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DOPPLER CALCULATION CHALLENGE IN MOX LATTICES QUALIFICATION ON MINERVE OSCILLATION EXPERIMENT

D. Bernard and A. Santamarina
CEA – Cadarache DEN/DER/SPRC
13108 Saint Paul lez Durance, France
david.bernard@cea.fr
alain.santamarina@cea.fr

ABSTRACT

This paper presents the analysis results of LWR reactivity Doppler coefficient. The experimental validation of APOLLO2 Doppler worth prediction is achieved using MINERVE oscillations of UOX and MOX samples up to 1000°C. The APOLLO2.5 reference scheme "CEA-97" uses probability tables method to perform the space-dependant self-shielding formalism. The C/E comparison points out a satisfactory Doppler calculation in UOX fuel; on the contrary, the Doppler worth in MOX fuel is overestimated –by about +10%±3%– for 5% Pu load.
First order perturbation method was used to separate each isotopic, energy and reaction contribution to fuel temperature effect; therefore physical insights were obtained on C/E disagreement. In a final step, the validation of the APOLLO2.5 calculation scheme is carried out against a reference continuous-energy Monte-Carlo TRIPOLI4.3 calculation. Results underline the importance of the resonance overlapping between ^{238}U and ^{240}Pu isotopes, precisely between the resonances E_0=20.5eV and 66.7eV for ^{240}Pu and E_0=20.9eV and 66.0eV for ^{238}U. Mutual shielding modeling in deterministic codes remains a challenging problem to calculate resonant rates and to meet the required target accuracy for LWR-MOX design parameters, such as conversion factor and fuel temperature coefficient.

Key Words: Doppler Coefficient, MOX, APOLLO2, MINERVE Experiment, Mutual Shielding

1. INTRODUCTION

Reactivity fuel temperature coefficient in LWR-UOX and MOX cores is a fundamental neutronic parameter for safety. As MOX assembly burn-up parity is a major program in French PWRs, the qualification of the Doppler calculation in MOX fuel lattices becomes an important objective. Doppler coefficient in MOX assemblies is increased due to ^{240}Pu broadening. The experimental validation of Doppler worth in UOX and MOX fuels was achieved through sample oscillations in MINERVE reactor from 20°C up to 1000°C. In order to analyse the experimental results, the APOLLO2 reference calculation scheme "CEA-97" was implemented. The recent APOLLO2.5 version and its associated library CEA93.V6 were used.
The first part of this paper describes the MINERVE experiment. The second part is devoted to the description of the "CEA-97" scheme used in APOLLO2, particularly probability tables implemented in the space-dependant self-shielding formalism. Doppler worth qualification against MINERVE experimental results is presented in the third section. The validation process against reference Monte-Carlo TRIPOLI4 results is reported in the last section, in order to highlight mutual shielding calculation challenge.

2. THE MINERVE OSCILLATION EXPERIMENT

MINERVE is a zero-power pool reactor. The central experimental zone can be removed (MELODIE for LWRs, ERMINE for the FBR spectra and MORGANE for HCPWRs). The facility is specially designed for oscillation measurements.

The different components of this Doppler experiment are [1]:

- the MELODIE block, located in the center: 800 UO_2 fuel rods with over cladding to simulate moderator ratio in PWR nominal conditions. The uranium enrichment of the oxide fuel is 3% and the fissile column is 50cm high.
- a driver core with MTR fuel assemblies (metallic uranium-aluminium alloy plates; ^{235}U enrichment 93%),

Control is ensured by hafnium plates in 4 special assemblies, located in the driver core.

The oscillation equipment replaces 9 fuel rods in the central axis. It is constituted by a tube with various strings of UO_2 fuels. The samples are located between two fuels of the string and oscillated between the midplane and a point above the upper reflector where a high frequency furnace heats them during a half period.

The periodic movement is of the pseudo-square type. The reactivity effect is recorded by a data processor from the automatic control rod positions.

Temperature is measured on the clad by thermocouples during the oscillation. Some preliminary analytical experiments have been made to determine the relation between the effective fuel temperature and the clad temperature. The heating is reconstituted in the same conditions and the various temperatures are recorded. A simple model of dynamic heating is introduced and is adjusted by modification of the fuel cladding thermal transfer coefficient. We also obtain the mean spatial temperature averaged on time.

The test samples are constituted by pellet of UO_2 or UO_2-PuO_2 in a stainless steel cladding. The outer diameter of the pellet is 8.9mm. The enrichment of UO_2 samples ranges from 0.2% to 5%. Three different isotopic compositions of Pu have been used for the fabrication of mixed oxide samples corresponding approximately to 12, 20 and 37% ^{240}Pu. The ratio of fissile plutonium over the total amount of heavy elements is 2%, 3.2% or 5% according to the various samples.

The sample temperature ranges from 20°C to 1000°C for uranium oxide samples and from 20°C to 800°C for mixed oxide samples.
Alumina samples have been used in order to correct the results for thermal expansion of the oscillating tube and components.

The experimental calibration signal is carried out through ^{235}U reactivity worth, using in cold experiments various UO_2 samples with increasing enrichments.

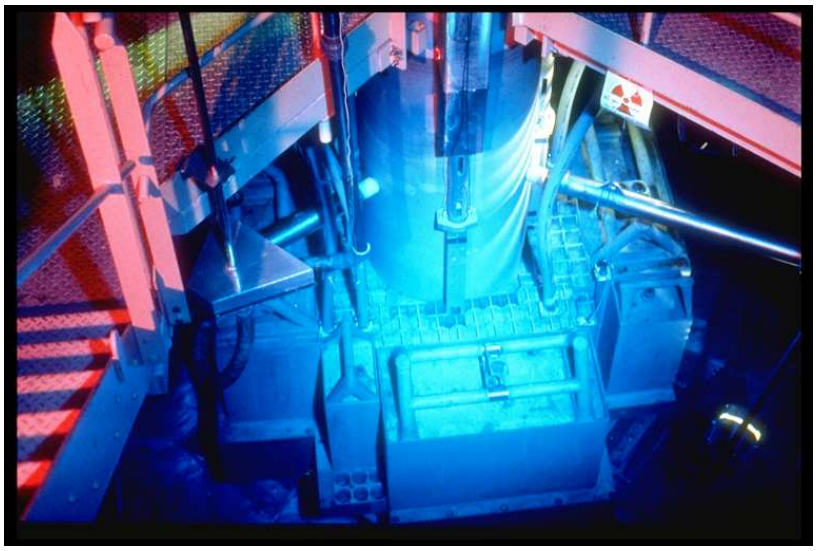

Figure 1. MINERVE core picture.

3. APOLLO2 DETERMINISTIC CALCULATIONS

The APOLLO2 code [2] is a modular code which solves both the Boltzmann integral equation and the integro-differential equation. The APOLLO2 reference calculation "CEA-97" is defined by selecting the code options which yield known and acceptable errors (consistent with target accuracy). The modeling errors were assessed by comparison with the reference continuous-energy Monte-Carlo calculations.
The current APOLLO2.5 version [3] uses the CEA93.V6 library, which was processed from the JEF2.2 file, the European XMAS 172 group-structure. The qualification of APOLLO2.5/CEA93.V6 product was carried out for every LWR parameter, using integral experiments [4].
Concerning cell and assembly calculations, the APOLLO2 code allows the use of several collision probability methods to solve the integral equation. The most accurate one is the exact 2D P_{ij} method in which the actual geometry of the lattice is described. However an accurate UP1 interface current method is available to save computer time: no cylindrisation, nor isotropic interface angular flux assumption is used.

3.1. Space-dependant self-shielding formalism

In order to have a "best-estimate calculation" when performing the resonance self-shielding calculation in a fuel pin with a temperature distribution, a method is implemented in the APOLLO2.5 code, which allows equivalent accuracy in self-shielding treatment for uniform temperature and actual temperature profile [5].
Previous formalism, mainly used in APOLLO1, was an approximate spatial model named P_{IC} which enables an uncoupling of resonant regions (quadratures allowing integration versus one single variable – the microscopic resonant cross-section at given temperature –).

The background cross-section of resonant isotope 0, for heterogeneous medium/homogeneous medium equivalence, is calculated as [6]:

$$\sigma_{ei}^{0} = \frac{\sigma_t^0 (1 - P_{ic})}{P_{ic}} \text{ where } P_{ic} = \sum_{\alpha \in fuel} P_{i\alpha} \tag{1}$$

Therefore, the P_{ic} model for calculating reaction rates in fuel region *i* assumes that the other self-shielded regions are at the same temperature.

In APOLLO2, a rigorous space-dependant self-shielding formalism is implemented.
The slowing down equation in resonant regions is:

$$\Sigma V \Phi_0 = P_0 V R_0 \Phi_0 + S_0 \tag{2}$$

where Φ_0 is the flux vector, *P* is the collision probability matrix, *R* is the slowing down operator, *V* is the volume and Σ is the total macroscopic cross-sections diagonal matrix.
Macroscopic flux is defined as:

$\Psi = \frac{R_{1j}\Phi_j}{\Sigma_{s1j}}$ where Σ_{s1j} is the macroscopic scattering cross-section in the moderator region *j*.

Fine structure function, usually called microscopic flux, is defined as: $\phi_i = \Phi_i / \Psi$.

$R_{1j}\Phi_j$ is roughly constant versus neutron lethargy. Therefore, macroscopic flux is also constant, unlike fine structure function in the resonance energy ranges.
To solve slowing down equation, we assume: $R_{0i}\Phi_i \approx \Psi_i R_{0i}\phi_i$. This assumption and previous definition lead to the following equation:

$$\Sigma_i V_i \phi_i = \sum_j P_{ij} V_j (R_{0j}\phi_j + \Sigma_{s1j}) \tag{3}$$

Consequently, we calculate the flux in each self-shielding region by solving the following matricial equation using P_{ij} formalism, using φ_0 the weighting average flux:

$$\varphi_0 = C r_0 \varphi_0 + S \tag{4}$$

where r_0 is the microscopic heavy slowing down operator and where the matrix C and the vector S are given by:

$$C_{\alpha\beta} = \frac{\sum_{i\in\alpha}\sum_{j\in\beta} P_{ij} V_j N_{oj}}{\sum_{i\in\alpha} \Sigma_i V_i} \qquad S_\alpha = \frac{\sum_{i\in\alpha}\sum_{j} P_{ij} V_j \Sigma_{s1j}}{\sum_{i\in\alpha} \Sigma_i V_i} \tag{5}$$

where α and β stand for the self-shielding regions, *i* and *j* for calculation regions, *P* is the collision probability matrix, and *V*, N_0 and Σ are respectively the volume, the resonant isotope concentration and the total macroscopic cross-section.
Direct Method consists in solving fine structure flux matricial equation after having approximated the heavy slowing down operator by a fitted model according to the energy range, and so searching all eigenvalues and eigenvectors of matrix *C*.
The aim is to find quadrature formulae allowing numerical integration, on a group *g*, of any function *f* depending on *n* variables which are the microscopic total cross-section for *n* temperatures (T_k) or the product of such a function *f* by any partial cross-section, for instance the partial cross-section for reaction *x* and temperature T_1:

$$f(\sigma^{T_1}(u), \sigma^{T_2}(u), ..., \sigma^{T_n}(u)) \quad \text{or} \quad \sigma_x^{T_1}(u)\, f(\sigma^{T_1}(u), \sigma^{T_2}(u), ..., \sigma^{T_n}(u)) \tag{6}$$

Quadrature formulae are a set of weights ($\omega_{i_1,i_2,...,i_n}$) and of quadrature points ($\sigma_{i_k}^{T_k}, \sigma_{x,i_k}^{T_k}$) such as:

$$\frac{1}{\Delta u^g}\int_g f(\sigma^{T_1}(u),\sigma^{T_2}(u),...,\sigma^{T_n}(u))du \approx \sum_{(i_1,i_2,...,i_n)} \omega_{i_1,i_2,...,i_n} f(\sigma^{T_1}(u),\sigma^{T_2}(u),...,\sigma^{T_n}(u))$$
$$\frac{1}{\Delta u^g}\int_g \sigma_x^{T_1}(u) f(\sigma^{T_1}(u),\sigma^{T_2}(u),...,\sigma^{T_n}(u))du \approx \sum_{(i_1,i_2,...,i_n)} \sigma_x^{T_1}(u)\omega_{i_1,i_2,...,i_n} f(\sigma^{T_1}(u),\sigma^{T_2}(u),...,\sigma^{T_n}(u)) \quad (7)$$

The keystone of this method consists in calculating, separately for each temperature T_k, quadrature formulae given by probability tables based on moments, ($p_{k,i_k}, \sigma_{i_k}^{T_k}, \sigma_{x,i_k}^{T_k}$), allowing the calculation of integrals depending on cross-sections at a given temperature.

3.2. APOLLO2 calculation for MINERVE experiment analysis

The experimental validation of APOLLO2.5 code deals with fuel temperature coefficient (Doppler effect is predominant in LWR lattices). APOLLO2 calculation uses P_{ij}-2D-UP1 model (interface current method with linear anisotropic angular fluxes), and four rings in every fuel pin (rim effect). Physical response is a reactivity variation due to the growth of temperature in the sample without leakage.
However, first order Perturbation was used to propagate technological uncertainties on Doppler effect (uncertainties linked to fuel isotopic concentrations amount to ±1% in one standard-deviation).
This analysis allows a limited calculation geometry: as shown in Figure 2, a 13x13 cell pattern was used. It is a regular UO_2-MELODIE lattice except 3x3 experimental device including oscillation tube.

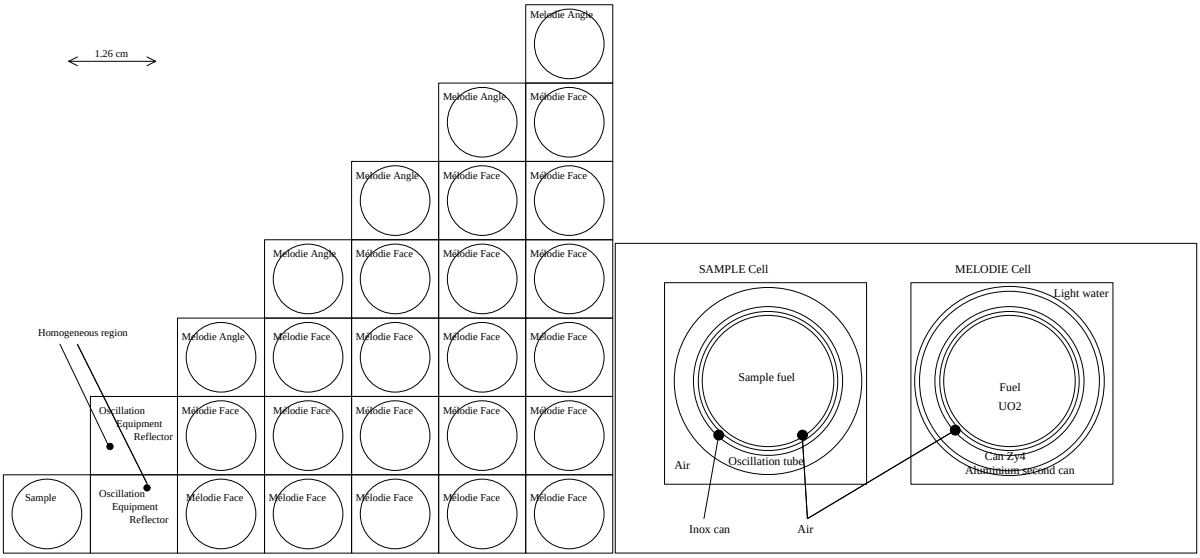

Figure 2. APOLLO2 Deterministic geometry

4. QUALIFICATION RESULTS

The calibration of the calculated reactivity worth (pcm) versus measured worth (UP: Pilots Units from the automated control rod) is carried out from the ^{235}U reactivity worth measured through the oscillation of 4 UO_2 cold samples with increasing enrichment (0.2% up to 5%). The accuracy of the calibration factor, obtained from least-square linear regression, is 2%.

Different models of Doppler broadening were used to perform interpretation calculation:

- Approximated Gas Model (crystalline binding in UO_2 pellet is neglected),
- Reference calculation Crystal Lattice [7] using an actual effective temperature T_{eff}^{RI} preserving ^{238}U resonance integral in the actual UO_2 crystal (using 2-phonons modes). This calculation corresponds to the APOLLO2 "CEA-97" recommended scheme.

The Calculation-Experiment comparison is summarized in Table 1. The experimental uncertainty (1σ) involves the statistical uncertainty of the pilot rod signal, the sample temperature uncertainty, the technological uncertainties mainly linked to actinide concentrations in the sample and the systematic uncertainty due to reactivity worth calibration.
The Calculation-Experiment bias (C-E)/E in % are shown in Table 1 both for the rough Gas Model using thermal temperature T and for the T_{eff}^{RI} Crystal Model. Crystalline binding effect on Doppler broadening decreases the fuel temperature effect by 2.6% (average value in the temperature range 20°C-800°C). Table 1 points out that APOLLO2 calculation of fuel temperature coefficient is satisfactory for UOX fuel, with the following average trend: (C-E)/E = +1.9% ± 3.0%. On the contrary, the temperature worth in MOX samples is overestimated in APOLLO2 by about +10.0% ± 3.0%.

Table 1. C/E-1 (in %) on MINERVE Doppler worth

Oscillation samples	**Temperatures 20°C up to 800°C**	
	Gas Model	T_{eff}^{RI} *Crystal Model*
UO_2 depleted (0.2% enrichment)	+5.5 ± 3.8	+2.5 ± 3.8
UO_2 nat. (0.7% enrichment)	+4.3 ± 4.1	+1.3 ± 4.1
MOX (2.53% Pu)	+10.8 ± 3.6	+8.5 ± 3.6
MOX (3.75% Pu)	+15.8 ± 3.8	+13.2 ± 3.8
MOX (4.73% Pu, ϕ8.0mm)	+11.9 ± 3.9	+9.3 ± 3.9
MOX (4.73% Pu, ϕ8.9mm)	+13.8 ± 4.3	+11.2 ± 4.3
MOX (5.24% Pu)	+13.3 ± 3.5	+10.6 ± 3.5
MOX (7.28%Pu)	+15.4 ± 4.3	+13.1 ± 4.3

The overestimation of Doppler effect in MOX versus Pu load is shown in Figure 3. For current Pu isotopic vector manufactured at La Hague reprocessing plant, the C/E discrepancy can be summarized as follow:

MOX 2.5% Pu: (C-E)/E = +8% ± 3%
MOX 4.7% Pu: (C-E)/E = +10% ± 3%
MOX 7.3% Pu: (C-E)/E = +11% ± 3%

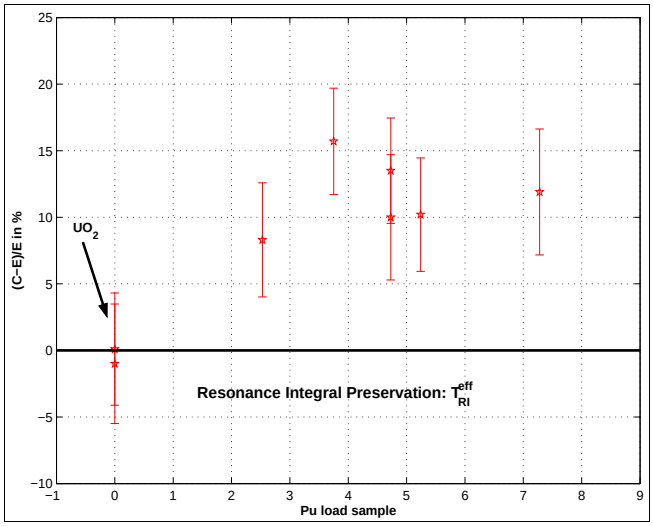

Figure 3. Doppler validation versus Pu load

5. DOPPLER ANALYSIS AND VALIDATION AGAINST CONTINOUS-ENERGY MONTE-CARLO CALCULATION

5.1. Isotopic contribution to Doppler effect

First order perturbation method allows the separation of each isotopic and reaction contribution to fuel temperature worth. For instance, the UO_2 nat. and in the high Pu load 7.28% MOX sample case are presented respectively in Tables 2 and 3 in UP (Pilots Units).
The oscillation sample and MELODIE fuel pellets are divided into four regions which are numbered from the center to the periphery with 50%-30%-15%-5% volume ratios.

Table 2. Reactivity worth components in the UOX sample (exp. unit UP)

UOX Sample	Fuel region 1	Fuel region 2	Fuel region 3	Fuel region 4	Full Fuel
^{238}U	-42.9	-36.2	-38.2	-29.4	**-146.7**
^{235}U	+0.1	0.0	0.0	0.0	**+0.1**
^{16}O					**+12.9**
Total	-42.8	-36.2	-38.2	-29.4	**-133.7**

(n,γ)	(n,f)	(n,n)	$\sigma_s^{g'\to g}$	Total
-148.2	+0.6	+1.5	+12.4	**-133.7**

These results points out that the major component is due to Doppler broadening in ^{238}U resonances. Table 2 emphasizes the Doppler worth of the fuel pin peripheral zone: regions 3+4 represent 46% of the Doppler effect for 20% volume fraction of the fuel. ^{235}U Doppler contribution is negligible owing to the cancellation of the weak fission and capture components. Table 2 shows a significant component of oxygen linked to spectral shift effect in the thermalization process.

Table 3. Reactivity worth components in MOX sample (Pu 7.28% load)

MOX Sample	Fuel region 1	Fuel region 2	Fuel region 3	Fuel region 4	Full Fuel
^{238}U	-42.9	-36.1	-42.1	-31.7	**-152.8**
^{240}Pu	-23.2	-22.8	-19.0	-6.6	**-71.6**
^{239}Pu	-0.6	-0.2	-0.1	0.0	**-0.9**
^{242}Pu	-0.5	-0.3	-0.1	0.0	**-0.9**
^{241}Pu	+0.1	+0.1	0.0	0.0	**+0.2**
^{235}U	+0.1	0.0	0.0	0.0	**+0.1**
^{16}O					**-6.6**
Total	-67.0	-59.3	-61.3	-38.3	**-232.5**

(n,γ)	(n,f)	(n,n)	$\sigma_s^{g' \to g}$	Total
-272.9	+42.4	+4.6	-6.6	**-232.5**

As we can notice, ^{238}U broadened resonance contribution to fuel temperature worth is almost the same in MOX as in UOX fuel. In MOX lattices, Doppler level increases by about 30% due to ^{240}Pu broadening. The ^{239}Pu Doppler worth is small because of the cancellation of the large capture and fission components. In case of multi-recycle of plutonium in LWRs, we can notice that the ^{242}Pu Doppler contribution would become significant.
Figures 4 and 5 show the energetic and spatial components of ^{238}U and ^{240}Pu worth, respectively. The rim effect in Doppler reactivity worth concerning ^{238}U(n,γ) broadening effect is mainly due to the first three large resonances.

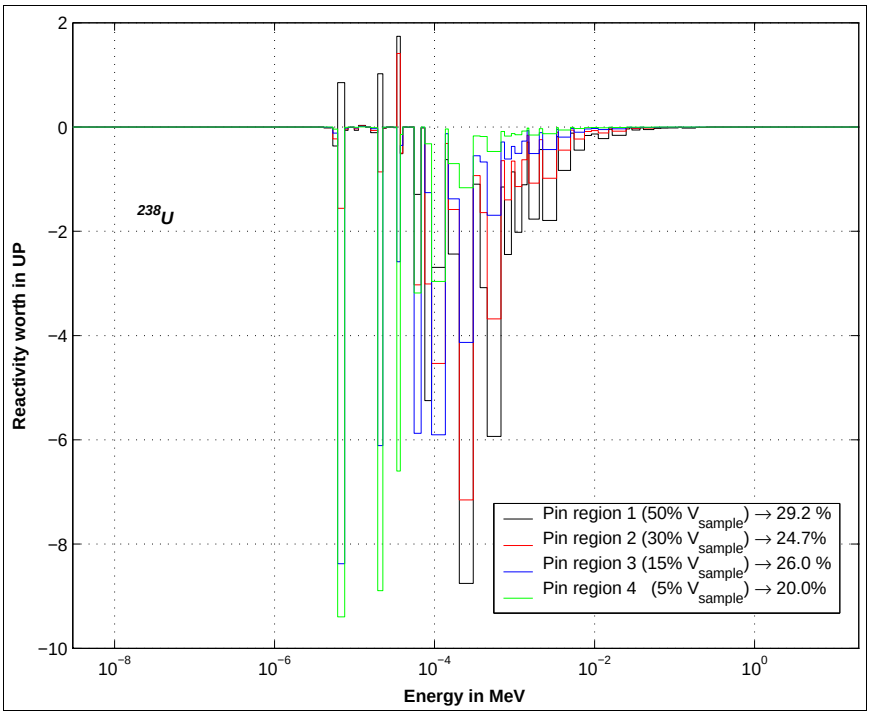

Figure 4. ^{238}U fuel temperature components versus energy

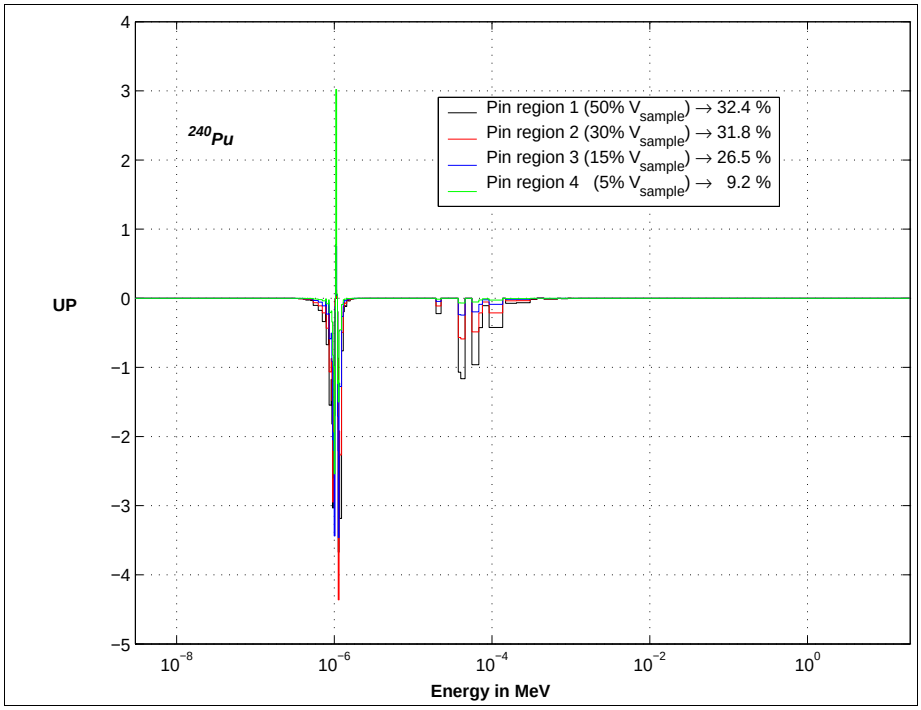

Figure 5. ^{240}Pu fuel temperature components versus energy

Concerning ^{240}Pu Doppler, 90% of the Doppler worth corresponds to the 1eV resonance; the remaining ^{240}Pu components arises mainly from the 38.3eV, 41.6eV and 66.7eV resonances.

5.2. Benchmark APOLLO2/TRIPOLI4

The over estimation trend of MOX Doppler calculation can be due to mutual shielding between ^{238}U and ^{240}Pu. A detailed inter-comparison has already been performed for the Doppler reactivity coefficient of MOX fueled LWR lattice between Osaka University and CEA Cadarache [8]. The same APOLLO2 overestimation was observed compared to continuous energy Monte-Carlo MVP results.
In order to check this conclusion, we benchmarked the APOLLO2.5 deterministic calculation against a reference TRIPOLI4.3 Monte-Carlo calculation [9] (using the same JEF2.2 nuclear data). The TRIPOLI4 code, developed at the CEA, is a continuous energy Monte-Carlo code. Probability tables are used for the unresolved resonance region. Direct method was used in both codes to determine the variation of ^{240}Pu capture rates τ due to 300K up to 900K pin temperature perturbation. Table 4 emphasizes the ^{240}Pu/^{238}U resonance overlapping problem in the 20.5eV and 66.7eV resonances. The APOLLO2.5 discrepancy on ^{240}Pu capture rate increases strongly with fuel temperature; therefore, the Doppler effect in these resonances is badly assessed. Due to mutual shielding effect, the actual Doppler worth in these resonances becomes positive, when a standard negative worth is calculated in the deterministic mutligroup calculation.

Table 4. Validation of ^{240}Pu capture rates

Energy range [19.4;26.6]eV	APOLLO2	TRIPOLI4 (1σ)	APOLLO2/TRIPOLI4 (1σ)
τ^{240}Pu(n,γ) 300K	123pcm	103pcm (±0.3pcm)	**+19.6% (±0.3%)**
τ^{240}Pu(n,γ) 900K	123pcm	83pcm (±0.2pcm)	**+49.4% (±0.3%)**
$\delta\tau^{240}$Pu(n,γ)	0pcm	-21pcm (±0.4pcm)	•

Energy range [55.6;67.9]eV	APOLLO2	TRIPOLI4 (1σ)	APOLLO2/TRIPOLI4 (1σ)
τ^{240}Pu(n,γ) 300K	115pcm	86pcm (±0.3pcm)	**+32.5% (±0.3%)**
τ^{240}Pu(n,γ) 900K	129pcm	73pcm (±0.2pcm)	**+77.0% (±0.3%)**
$\delta\tau^{240}$Pu(n,γ)	+14pcm	-14pcm (±0.4pcm)	•

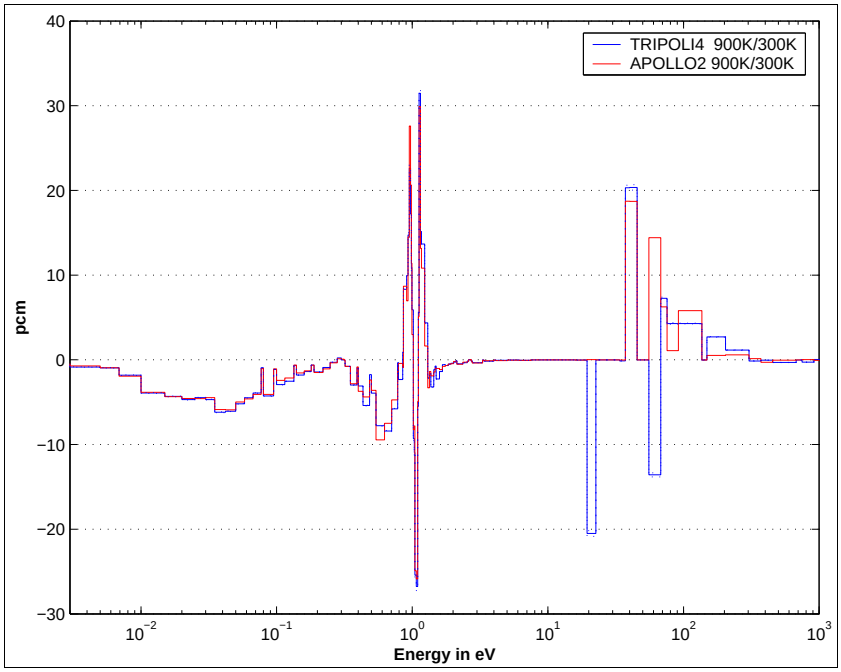

Figure 6. Numerical validation of ^{240}Pu capture rate variation from 300K to 900K

The ^{240}Pu capture variation versus energy is plotted in Figure 6. Due to Maxwell spectrum hardening with temperature, ^{240}Pu capture decreases in the 0.1eV range. The effect of the 0.3eV ^{239}Pu resonance broadening is also described in Figure 6. ^{240}Pu capture rate increases in the 1eV resonance wings and decreases around the peak. All these thermal/epithermal phenomena are well calculated by the deterministic calculation in the refined XMAS group structure.
In the 10-100eV energy range, the variation of ^{240}Pu resonance rates is badly predicted by the deterministic calculations owing to multigroup treatment of the ^{240}Pu /^{238}U mutual shielding. Figure 7 stresses the ^{240}Pu /^{238}U resonance overlap around 66eV (group n°69 in XMAS energy mesh):

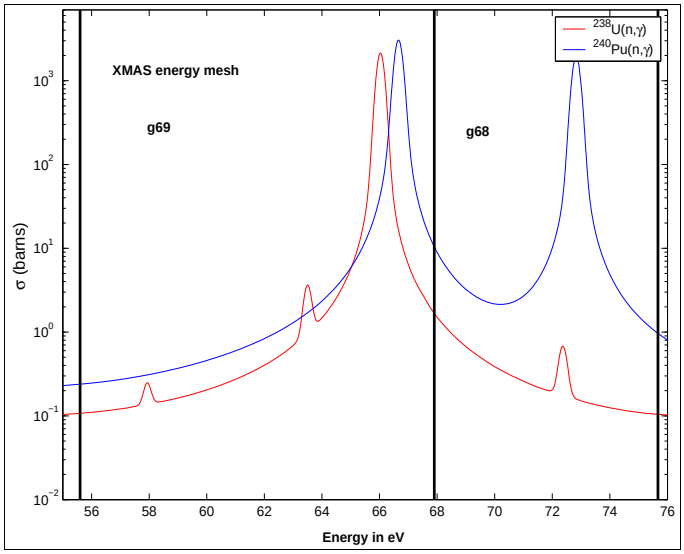

Figure 7. ^{238}U and ^{240}Pu resonance overlapping (XMAS energy mesh)

The TRIPOLI4 ^{240}Pu capture rate in the 64-74eV range is shown in Figure 8 for 300K and 900K. This reference calculation points out the actual mutual shielding effect: the capture rate in the 66.7eV left wing decreases with temperature due to the 66.0eV ^{238}U resonance overlapping.

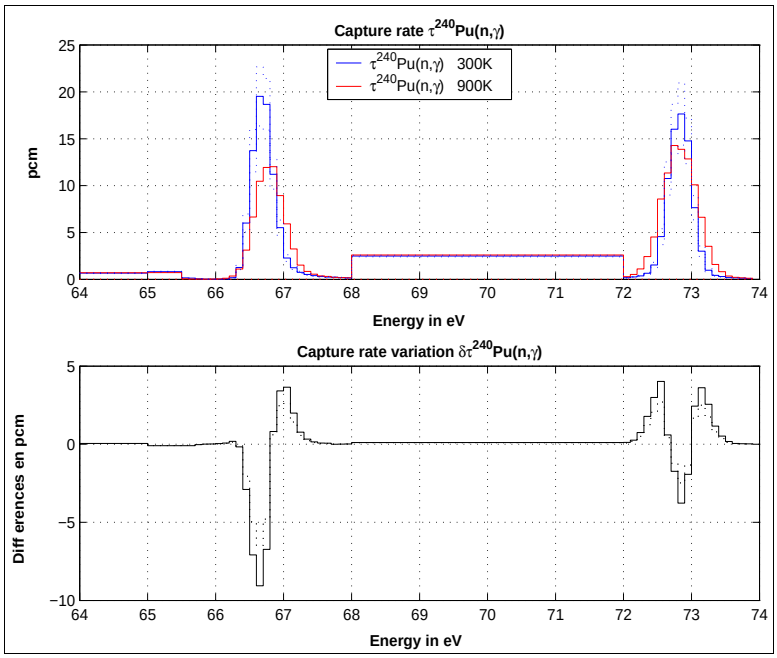

Figure 8. ^{240}Pu capture rate variation in reference TRIPOLI4 calculation, 66eV resonance overlap

6. CONCLUSION

The experimental validation of APOLLO2.5 and its CEA93.V6 library was achieved through the analysis of the MINERVE-Doppler experiment, based on oscillation of UOX and MOX fuel samples heated up to 1000°C.
Fuel temperature worth in UOX lattices is well calculated: (C/E-1)= +2% ± 3% and is independent of ^{235}U enrichment. Fuel temperature worth increases by about 40% in MOX fuels, mainly due to ^{240}Pu broadening. The Doppler reactivity worth, is overestimated by +10% ± 3%, for these MOX samples. The most accurate broadening model (Crystal Lattice) reduces discrepancies C/E by about 2.6%, regarding to Gas Model.
The results of the APOLLO2.5 validation against Monte-Carlo TRIPOLI4.3 calculations points out the importance of the resonance overlapping between ^{238}U and ^{240}Pu.
Mutual shielding modeling in deterministic codes remains a crucial calculation challenge to meet the required target accuracy for LWR-MOX design parameters, such as conversion factor and fuel temperature coefficient.

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REFERENCES

1. C. Golinelli et al., "Temperature coefficient and Doppler measurements" *Proc. of ANS Reactor Physics Conference*, Sun Valley (USA), 1980
2. R. Sanchez et al., "APOLLO-II: A User-Oriented, Portable, Modular Code for Multigroup Transport Assembly Calculations", *Proc. of Int. Top. Mtg. Advances in Reactor Physics, Mathematics and Computation*, Paris (France), April 27-30 1987
3. S. Loubière et al., "APOLLO2, twelve years later", *Proc. of Int. Conf. Mathematical and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid (Spain), 1999
4. A. Santamarina, C. Chabert, A. Courcelle, O. Litaize, G. Willermoz, "Qualification of the APOLLO2.5/CEA93.V6 for UOX and MOX fuelled PWRs", *Proc. of Int. Conf. ANS Reactor Physics Meeting PHYSOR2002*, Seoul (Korea), October 7-10 (2002), 5A-01.
5. M. Coste, S. Perruchot-Triboulet, C. Van Der Gucht, "Self-shielding calculations by APOLLO2 code for fuel pins with a temperature distribution", *Proc. of Int. Conf., Mathematical and Computational sciences*, Saratoga (USA), October 5-9 1997, Vol. 2, pp. 446-455
6. A. Santamarina, H.J. Smith, E. Whitesides, "NEACRP standard problem exercise on criticality codes for dissolving fissile oxides in acids. A reference method for treating the fuel double heterogeneity", *Proc. of Int. Conf. On the Physics of Reactors, PHYSOR1990*, Marseille (France), April 23-27 1990, Vol. 2, pp. 95-107
7. A. Meister, A. Santamarina, "The influence of the crystalline binding effect of UO2 on the Doppler broadening. Recommended effective temperatures for APOLLO calculations", *Proc. of Int. Conf.* Long Island (USA), October 5-8 1998
8. T. Takeda, M. Hattori and A. Santamarina, C. Chabert, "Inter-comparison of Doppler Reactivity Coefficients for LWR UO2 and MOX Cells", *Proc. of Int. Conf., ANS Reactor Physics Meeting PHYSOR2002*, Seoul (Korea), October 7-10 2002, 11A-04
9. J.P. Both, H. Derriennic, B. Morillon, J.C. Nimal, "A Survey of Tripoli4, " *Proc. of Int. Conf. on Radiation Shielding 8*, Arlington (USA), Apr. 24-28 1994, Vol. 1, pp. 373-380