	APOLLO2 (pcm/ppm)	(C-E)/E ± 1σ (%)
Divergence Method	-15.4 ± 1.6	---	---
ASM Method	-15.8 ± 1.5	---	---
α (average)	-15.6 ± 1.1	-16.10	3.4 ± 7.0

Furthermore, the boron integral efficiency was measured up to 600 ppm in both cores by the ASM Amplification Source Method (±4% uncertainty). The average of the differential and integral boron worth measurements gives the following APOLLO2.5 calibration in 100% MOX cores :

(C-E)/E = 0.1% ± 3% (1σ).

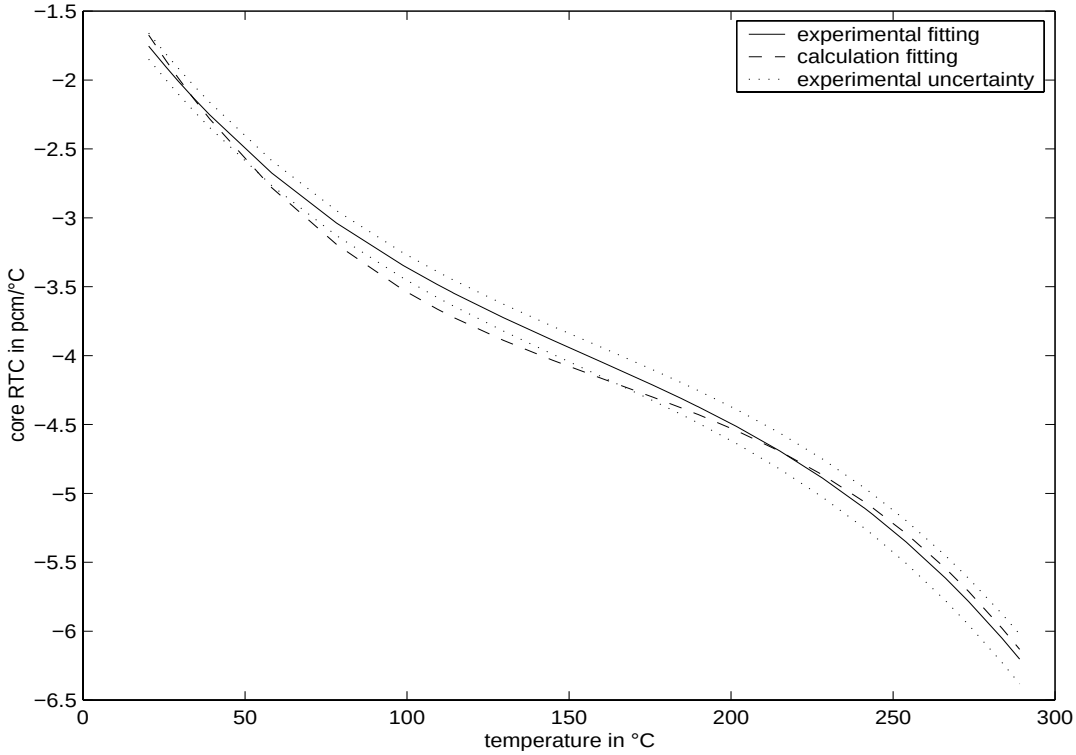

Figure 4. APOLLO2 –Experiment comparison on differential RTC in CREOLE-UOX

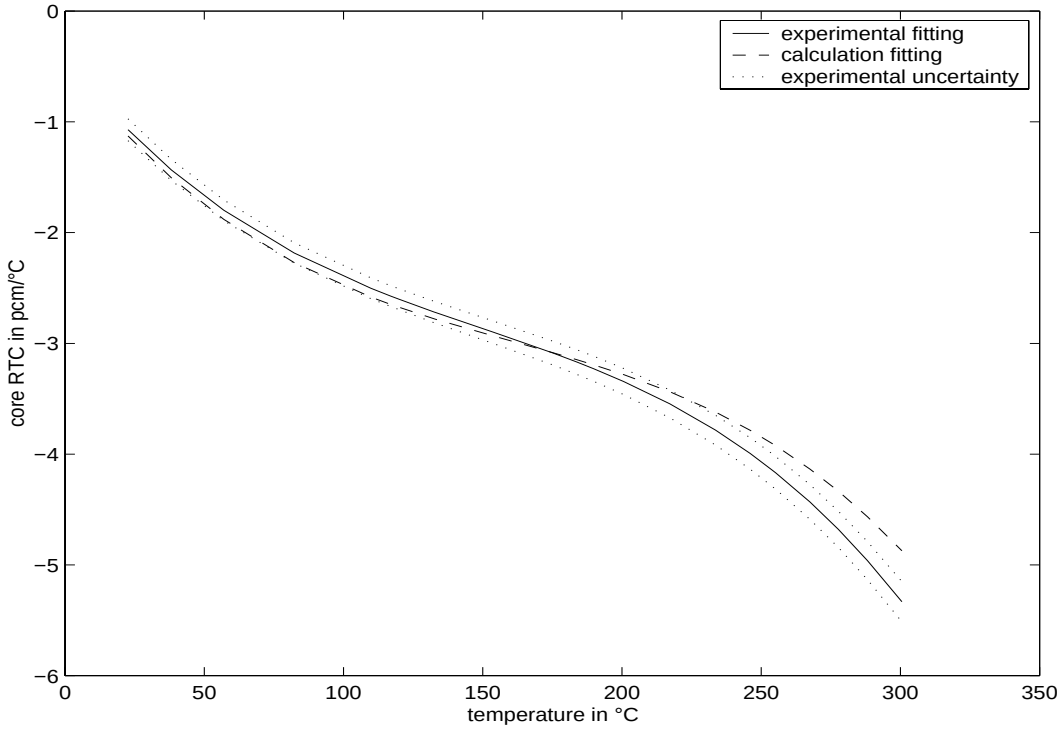

Figure 5. APOLLO2 –Experiment comparison on differential RTC in CREOLE-MOX

8. KINETICS PARAMETERS

The MISTRAL experiments point out that the effective delayed neutron fraction is fairly predicted by APOLLO2.5/CEA93.V6 in both UOX and MOX cores [14] : the C/E difference in βeff always lies within the ± 3% (2σ) uncertainty margin. The APOLLO2.5 qualification of neutron lifetime Λ was derived from $\alpha_c = \beta eff / \Lambda$ measurements :

$(C - E) / E = +4\% \pm 3\%$ LWR-UOX
$(C - E) / E = +6\% \pm 3\%$ LWR-MOX

9. REACTIVITY LOSS WITH BURNUP AND CYCLE LENGTH

The fuel reactivity loss with burnup was measured through sample oscillations of PWR rod cuts. The reactivity worth of these spent fuel samples were measured at the centre of the R1-UO2 PWR-type Minerve lattice. The C/E comparison summarised in Table 10 allows the conclusion that the reactivity loss is predicted as follows: (C–E) / E = + 0.5% ± 2% (1σ).

Table 10. APOLLO2.5/CEA93 Analysis of Burnup Reactivity Loss

Reactor/ Assembly	PWR samples Pin (height)	BU ass (Gwd/t)	Δρ exp. (a.u)	(C-E)/E ± 1σ
BUGEY 3 e^{235} = 3.10 %	G11 (196)	20.4	- 261.6	1.9 % ± 2.3 %
	K07 (196)	24.7	- 313.0	- 3.4 % ± 2.2 %
	K11 (196)	38.3	- 439.6	- 2.2 % ± 2.2 %
	K11 (300)	38.3	- 409.9	4.3 % ± 2.9 %
GRAVELINES e^{235} = 4.5 %	K08 (190)	26.6	- 306.8	3.6 % ± 2.4 %
	J07 (190)	61.0	- 565.7	0.6 % ± 2.1 %
FESSENHEIM 2 e^{235} = 3.14 %	H11 (196)	49.8	- 493.1	- 0.1 % ± 2.2 %
	G10 (196)	57.5	- 534.5	0.1 % ± 2.1 %

10. LUMPED BURNABLE POISON UO_2-Gd_2O_3

The depletion calculation of UO_2-Gd_2O_3 LBPs, and their poisoning worth versus exposure, was checked against the GEDEON1 irradiation [15]. In this experiment performed at the 8 MW Melusine CEA reactor, a 13x13 PWR-type assembly was burned up to 11 Gwd/t at the centre of the MTR bundles. The GEDEON1 assembly consists of 3.5%-enriched UO2 fuel pins and four UO_2-Gd_2O_3 poison pins loaded with 500mg/cm^3 of Gd_2O_3.The location of these four LBPs inside the GEDEON1 assembly avoids Gd/Gd shadowing effect, as well as feeder zone perturbation.

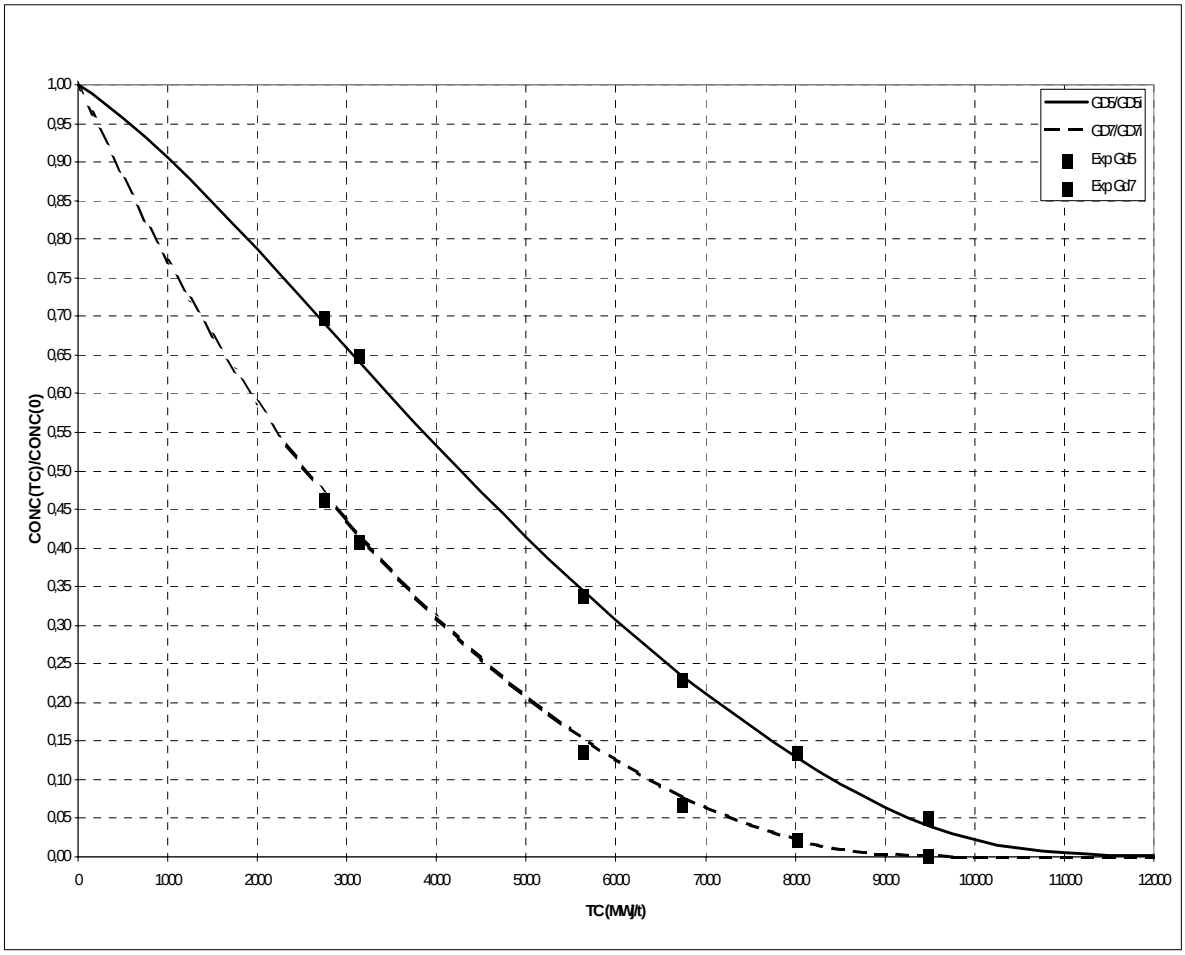

Figure 6. APOLLO2 analysis of Gd155 and Gd157 chemical assays versus GEDEON1 burnup

The results of the APOLLO2 core depletion calculation are compared in Figure 6 to the Gd155 and Gd157 chemical assays at increasing GEDEON1 burnups. This C/E comparison is satisfactory because APOLLO2 predicts the depletion of the two Gd absorbing isotopes within 1% accuracy (of their initial content).

11. CONCLUSION

The average of the C/E errors among the various integral experiments allowed the "calibration" of the APOLLO2.5/CEA93.V6/*CEA-97* product, as well as the associated uncertainty (Table 11).

Table11. Average error, and associated uncertainty,of the APOLLO2.5/CEA93 tool

PWR Parameter	**UOX**	**MOX**
Keff	+ 270 ± 150 pcm	+ 10 ± 250 pcm
Power Peak	- 0.4 ± 0.7 %	+ 1.0 ± 1.5 %
$\Delta\rho^{cycle}$	+ 0.5 ± 2 %	-
dK/dT_{fuel} (Doppler)	0 ± 15 %	0 ± 20 %
dK/dT_{mod} T = 20°C-80°C	- 0.0 ± 0.3 pcm/°C	- 1.5 ± 0.3 pcm/°C
dK/dT_{mod} T ≅ 300°C	- 0.9 ± 1.0 pcm/°C	+ 3.0 ± 2.2 pcm/°C
dK/dC_B (boron coeff)	+ 3 ± 8 %	+ 0 ± 3 %
$\Delta K/\Delta V_{mod}$ (void coeff)	+ 0 ± 3 %	+ 5 ± 3 %
βeff	+ 2.4 ± 1.6 %	+ 0.1 ± 1.6 %
Neutron Lifetime Λ	+ 4 ± 3%	+ 6 ± 3%
$\rho^{Cluster}$ (24 B_4C or Ag-In-Cd)	+ 1 ± 1 %	-
$\rho^{Grey\ Cluster}$	+ 4 ± 2 %	-
Pyrex 24 SiO_2-B_2O_3 $\rho_{initial}$	+ 2.7 ± 1.5 %	x
UO_2-Gd_2O_3 $\rho_{initial}$	+ 0.2 ± 0.6 %	x
UO_2-Gd_2O_3 $\rho_{(BU)}$	+ 0 ± 2 %	x
Reflector Saving	- 1.4 ± 2 %	+3.5 ± 2 %

These APOLLO2 results were globally confirmed by the follow-up of French PWRs. Start-up experiments at BOC for 900Mwe Tricastin3 and 1450Mwe Chooz reactors were carefully analysed.
The current qualification of the APOLLO2.5 package extends up to 4.8% U235-enrichment for LWR-UOX fuel and 7% Pu enrichment for MOX fuel. Concerning burnup range, the APOLLO2.5 qualification spans the 0 – 60 Gwd/t range for UOX fuel, and extends up to 45 Gwd/t for MOX fuel.
Based on a new P.I.E programme on high burnup PWR assemblies, the qualification range will be extended during the next three years to 80 Gwd/t and 65Gwd/t respectively for UOX and MOX fuel.

REFERENCES

[1] S. Loubiere, R. Sanchez, M. Coste, A. Hebert, Z. Stanskovski, I. Zmijarevic "APOLLO2 Twelve Years After", Int. Top. Meeting on Mathematics and Computation M&C99, Madrid (Spain), Sept. 1999

[2] P. Girieud, L. Daudin, C. Garat, P. Marotte, S. Tarlé "SCIENCE Version 2. The most recent capabilities of the Framatome 3D Nuclear Code Package", ICÔNE 9 Nice Acropolis, France, April 8-12, 2001

[3] O. Litaize, A. Santamarina, C. Chabert "Analysis of the MISTRAL Experiment with the APOLLO2 code". This Conference.

[4] A. Santamarina, P. Albarede, P. Andrieu, J.P. Chauvin, F. Garcia, B. Gastaldi, B. Roque, "Experimental Validation of Burnup Credit Calculations by Reactivity Worth Measurements in the Minerve Reactor", Proc. Int. Conf. on Nucl. Criticality ICNC'95, Albuquerque (USA), 17-21 September 1995

[5] A. Courcelle, A. Santamarina, C. Chabert, O. Serot , B. Roque, O. Litaize, "Experimental Validation of the main Actinide and FP Nuclear Data. Improvements for JEFF". This Conference.

[6] L. Martin-deidier, A. Santamarina, D. Doutriaux, M. Roshd, "CAMELEON : a Benchmark Experiment for Absorbers and Burnable Poisons in PWRs", ANS - Transactions, Vol. 46 pp 755-756, Juin 1984

[7] A. Santamarina, S. Cathalau, J.P. Chauvin, "Undermoderated PWR neutronic Qualification through the ERASME Experiment", Proc Int. Top. Meeting on Advances in Reactor Physics, Paris, 27-30 April 1987

[8] J. Mondot et al., "EPICURE: an experimental programme devoted to the validation of Pu recycling in PWRs", Int. Conf. on the the Physics of Reactors PHYSOR'90, Marseille (France), 23-27 April 1990

[9] S. Cathalau, P. Fougeras, P. Blaise, A. Santamarina, O. Litaize, C. Chabert, T. Yamamoto, M. Ueji, P. Girieud, D. Biron, M. Tatsumi, T. Kan, M. Ando, K. Ishii, "Full MOX recycling in ALWR : Lessons drawn through the MISTRAL Programme". This Conference.

[10] C. Chabert, A. Santamarina, R. Dorel, D. Biron, C. Poinot, "Qualification of the APOLLO2 Assembly Code using PWR-UO2 Isotopics Assays. The importance of Irradiation History and Thermo-mechanics on Fuel Inventory Prediction", Int. Conf. on the the Physics of Reactors PHYSOR'2000, Pittsburg (USA), May 7-11, 2000

[11] C. Chabert, A. Santamarina, P. Bioux, "Elaboration and Experimental Validation of the APOLLO2 Depletion Transport Route for PWR Pu Recycling", Int. Conf. on the the Physics of Reactors PHYSOR'2000, Pittsburg (USA), May 7-11, 2000

[12] A. Meister, A. Santamarina, “The Effective Temperature for Doppler Broadening of Neutron Resonances in UO_2.”, International Conference on the Physics of Nuclear Science and Technology PHYSOR-98, Long Island (NY), USA, 5-8 Octobre 1998.

[13] L. Erradi, A. Santamarina, “Analysis of the CREOLE Experiment on the Reactivity Temperature Coefficient using the APOLLO2 code and the JEF2.2 Nuclear Data File”, Int. Conf. on the the Physics of Reactors PHYSOR'2000, Pittsburg (USA), May 7-11, 2000

[14] O. Litaize, A. Santamarina, “Experimental Validation of Effective Delayed Neutron Fraction in LWR-MOX Core”, This conference

[15] P. Chaucheprat, A. Santamarina“, Qualification of the UO_2-Gd_2O_3 Depletion Calculation through the GEDEON Experiments”, Proc Int. Top. Meeting on Advances in Reactor Physics, Vol.1 p199, Paris, 27-30 April 1987