ANALYSIS OF THE MISTRAL EXPERIMENT WITH APOLLO2 QUALIFICATION OF NEUTRONIC PARAMETERS OF UOX AND MOX CORES

Olivier Litaize, Alain Santamarina, and Christine Chabert
DEN/DER/SPRC - CEA Cadarache
13108 Saint Paul-lez-Durance, France
olitaize@cea.fr ; alain.santamarina@.cea.fr

ABSTRACT

This article describes the analysis results of MISTRAL1, MISTRAL2 and MISTRAL3 core configurations. The analysis of these experiments was carried out in the framework of the NUPEC - CEA/DEN co-operation using current Japanese and French neutronic tools. In this work, APOLLO2 code was used and, in order to uncouple calculation route biases from nuclear data errors, the continuous energy Monte Carlo code TRIPOLI4 was also used to obtain reference calculations. Several parameters such as reactivity, reactivity temperature coefficient, boron efficiency, spectrum indices and absorber worth were investigated.
Radial power maps are well reproduced by 2D and 3D ; the fuel lattice / reflector interface is well mocked up and the local fission rate increase is fairly well predicted. The UOX reactivity (MISTRAL1 core) is overpredicted with APOLLO2 by +400 and by +700 pcm for MOX cores. Spectrum index measurements demonstrated that JEF2 fission cross sections of Pu239 and Pu241 are satisfactory, particularly in the large thermal resonance at 0.3eV.
The modified conversion ratio measurements showed that U238 resonant capture rate is slightly overestimated by 2% ± 1.4% in JEF2.2 (APOLLO2 and reference TRIPOLI4 calculations).
The reactivity worth of burnable poisons (Pyrex and UO2-Gd2O3) and absorbers (Ag-In-Cd, B4C, enriched B4C) is reproduced within ±2% accuracy by APOLLO2 calculation, which used the SPH homogenisation method to preserve absorber reaction rates.
The various LWR Reactivity Coefficients are well predicted by APOLLO2 and its CEA93 library.
The C/E analysis allowed the qualification of the JEF2.2 nuclear data file; some trends were inferred to improve the evaluation. Furthermore, the validation of the neutronic tools was met for design calculations of the main PWR parameters. Calculation route improvements were emphasised.

1. INTRODUCTION

Nuclear Power Engineering Corporation (NUPEC) and the Nuclear Energy Division of the Commissariat à l'Energie Atomique (CEA/DEN) have jointly established a reactor physics experimental program (MISTRAL program [1]: Mox Investigation of Systems Technically Relevant of Advanced Light water reactors) to carry out reactor physics experiments of 100% MOX cores in the EOLE facility. The analysis of the MISTRAL experiments was carried out using current french neutronic tools, i.e. the APOLLO2 package [2], [3]. In order to decouple calculation route biases from nuclear data errors, the continuous energy Monte Carlo code TRIPOLI4

was also used to obtain reference calculations. This paper describes the analysis results of MISTRAL1, MISTRAL2 and MISTRAL3 core configurations (Figure 1, Figure 2 and Figure 3) :

- MISTRAL1 : Regular enriched UO2 (3.7 wt% in 235U) core involving about 750 fuel pins in a square pitch of 1.32 cm (moderation ratio Rmod = Vmod/Vfuel = 1.7). The criticality was obtained by adjusting the soluble boron concentration : $C_B \approx 300$ ppm. The experimental study ended in November 1996.

- MISTRAL2 : Regular 100% MOX (7 % of Pu) core involving about 1600 fuel pins in the same lattice as above (moderation ratio Rmod = 1.7). No boron was diluted in the moderator and the criticality was obtained by adjusting the number of fuel pins. The experimental study ended in April 1998.

- MISTRAL3 : Regular 100% MOX (7 % of Pu) core involving about 1600 fuel pins in a square lattice pitch of 1.39 cm (moderation ratio Rmod = 2.1). The criticality was obtained by adjusting the soluble boron concentration : $C_B \approx 200$ ppm. The experimental study ended in April 1999.

These experiments enable the qualification of neutronic calculational tools in LWR lattices (UOX and MOX fuels) in the relevant range of moderation ratio, i.e from Rmod = 1.7 up to Rmod = 2.1.

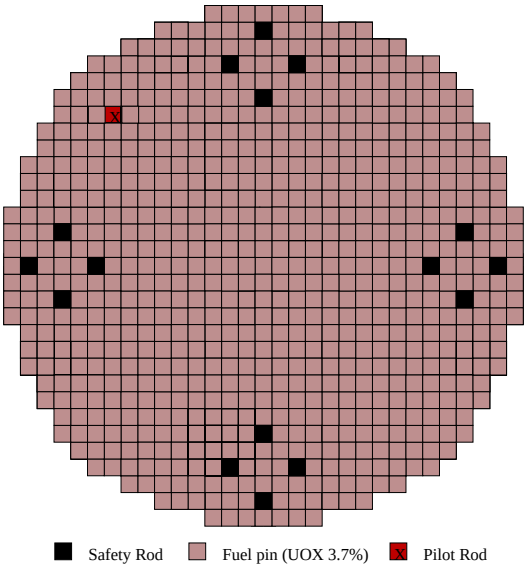

Figure 1. MISTRAL1 Homogeneous Core

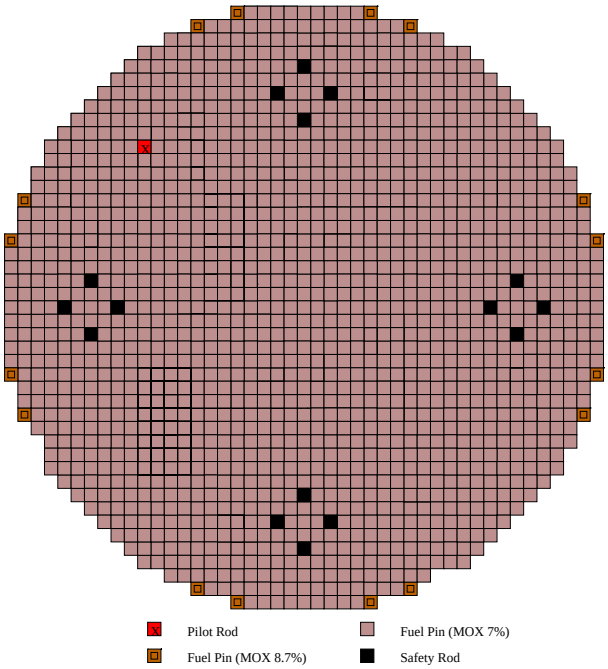

Figure 2. MISTRAL2 Homogeneous Core

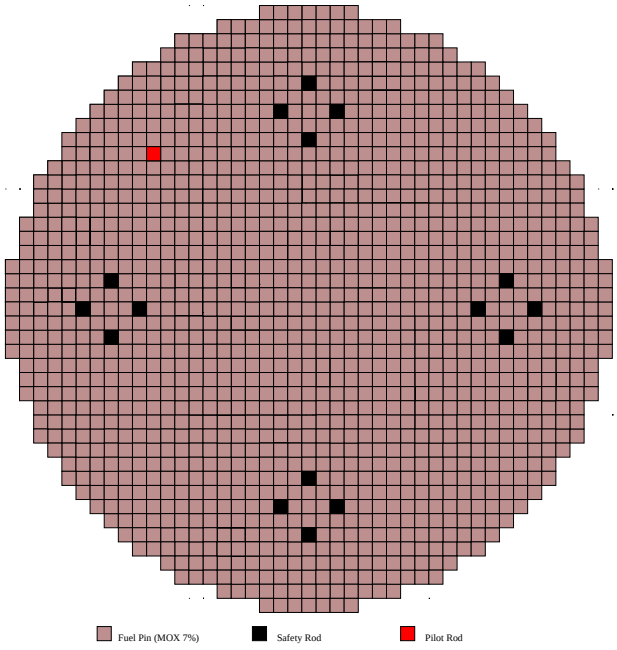

Figure 3. MISTRAL3 Homogeneous Core

2. CALCULATION ROUTE

2.1 GENERAL OUTLINE

The Calculation Route is based on the consistent french transport code package which is composed of the deterministic code APOLLO2 [4] and the stochastic code TRIPOLI4 [5],[6], both developed by CEA. The deterministic APOLLO2 code is used both for assembly spectrum calculations (or/and cell calculations) and for S_N core calculations. Its CEA93 library is used in the European X-MAS group structure (172 energy-groups). The APOLLO2 reference calculation scheme, called 'CEA-97' is used. The reference route is based on the three-dimensional continuous-energy Monte Carlo code TRIPOLI4. Both codes use libraries based on the same European JEF2.2 nuclear data file.

2.2 NUCLEAR DATA FILES AND LIBRARIES

Both CEA93 library of APOLLO2 and TRIPOLI4 pointwise nuclear data are based on the JEF2.2 data file. The processing was carried out by the NJOY code. TRIPOLI4 automatically handles its pointwise cross section set in the PENDF format coming from the NJOY processing. The X-MAS 172-group structure of the APOLLO2 code is sufficiently refined to account for the flux tilt in the thermal resonances of Pu-239 and Pu-240 at 0.3 eV and 1 eV respectively. An optimised energy structure with 20 macrogroups, is used in S_N core calculations.

2.3 LATTICE CALCULATION

The fuel pellet is divided in 4 rings, a clad and an over-clad separated by a gap are added. Three regions are considered in the moderator, so 11 Pij mesh-points are distinguished. The integral transport equation is solved by a collision probability method (Pij) to calculate the cell averaged macroscopic cross-sections. A two-dimensional Pij method is used to perform the calculations : an accurate interface current method using a UP1 model (linear anisotropic angular flux assumption) is used for infinite lattice calculation and for water-hole cell calculations (guide-tube of the Pilot Rod and the Safety Control Rods are represented by a 3×3 multicell). This calculation is as accurate as the exact two-dimensional Pij calculation, as demonstrated by the reference calculation TRIPOLI4 [7]. Concerning the calculation of a central absorber, an heterogeneous 11×11 multicell calculation is performed ; this fine flux calculation is based on a satisfactory Pij-UP1 model [8]. The scattering anisotropy is approximated by a transport correction (P0c). The criticality is obtained by a $D^g_{B1}\, B^2\, \Phi^g$ leakage model.

2.4 SELF-SHIELDING

The resonance absorption during neutron slowing-down is described by an accurate space-dependent self-shielding formalism. This self-shielding formalism is based on an equivalence method between the heterogeneous geometry and an homogeneous medium ; the exact fine structure equation is solved in order to obtain the effective cross-sections (neither Bondarenko, nor WR approximation is used). The self-shielded isotopes in a calculation of UOX or MOX pins are the following ones: U-238, U-235, U-236, Pu-239, Pu-240, Pu-241, Pu-242, Am-241 and Zr. Concerning the UO_2-Gd_2O_3 pins, Gd-155, Gd-156, Gd-157 and Gd-

158 are self-shielded. U-238 is treated by a space-dependent self-shielding: four rings in the fuel pellet to deal with the rim effect. In order to calculate accurately the Dancoff effect, two-dimensional Pij calculations are done (using UP1 model). A Doppler broadening is made below the thermal cut-off energy for isotopes such as U-235, Pu-239, Pu-240 and Pu-241; due to the refined mesh below 2eV, specific self-shielding calculation is not needed in the thermal resonances (E_{Pu0}=1eV, E_{Pu9}=0.3eV, ...) which are only Doppler broadened. The crystalline structure of UO_2 is taken into account by an effective temperature for the Doppler broadening.

2.5 CELL HOMOGENISATION AND GROUP COLLAPSING

The difficulty of the S_N resolution is the need for homogenisation of cells. This implies the use of an heterogeneous/homogeneous equivalence process. The SPH method, automated in the APOLLO2 code is used: this function allows reaction rate preservation in the homogenised cells [9]. The 20 energy-group structure is used for all core calculations: this 'universal' structure allows group collapsing in various spectra, from FBRs to thermalised fissile solutions (criticality-safety topic) [10].

2.6 CORE CALCULATION BY APOLLO2

The core calculation is carried out by the nodal S_N method. An S_8 angular quadrature is used. P1 matrices enable anisotropic scattering modelling. Polynomials of the nodal method are linear in the node and on the node boundaries; one mesh point per cell only is necessary in this case. A ¼ symmetrical XY geometry is implemented. The axial leakage is simulated through the axial buckling. Generally, the experimental value B^2_Z is used; however, for slight modification of the axial reflector (temperature coefficient measurements, soluble boron efficiency), the modification of the reflector saving was obtained from RZ core calculations.

3. RESULTS OF EXPERIMENT ANALYSIS

3.1 CRITICALITY

The calculations were carried out using the latest APOLLO2 code version : APOLLO2.5/CEA93.V6.

3.1.1 BUCKLING MEASUREMENT AND LATTICE REACTIVITY

The reactivity of the MISTRAL LWR lattice is obtained from the Material Buckling measurements. We used the "rough" Buckling experimental value $B^2g = B^2r + B^2z$ (corresponding to the experimental Reports), but also the corrected Material Buckling value B^2m derived from the experimental maps and a 3D core simulator calculation.
The P_{ij}2D lattice calculation yields the following Calc-Exp results (Table I):

Table I. Lattice Reactivity Comparison

Experiment	Pitch (cm)	V_{H2O}/V_{fuel}	k_{eff}-1 (pcm)	$\delta k_{eff}(1\sigma)$ (pcm)
MISTRAL-1	1.32	1.75	-223	±500
MISTRAL-2	1.32	1.75	+73	±350
MISTRAL-3	1.39	2.11	+308	±350

The reactivity of LWR Pu-fueled lattices is well predicted by APOLLO2/CEA93, however a trend to overestimate the reactivity arises with increasing moderation ratio or/and Pu ageing.

3.1.2 CRITICAL SIZE AND CORE REACTIVITY

The core reactivity is accurately measured through the critical fuel loading or/and critical soluble boron concentration. The analysis based on the APOLLO2 S_N core calculation and the Tripoli4 Monte Carlo full 3D model gives the following results (Table II) :

Table II. Core Reactivity Comparison

Experiment	Pitch (cm)	V_{H2O}/V_{fuel}	k_{eff} Experiment	k_{eff} Apollo2	C- E (pcm)	k_{eff} Tripoli4 +/- 1σ
MISTRAL1	1.32	1.75	1.00109	1.00529	+420	1.00215 +/- 0.00020
MISTRAL2	1.32	1.75	1.00060	1.00739	+679	1.00473 +/- 0.00020
MISTRAL3	1.39	2.11	1.00060	1.00810	+750	1.00646 +/- 0.00020

The Calculation-Experiment comparison points out that the reactivity of PWR-UO2 cores is overestimated by 400 pcm ; this is due to the 10% underestimation of the U235 Capture Resonance Integral in the JEF2.2 file [11]. The use of the new U235 evaluation, in the case of the Monte Carlo calculation of Mistral1 core, leads to an effective multiplication factor of about 0.99800 +/- 20 pcm (1s).
The overestimation of the reactivity of MOX cores increases up to +750 pcm in an overmoderated lattice. In the case of the analysis of MISTRAL3, this discrepancy can be decomposed as follows :

- error due to MOX lattice calculation : ≈ +300 pcm, as pointed out in the previous chapter by the material buckling analysis.
- bias due to UP1 lattice calculation : ≈ +130 pcm.
- bias due to discretisation (condensation from 172 to 20 energy groups in Sn core calculation, …) : ≈ +100 pcm.
- error due to "reflector saving" calculation : ≈ +200 pcm.

The accurate calculation of the radial flux maps is demonstrated by the calculation-Experiment comparison presented in Figure 4 for fuel fission rates in the case of MISTRAL2. These results point out a satisfactory C/E agreement in the radial geometrical buckling; however, a slight overestimation of the reflector saving is found in the APOLLO2 core calculation.

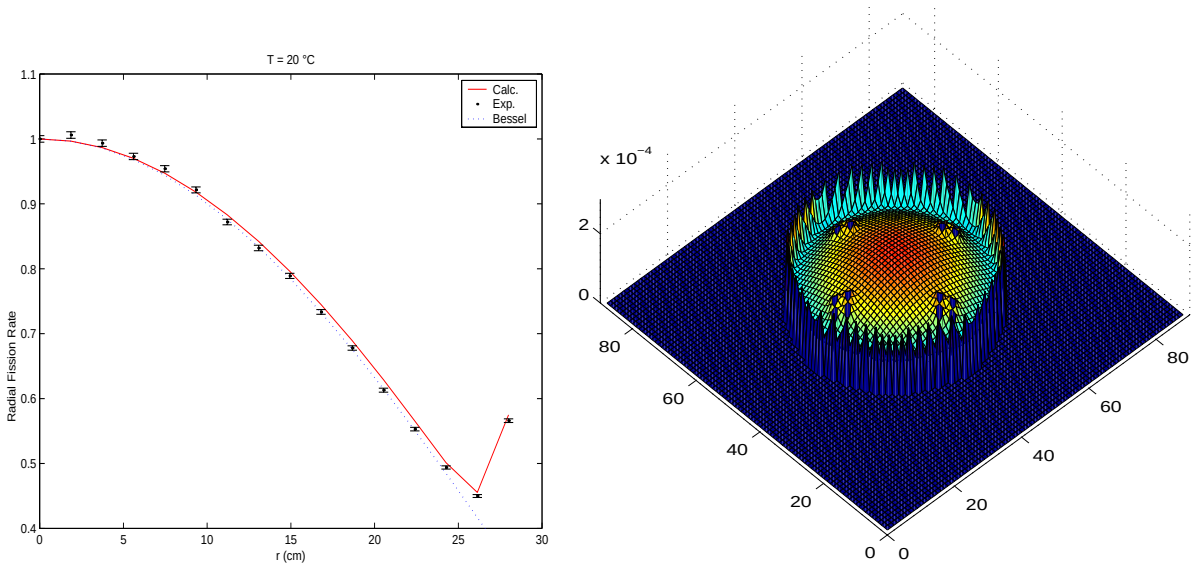

Figure 4. Radial Fission Rate in Mistral2

3.1.3 SPECTRUM INDICES

The Collision Probability Method was used to calculate spectral indices. These calculations were performed with 172-groups structure in 7x7 multicell. The differents options considered for these calculations were those of the CEA-97 calculation scheme.
Table III summarizes the calculation results of spectral indices for MISTRAL1 experiment and Table IV summarizes the results for MISTRAL2 experiment. The C/E comparison is the average value of two measurements performed in different locations.
These results show that fission cross-sections of the main actinides in JEF2.2 library are satisfactory. The Calculation-Experiment comparison is particularly good for fissile isotopes Pu239 and Pu241 ; these results point out that fission cross-section of Pu239 and Pu241 is satisfactory in the large resonance at 0.3 eV.
Concerning threshold reactions, results are acceptable because the discrepancy between Calculation and Experiment lies within the 90% confidence interval for the MISTRAL2 experiment.
However, in the case of UOX lattice (MISTRAL1 experiment), the fast fission spectrum indices U8/U5 and Np7/Pu9 seem to indicate a too soft spectrum in the APOLLO2 and TRIPOLI4 calculations.

Table III. Spectrum Indices in Mistral1

Spectral Indices	Exp. Standard Deviation (%)	(C–E)/E (%)
U8/U5	8	-24 ± 8
Pu9/U5	2	+0.2 ± 2
Pu1/Pu9	2	+1.2 ± 2
Pu0/Pu9	5	+14 ± 5
Np7/Pu9	4	-17 ± 4

Table IV. Spectrum Indices in Mistral2

Spectral Indices	Exp. Standard Deviation (%)	(C–E)/E (%)
U8/U5	6.7	-2 ± 5
Pu9/U5	2.4	+2.1 ± 2
Pu1/Pu9	2.7	+0.3 ± 2
Pu0/Pu9	5.9	-3 ± 5
Pu2/Pu9	7.6	+12 ± 7
Np7/Pu9	3.2	-5.4 ± 3

3.1.4 CONVERSION FACTOR

The most important reaction for LWR calculations is the U238(n,γ) reaction in the resonances. It was directly measured on the UOX and MOX fuel pins during MISTRAL1 and MISTRAL2 experiments. The experimental modified conversion factor was derived from the simultaneous measurement of the total fission rate Ftot in the fuel pellet. Calculations of the conversion factor were performed by APOLLO2/CEA93 (collision probability method) and TRIPOLI4/JEF2.2. Table V summarizes the calculation results of the modified conversion factor in MISTRAL1 and MISTRAL2 experiments.

Table V. Conversion Factors

	(C-E)/E (%)	
	APOLLO2/CEA93	TRIPOLI4/JEF2.2
MISTRAL 1 (UOX)	+1.5	+2.2 ± 0.2
MISTRAL 2 (MOX)	+2.1	+2.3 ± 0.2

This experimental technique seems to indicate that the U238 capture is slightly overestimated, i.e +2.2 ± 1.4%, in JEF2.2 (as well as in the CEA93 working library processed from JEF2).

3.1.4 PERIPHERAL ROD WORTH

APOLLO2 was used to calculate the reactivity worth of 8 peripheral rods for MISTRAL-1 (UOX 3.7%) and 8, 24, 40 and 48 peripheral rods for MISTRAL-2 (MOX 8.7%) at 20.0 °*C* . Core Sn calculations in 20-energy group structure were performed using the CEA-97 reference calculation scheme. The reactivities in core calculations are presented in Table VI. The APOLLO2 peripheral rod worths per rod are compared to the experimental values in Table VII. The calculated results are in good agreement with the measured worth.

Table VI . Reactivity for Peripheral Rod Worth Measurements

	Number of peripheral rods	Core Reactivity (pcm) APOLLO2
MISTRAL1	0	349.3
	8	557.3
MISTRAL2	0	381.2
	8	437.7
	24	577.0
	40	680.3
	48	728.2

Table VII. Peripheral Rod Worth

	Number of Peripheral Rods	Measurement ($)	Worth/pin APOLLO2		(C-E)/E (%)
			($)	(pcm)	
MISTRAL1	8	0.0319 ± 0.0070	0.0331	25.9	+ 3.8 ± 20
MISTRAL2	8	0.0191 ± 0.0012	0.0197	7.1	+ 3.1 ± 6
	24	0.0226 ± 0.0015	0.0227	8.2	+ 0.4 ± 6
	40	0.0203 ± 0.0013	0.0208	7.5	+ 2.5 ± 6
	48	0.0195 ± 0.0013	0.0199	7.2	+ 2.0 ± 6

3.1.5 ABSORBER WORTH

Different absorbers were analysed in MISTRAL1 and MISTRAL2 experiments. In these experiments, an absorber pin is introduced in the central cell of a regular core (UO_2 3,7 % for MISTRAL1 configurations and MOX 7 % for MISTRAL2 configuration). The reactivity effect of an absorber pin is measured by adjusting the critical boron concentration (or the critical size in MISTRAL2) and by ASM technique. Concerning the first method, the analysis is carried out by core calculations of the two actual critical configurations; therefore, the calculated residual reactivities ($\rho\ calc$) of the "reference" and "1 central absorber" core are obtained. The discrepancy between Calculation and Experiment of the absorber worth is :

$$C - E = (\rho_{calc}^{abs} - \rho_{calc}^{ref}) - (\rho_{\exp}^{abs} - \rho_{\exp}^{ref}) \quad (1)$$

thus the relative error is deduced as :

$$(C - E) / E = (C - E) / W_{abs} \quad (2)$$

where W_{abs} , the absorber reactivity worth in the configuration, is evaluated as follows :

$$|W_{abs}| = (C_B^{abs} - C_B^{ref}) \frac{d\rho}{dC_B} - (\rho_{\exp}^{abs} - \rho_{\exp}^{ref}) \quad (3)$$

The analysis of these experiments was performed by APOLLO2/CEA93 and the CEA-97 calculation scheme, using a specific procedure based on SPH equivalence which preserves the exact reaction rates in the homogeneous geometry.

Concerning the UOX lattices, Table VIII summarizes the calculation results of absorber efficiency. These results are confirmed by fission rate measurements around the absorber pin (integral γ-spectrometry on fuel pin). The radial power map analysis is presented in Table IX and Table X for AIC and enriched B_4C in MISTRAL1. One can note that the high thermal flux and power tilts around the absorber rod is well reproduced by APOLLO2. The Calculation-Experiment discrepancies are lower than 2%, which corresponds to a 95% confidence interval of the experimental uncertainty.

Concerning the MOX lattices, analyses were performed in the same moderation ratio on MOX Pu-7% regular lattice : MISTRAL 2. The calculation results of absorber efficiency in MOX lattices are also very satisfactory. With a small experimental uncertainty (± 1.3% in 1σ), the MISTRAL2 experiment allows to guarantee the APOLLO2/CEA93 calculation of LWR absorber efficiency within 2% accuracy. These results are confirmed by the analysis of fission rate map.

Note that these good results for UOX and MOX lattices are partly due to the SPH equivalence procedure used in the CEA-97 calculation route which is necessary for the homogenisation of absorber cell.

Table VIII. Absorber Efficiency

	MISTRAL1 (C-E)/E (%)	MISTRAL 2 (C-E)/E (%)
Ag - In - Cd	- 0.2 ± 2.3	- 0.1 ± 1.2
B_4C nat	- 1.5 ± 2.1	+ 0.5 ± 1.3
B_4C 90 % B10	- 1.3 ± 1.4	+ 0.6 ± 1.3
UO_2 - Gd_20_3	+ 0.2 ± 3.6	- 1.7 ± 1.3

Table IX. Power Map around AIC rod in Mistral1

							0.72 %
0.38 %						0.15 %	
	0.47 %	- 0.22 %	- 0.30 %	0.02 %	0.01 %		
	0.48 %	- 0.60 %	0.07 %	- 0.24 %	0.54 %		
	- 0.30 %	- 0.84 %	A	0.53 %	- 0.48 %		A = AIC
	0.31 %	- 0.60 %	0.33 %	0.50 %	- 0.85 %		
	0.12 %	0.66 %	0.23 %	0.84 %	0.76 %		
1.21 %	- 0.30 %	- 0.26 %	- 0.90 %	- 0.37 %	0.34 %	1.09 %	

Table X. Power map around Enriched B_4C in Mistral1

							0.45 %
0.38 %						-	
	0.84 %	1.06 %	0.93 %	-	-		
	0.63 %	1.45 %	0.94 %	-	0.45 %		
	1.69 %	-	A	-	0.44 %	A = enriched B_4C	
	1.00 %	0.61 %	-	0.48 %	0.02 %		
	0.66 %	0.21 %	-	0.63 %	0.36 %		
1.20 %	-	-	0.86 %	0.54 %	0.80 %	1.32 %	

3.1.5 ISOTHERMAL TEMPERATURE COEFFICIENT

In this experiment, criticality was maintained by adjusting the soluble boron concentration each 5°C (through dilution with pure water). The Iso-thermal Temperature Coefficient was measured in the temperature range from 5°C to 80°C.
The analysis is carried out with a S_N XY core calculation for each temperature step.
The homogenised and 20-energy group collapsed cross sections for the water hole (guide-tubes of the control rods) and for the reflector are performed by a multicell UP1 Pij calculation on a 3×3 geometry with a central guide-tube.
A first core calculation is performed in diffusion theory to initialise the integral flux. Then, the transport calculation is performed in S8/P1 using the nodal option.
Radial fission rate distributions are measured and allows the determination of the radial buckling at 20°C, 65°C and 80°C. The radial distribution shape and its change with the temperature rise are well represented by the core calculation (Figure 5) : these results point out that no bias is introduced in the analysis due to the important leakage rate (small radial dimension of the MISTRAL-1 core).

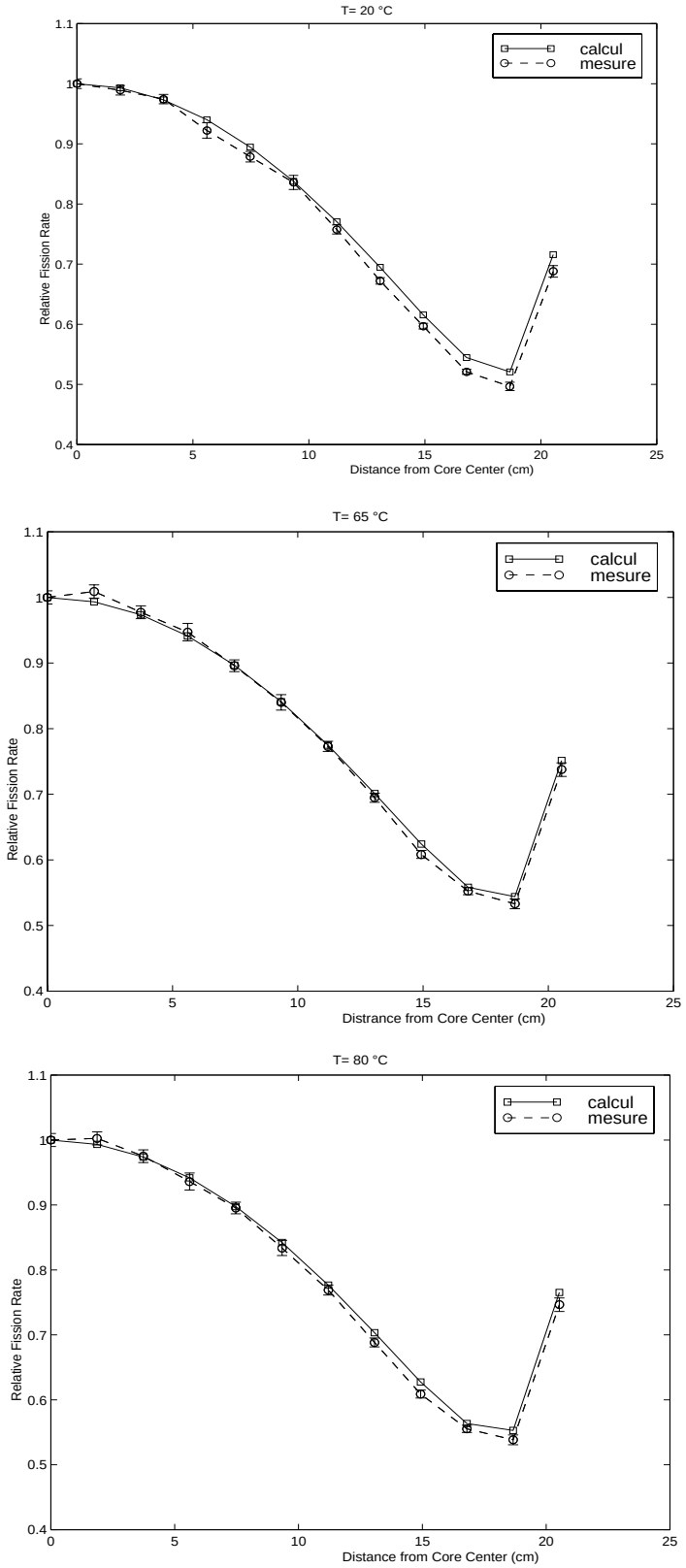

Figure 5. Radial Fission Rate in Mistral1 (T=20°C, T=65°C and T=80°C)

Thermal expansion of materials (fuel, over-clad, grid) due to the temperature rise is taken into account. This reactivity effect is about +0.32 pcm/°C.
The decrease in the boron concentration with the temperature rise leads to a change of the axial reflector saving; this effect was assessed by RZ core calculations. Thus the modification of the axial leakage, with the temperature and the boron content of the axial reflector, was handled in the XY calculation by a variable axial buckling : the B^2z total variation amounts to -2E-5 cm^{-2} in the range of temperature considered.
The reactivity difference between calculation and experiment ($\Delta\rho = \rho^{calc} - \rho^{exp}$) is obtained for every temperature step. A linear polynomial form is used to fit these values to obtain a first approximation of $\Delta\rho$ and then an average value of the difference between the calculated iso-thermal temperature coefficient and the experimental one: $\Delta\alpha = \alpha^{calc} - \alpha^{exp} = 0.1 \pm 0.2$ pcm/°C (1σ). This is simply carried out by taking the derivative of the polynomial form of the reactivity difference :

$$\Delta\alpha = \alpha^{calc} - \alpha^{exp} = d/dT(\Delta\rho) = d/dT(\rho^{calc} - \rho^{exp}) \quad (4)$$

A 3rd degree polynomial form is used to fit $\Delta\rho$ and so a parabolic expression is obtained for $\Delta\alpha$.The first part of Figure 6 shows this $\Delta\alpha$ parabolic form. The C/E disagreement around 20°C is about $\Delta\alpha \sim 0.3 \pm 0.3$ pcm/°C (1σ). A slightly negative trend seems to appear above 60°C due to the water density effect. In summary, the Reactivity Temperature Coefficient in UOX lattice is well predicted by APOLLO2 and the CEA93 library, thanks in part to our recommended η235 shape [12] which was adopted in the JEF2 File.

In the case of MISTRAL-2 core, criticality is obtained by modifying the number of peripheral 8.7% MOX fuel pins versus the water temperature. The number of peripheral fuel pins was adjusted from 32 at 10°C to 188 at 80°C to reach criticality. Two core configurations (one with 0 additional peripheral pins and another one with 8 peripheral fuel pins) were achieved to determine the reactivity worth of these 8.7% MOX fuel pins using a neutron source multiplication method.
The analysis of the radial distribution shape, and its change with the temperature rise, demonstrates that the XY S8/P1 core calculation is correct. A 3rd degree polynomial form is used to fit $\Delta\rho$ and so a parabolic expression of the Calc – Exp temperature coefficient $\Delta\alpha$ is obtained. The second part of Figure 6 shows the $\Delta\alpha$ parabolic form. The average value of this C/E disagreement is about : $\Delta\alpha \sim -1.5 \pm 0.3$ pcm/°C (1σ).
The discrepancy becomes smaller in magnitude as the temperature increases, when the water density component becomes predominant.

Same kind of results were obtained with MISTRAL3 experiment. The average value between 10°C and 80°C was about : $\Delta\alpha \sim -1.6 \pm 0.3$ pcm/°C (1σ). The polynomial form of $\Delta\alpha$ is shown in the third part of Figure 6.

The APOLLO2 results obtained in the analysis of the Reactivity Temperature Coefficient in MISTRAL1, MISTRAL2 and MISTRAL3 are consistent with the conclusions drawn from the analysis of the pressurised loop CREOLE Experiment [13].
A complete analysis of the Reactivity Temperature Coefficient in light water moderated UO_2 and UO_2-PuO_2 lattices is performed in the reference [14].

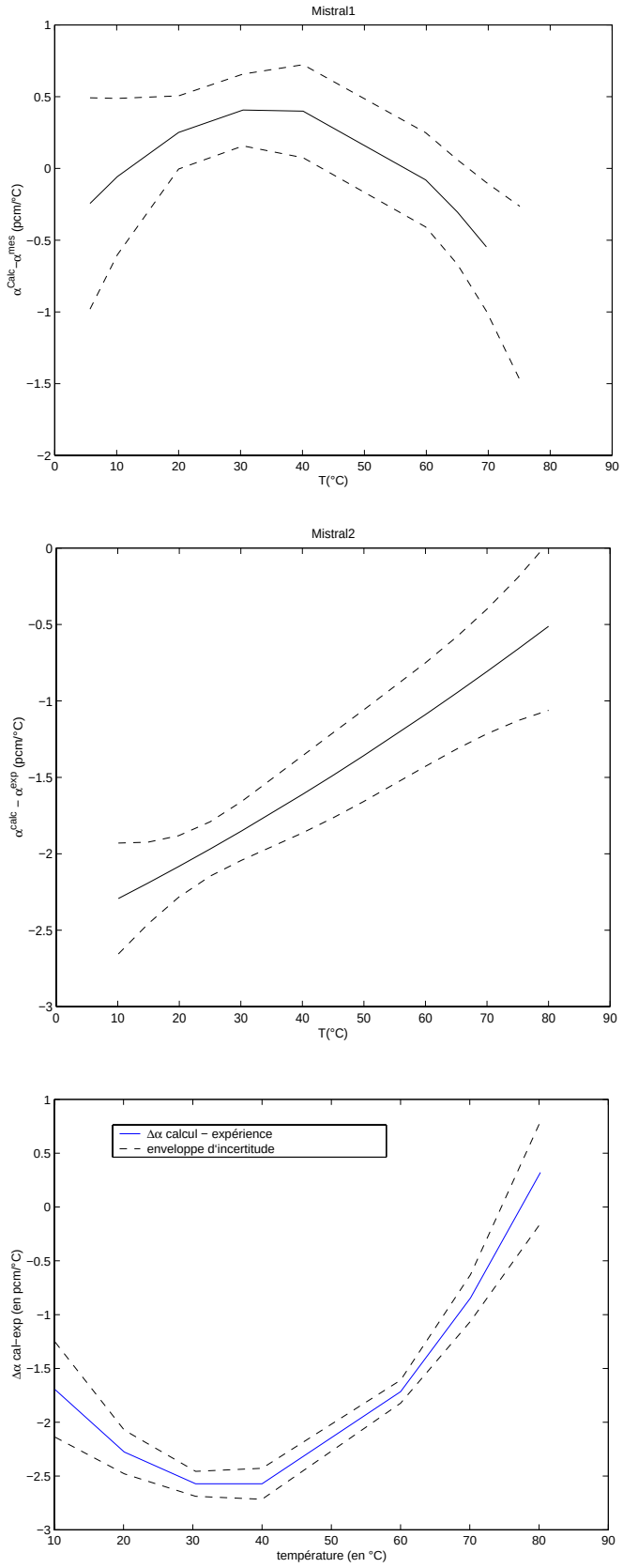

Figure 6. Calc-Exp Comparison of the RTC in MISTRAL1, 2 and 3 Experiments

3.1.6 DIFFERENTIAL SOLUBLE BORON EFFICIENCY

In the MISTRAL-1 experiment, for which criticality was performed by adjusting the soluble boron concentration, the differential efficiency of soluble boron was measured by changing its concentration by plus or minus 3 ppm around the reference boron concentration.
A first axial study was performed to determine the borication effect of the axial reflector (reactivity effect is -0.22 pcm/ppm).
S_N XY core calculations, using the B^2_Z value corresponding to the actual axial reflector borication, were performed. The calculated boron coefficient is in good agreement with the measured one, as shown in Table XI.

Table XI. Differential Boron Efficiency in Mistral1

$\alpha = dk_{eff}/dC_B$	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

For MISTRAL-2 experiment, calculations were performed for two configurations : the first one is the reference configuration with no boron and in the second one, the boron concentration is 6 ppm.
The S_N XY core calculations account for the axial buckling variation due to axial reflector borication ; this effect contributes weakly to the boron coefficient : -0.3 pcm/ppm.
Table XII summarises the results of the differential boron efficiency in the MISTRAL2 experiment. The calculated value is in good agreement with measurements for this MOX core.

Table XII. Differential Boron Efficiency in Mistral2

$\alpha = dk_{eff}/dC_B$	Experiment (pcm/ppm)	APOLLO2 (pcm/ppm)	(C-E)/E ± 1σ (%)
Divergence Method	-8.6 ± 0.5	---	---
ASM Method	-8.1 ± 0.5	---	---
α (average)	-8.4 ± 0.4	-9.0	7 ± 5

3.1.7 INTEGRAL BORON EFFICIENCY

The boron integral efficiency was calculated between 0 ppm and 600.4 ppm at 20 °C. The axial buckling variation due to the moderator borication was determined and introduced in the radial core calculation : B^2_Z (C_B = 0 ppm) = 1.0170E-3 cm^{-2} and B^2_Z (C_B = 600 ppm) = 1.0864E-3 cm^{-2}; this axial buckling correction corresponds to a reactivity worth of -230 pcm. The Sn XY calculations account for the fission chambers placed inside the MISTRAL2 core for ASM measurements. The Calculation-Experiment comparison for the Boron Integral Efficiency between 0 ppm and 600 ppm is summarised in Table XIII.

Table XIII. Integral Boron efficiency in Mistral2

	Reactivity (C_B = 0 ppm)	Reactivity (C_B = 600.4 ppm)	Boron Worth
Experiment	$\rho = -37 \pm 3$ pcm	$\rho = -4958 \pm 200$ pcm	$\Delta\rho = -4920 \pm 200$ pcm
Calculation	$\rho = 700.5$ pcm	$\rho = -3973.5$ pcm	$\Delta\rho = -4674$ pcm
			(C-E)/E ± 1σ
			-5. % ± 4. %

The boron efficiency is well predicted by the APOLLO2 calculation : the (C-E)/E = -5% bias lies within the ±8% (2σ) experimental margins. We can notice that this slight underestimation by APOLLO2 is perfectly coherent with the SRAC calculated value at C_B = 600ppm [15].

CONCLUSIONS

This paper has presented the analysis of LWR clean experiments performed in the framework of the MISTRAL programme. The "homogeneous" configuration UOX 3.7% MISTRAL1 was analysed, as well as MOX 7% configurations MISTRAL2 and MISTRAL3. The Experiments were calculated with APOLLO2 and TRIPOLI4 codes based on JEF2.2 library.
The radial and axial **buckling measurements** allowed the qualification of the core calculations. Radial power maps are well reproduced by our 2D and 3D calculations ; the fuel lattice / reflector interface is well mocked up and the local fission rate increase is fairly well predicted.
The UOX **reactivity** (MISTRAL1 core) is overpredicted by +400 pcm in our calculations. Concerning MOX lattice reactivity, APOLLO2 calculation indicates a trend towards an overestimation with increasing moderation ratio and/or Pu ageing.
Concerning **Spectrum indices**, fissile isotope measurements demonstrated that JEF2 fission cross sections of Pu239 and Pu241 are satisfactory, particularly in the large thermal resonance at 0.3eV.
The modified **conversion ratio** measurements showed that U238 resonant capture rate is slightly overestimated by 2% ± 1.4% in JEF2.2 (APOLLO2 and reference TRIPOLI4 calculations).

The analysis of the **reactivity worth of the peripheral fuel pins** is well predicted by transport calculations with APOLLO2.
The reactivity worth of **burnable poisons** (Pyrex and UO2-Gd2O3) and **absorbers** (Ag-In-Cd, B4C, enriched B4C) is reproduced within ±2% accuracy by APOLLO2 calculation, which used the SPH homogenisation method to preserve absorber reaction rates.
The Reactivity **Temperature Coefficient** in UOX lattice is well predicted by APOLLO2 and the CEA93 library, which confirms that our recommended η235 shape, which was adopted in the JEF2 File, is correct. Concerning the RTC in MOX fuel, the APOLLO2 absolute value is overestimated from 2 pcm/°C at room temperature down to 1.0 ± 0.3 pcm/°C at 70°C.
The **Boron Coefficient** is well predicted by APOLLO2 calculation, both in UOX and MOX core : +3% ± 7% and +7% ± 5% respectively in MISTRAL1 and MISTRAL2. Diffusion calculations could rise higher C/E differences : +8% and +11% respectively.
The **Integral Boron Efficiency,** measured between 0 ppm and 600 ppm in the MISTRAL MOX core, is reproduced within the ± 5% (1σ) experimental uncertainty.
The **effective delayed neutron fraction** is satisfactory predicted by APOLLO2/JEF2 and the results are presented to this conference in a companion paper.

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