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VALIDATION OF MOX CORE REACTIVITY VERSUS FLUX VARIATION. FEEDBACK ON DELAYED NEUTRON DATA (ν_d, α_i, λ_i)

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ABSTRACT

The reactivity of commercial Light Water Reactors (LWR) is given by the reactimeter, which computes the core reactivity from the flux variation measurement. The correspondence is obtained from the kinetics equations with a large 6-10% uncertainty due to the delayed neutron (DN) data. This paper presents the first direct validation of the relationship between the measured flux variation and the MOX core reactivity, thanks to the boron reactivity worth measurements in EOLE-MISTRAL2 experiment. The kinetics relationship based on JEFF3 DN data is satisfactory. On the contrary, using B-VII DN data leads to an under-prediction by -8.3% ± 2.7% of MOX core reactivity. Considering the satisfactory prediction within 2% of the measured β_{eff} value, we can conclude that this large boron worth bias is mainly due the DN time dependence in BVII data.

Key Words: MOX core reactivity, EOLE-MISTRAL2, Delayed neutrons, JEFF3, ENDF/B-VII

1. INTRODUCTION

The reactivity of commercial Light Water Reactors (LWR) is given by the reactimeter, which computes the core reactivity from the flux variation measurement. In the same way, the core reactivity of experimental zero-power reactors (measurement of reactivity worth) is deduced from the Doubling Time measurement. In both cases, the reactivities are computed from the kinetics equations and the accuracy depends on the knowledge of the delayed neutron data (ν_d, α_i, λ_i, $\chi_{d,i}(E)$, i=6 or 8 time groups) for each fissile nuclide.

There is no direct experimental validation of the relationship between the measured flux variation and the core reactivity. Up to now, the uncertainty on the reactivity (calculated from the flux measurement) is obtained by propagation of the uncertainty of the Delayed Neutron (DN) data. Unfortunately, even using the more advanced DN data improved by reactor noise experiments (OECD WPEC Expert Group-6), the uncertainty on the predicted reactivity in the relevant range {-200 ; +200 pcm} amounts to ±6% (1σ) in UOX fuels and ±10% in MOX fuels [1]. Furthermore, using the different DN data proposed by two recent international libraries JEFF3.1.1 [2] and ENDF/B-VII.0 [3], the LWR reactivity associated with the same doubling time differs by 16% in UOX fuels [4] and by 10% in MOX fuels. This strong disagreement is mainly due to the average lifetime $\tau = \sum \alpha_i/\lambda_i$ of delayed neutron. While the total delayed neutron fraction β can be validated within 2% accuracy thanks to core noise measurements [5], it will be difficult to reduce τ uncertainty below 6% (1σ), because of the strong uncertainty on the proportion of delayed neutrons α_i emitted in each time group i. Since the predicted reactivity is quite proportional to the β_{eff} τ product, the 12% 2σ-uncertainty on the reactivity is far from the LWR design target-accuracy ±4%.

Recently we performed a direct experimental validation of the kinetics relationship between the reactivity and the flux variation in LWR UO_2 cores [6]. This paper presents the direct validation of the kinetics relationship for LWR MOX fuels, through the MISTRAL2 100%MOX core performed in the EOLE experimental reactor (CEA Cadarache research center). From this validation work, a recommendation is finally proposed for improvement of the Delayed Neutron (DN) data in the current international libraries.

2. DELAYED NEUTRON DATA

A new 8-group structure of the time dependence of neutron emission [1], based on the work of Spriggs, Campbell and Piksaikin [7], has been adopted in JEFF-3.1.1 in order to improve kinetics parameters prediction. In this 8-group representation, the same set of half-lives is defined for all fissioning isotopes, with the half-lives adopted for the three longest lived groups corresponding to the three dominant precursors ^{87}Br, ^{137}I and ^{88}Br : $T_{½}$ = 55.6s, 24.5s and 16.3s respectively.

The 8-group relative abundances $\alpha_i = \nu_{di}/\nu_d$ were obtained by Campbell and Spriggs from the original analyses of the measured data, i.e Keepin [8] for ^{238}U and thermal fissions of ^{235}U and ^{239}Pu. JEFF-3.1.1 preserves the Keepin's lifetime τ, as pointed out in Table I.

The total DN yields ν_d from WPEC Subgroup 6, adopted in JEFF-3.1.1, are mainly based for ^{235}U, ^{238}U and ^{239}Pu, on CEA work in EOLE-MISTRAL for LWR spectra and MASURCA, FCA, SNEAK, ZPR for fast spectra. Table I summarizes the comparison of DN data in international libraries and Keepin measured values, as well as Tuttle recommendations [9].

Table I. Delayed neutron Yields ν_d and average Lifetime τ for ^{239}Pu and ^{238}U fissions.

		Keepin	Tuttle	JEFF3.1.1	ENDF/B-VII.0
^{239}Pu thermal	**ν_d**	0.0061±0.0003	0.00628	0.00650	0.00645
	τ (s)	15.4	14.6	15.4	13.3
^{238}U E_n=2MeV	**ν_d**	0.0412 ±5%	0.0439	0.0478	0.0440
	τ (s)	7.67	7.58	7.67	7.23

Concerning ^{239}Pu, Table I shows a higher ν_d^{239} value in current libraries compared to the Keepin and Tuttle evaluations, and the time dependence in B-VII.0 induces a small DN lifetime τ. Concerning ^{238}U, Table I points out a large spread of ν_d^{238} values: the JEFF3.1.1 is clearly higher than other evaluations.

3. DETERMINATION OF THE REACTIVITY FROM CORE FLUX VARIATION

Variations of the neutron population in the core are described by the point kinetics equations:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta_{eff}}{\Lambda} n(t) + \sum_i \lambda_i C_i(t) + S(t)$$
$$\frac{dC_i(t)}{dt} = \frac{\beta_{eff,i}}{\Lambda} n(t) - \lambda_i C_i(t) \quad (1)$$

Therefore, core reactivity can be deduced from the variation of the flux:

$$\rho(t) = \frac{\Lambda}{n(t)}\left(\frac{dn(t)}{dt} + \sum_i \frac{dC_i(t)}{dt}\right) \quad (2)$$

a) In power reactors, the measurement of the flux variation versus time allows the reactimeter to deduce the core reactivity by the following algorithm:

$$\rho(k) = \frac{\Lambda}{\bar{n}(k)}\left(\frac{\bar{n}(k) - \bar{n}(k-1)}{T_e} + \sum_i \frac{C_i(k) - C_i(k-1)}{T_e}\right)$$
$$k = \frac{t}{T_e} \quad (3)$$
$$C_i(k) = \left(1 - e^{-\lambda_i T_e}\right)\frac{\beta_{eff,i}}{\Lambda\lambda_i}\bar{n}(k-1) + e^{-\lambda_i T_e} C_i(k-1)$$

b) In experimental reactors, the inhour equation is used:

$$\rho = \omega\left(\Lambda + \sum_{i=1}^{n} \frac{\beta_{\mathrm{eff}i}}{\omega + \lambda_i}\right) \quad (4)$$

After the cancellation of transients, the doubling time $T_d = Ln2/\omega_0$ is measured and the reactivity can be derived by the kinetics relationship:

$$\rho = \frac{\ln 2}{T_d}\left(\Lambda + \sum_{i=1}^{n} \frac{\beta_{\mathrm{eff}i}}{\frac{Ln2}{T_d} + \lambda_i}\right) \quad (5)$$

In experimental reactors, only small reactivities are measured and $T_D/Ln2 \geq \tau_i$, (i=2,n). Thus, the kinetics relationship (5) points out that the experimental core reactivity deduced from the doubling time measurement T_d is proportional to the DN total yield and quite proportional to the average DN lifetime τ. Therefore, DN data (see Table I) given by various libraries must be validated.

4. β_{eff} EXPERIMENTAL VALIDATION

The effective delayed neutron fraction β_{eff} of LWR 100%MOX cores was accurately measured by neutron noise in EOLE-MISTRAL2 experiment [10] [11].

MISTRAL-2 in EOLE is a regular 100%MOX (7 wt% Pu) core with about 1600 PWR-type fuel pins, in a square pitch of 1.32 cm. The moderation ratio is $V_{mod}/V_{fuel} = 1.7$. Along the experiment, the criticality was adjusted by modifying the core size (addition of peripheral MOX pins to compensate the Pu aging).

The effective DN fraction for each time-group *i* is obtained by an improved Keepin formalism (without assumption of energy independence of the DN yields):

$$\beta_{eff,i} = \frac{\int d\vec{r} \int dE \Phi^+(\vec{r},E) \sum_j \chi_{i,j}^d(E) \int dE' \nu_{i,j}^d(E') \Sigma_{f,j}(E') \Phi(\vec{r},E')}{\int d\vec{r} \int dE \Phi^+(\vec{r},E) \sum_j \chi_j(E) \int dE' \nu(E') \Sigma_{f,j}(E') \Phi(\vec{r},E')}$$

Where the parameters have the following meaning:
Φ, Φ^+: direct and adjoint flux respectively
j : fissile isotope
χ_j : total fission spectrum for isotope j
$\chi^d_{i,j}$: delayed neutron emission spectrum for time-group i and isotope j
$\nu^d_{i,j}$: fractional delayed neutron yield for the time-group i and isotope j
$\nu\Sigma_{f,j}$: total production cross section for isotope j

Reference calculations of the 3D core and β_{eff} values were performed by the continuous-energy Monte-Carlo code TRIPOLI4, using the IFP method for the neutron Importance Φ^+ [12]. The deterministic analysis of β_{eff} measurement was also performed by APOLLO2.8 [13], using the 2D-exact MOC method [14] and the refined energy mesh SHEM [15].

Calculation-Experiment comparison is shown in Table II, for DN data both from JEFF3.1.1 and B-VII.0. TRIPOLI-4 and APOLLO2 calculations give consistent results. The analysis based on DN data from JEFF3.1.1 is satisfactory for this 100%MOX core, meanwhile ENDF/B-VII DN data seems to underestimate the measured β_{eff} value, owing to lower ν_d values (see Table I).

Table II. Calculated vs Experimental β_{eff} values in the MISTRAL2 100%MOX core: (C-E)/E in %

Experiment	Measurement β_{eff} in pcm	TRIPOLI-4 JEFF-3.1.1	TRIPOLI-4 ENDF/B-VII.0	APOLLO2.8 JEFF-3.1.1	APOLLO2.8 ENDF/B-VII.0
MISTRAL-2	$\beta_{eff} = 370.3 \pm 6.0(1\sigma)$	-0.5 ± 1.7%*	-1.7 ± 1.7%*	+0.1 ± 1.6%	-1.9 ± 1.6%

* Uncertainty combining the TRIPOLI4 statistical uncertainty and the experimental uncertainty

5. VALIDATION OF KINETICS RELATIONSHIP IN THE MISTRAL2 EXPERIMENT

In the MISTRAL2 100%MOX core, the reactivity worth of soluble boron was measured by variation of the doubling time T_d (due to the variation of the core residual reactivity). The soluble boron worth was measured twice: first introducing 6 ppm of boron in the pure water moderator, and second between C_B = 6 ppm and C_B = 0 ppm boron dilution.

The 3D geometry of the TRIPOLI-4 Monte-Carlo calculation is shown in Figure 1. Each core calculation involved four billions of neutron histories (TRIPOLI4 statistical uncertainty on Keff amounts to 1.4 pcm). The 6 ppm soluble boron worth was calculated by three distinct methods:

- Direct calculation of Keff variation when the MISTRAL2 core is poisoned by 6 ppm of soluble boron: $\Delta\rho^B_{direct} = -52.3 \pm 1.8$ pcm
- Correlated samples method [16]: $\Delta\rho^B_{corr} = -54.78 \pm 1.5$ pcm
- IFP reference method [12]: $\Delta\rho^B_{IFP} = -54.18 \pm 0.38$ pcm.

Therefore, the average calculated value is $\Delta\rho^B_{Tripoli} = -54.1 \pm 0.36$ pcm.

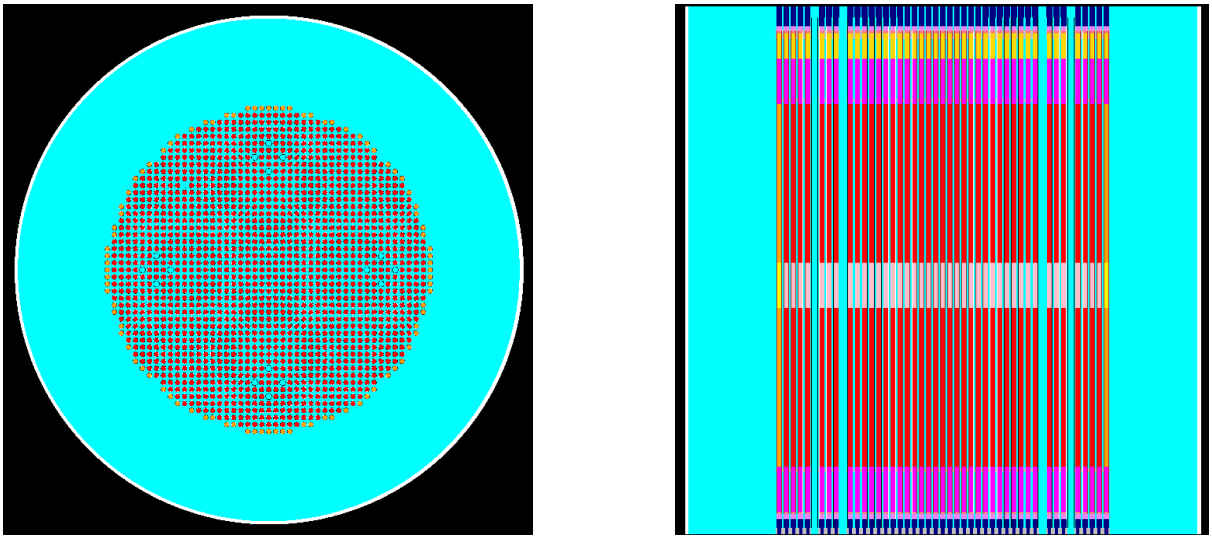

Figure 1. TRIPOLI-4 radial and axial cut-off of the MISTRAL2 core.

Since the $^{10}B(n,\alpha)$ capture cross-section is a standard known within ±0.3% (1σ) uncertainty [17], TRIPOLI4/JEFF3 calculation of 6 ppm soluble boron worth can be considered as the reliable worth value: $\Delta\rho^{B}_{Ref}$ = 54.1 ± 0.8 pcm. This 0.8 pcm total uncertainty combines both ±0.7% statistical component, ±0.3% boron cross-section component, ±0.9% boron concentration measurement and ±0.4% technological uncertainty (mainly due to the over-clad outer diameter).

Table III summarizes the T_d measured values corresponding to the residual reactivities of the MISTRAL2 cores, with and without 6 ppm boron poisoning. Since the experimental uncertainty is significant only for the large reactivities of the two pure water configurations (small T_d values), the soluble boron worth can be considered as measured twice: between C_B = 0 ppm and 6 ppm, and between C_B = 6 ppm and 0 ppm. However, one must correct residual reactivities from Pu aging; in the MISTRAL2 100%MOX core the Pu aging was measured both by Amplification Source Method and by Critical Size variation: $\Delta\rho^{Pu}$ = -1.46 ± 0.04 pcm/day. After Pu aging correction, the soluble boron worth obtained by difference of the residual reactivities of 1^{rst} and 2nd core amounts to 54.3 ± 2.1 pcm, meanwhile the soluble boron worth deduced from residual reactivities of 2nd and 3rd core is 51.4 ± 1.4 pcm. Thus, the average boron worth (6 ppm) based on JEFF3 DN data is: $\Delta\rho^{B}_{Td}$ = 52.3 ± 1.2 pcm. Since in B-VII the $\beta_{eff}.\tau$ value is lower by -5.9% than in JEFF3, the average boron worth based on B-VII DN data is reduced by 5.2%: $\Delta\rho^{B}_{Td}$ = 49.6 ± 1.2 pcm.

Table III. T_d measurements in MISTRAL2 cores related to Soluble Boron worth (6 ppm).

		Reactivity (pcm) from T_d	
		JEFF3.1.1	B-VII.0
1^{rst} Core with C_B = 0 ppm 23 March 1998	T_d = 12.8 ± 0.5 s	105.57 ± 2.1	99.95 ± 2.1
2nd Core with C_B = 6 ppm 30 March 1998	T_d = 56.8 ± 0.5 s	41.05 ± 0.3	38.62 ± 0.3
3rd Core with C_B = 0 ppm 2 April 1998	T_d = 17.9 ± 0.5 s	88.03 ± 1.4	83.16 ± 1.4
Average 6ppm Boron worth $\Delta\rho^{B}_{Td}$		52.3 ± 1.2*	49.6 ± 1.2*

* Uncertainty combining T_d measurement and Pu aging uncertainties

Table IV compares the $\Delta\rho^{B}_{Td}$ values deduced from T_d doubling time measurement to the $\Delta\rho^{B}_{Ref}$ worth value. These results show that the $\Delta\rho^{B}_{Td}$ value deduced from JEFF3 DN data is consistent with the "Reference" soluble boron worth within the 1.2σ uncertainty range ; this validation confirms the relevance of (ν_d, α_i, λ_i, i=8 time groups) for ^{239}Pu in JEFF3. On the contrary, the $\Delta\rho^{B}_{Td}$ value deduced from B-VII.0 DN data is underestimated mainly due to the too low τ^{Pu239} DN average lifetime.

Table IV. Soluble boron worth (6 ppm) in MISTRAL2 100%MOX core.

	Reactivity worth of soluble boron	
	JEFF3.1.1	B-VII.0
Boron worth $\Delta\rho^{B}_{Td}$ deduced from T_d	52.3 ± 1.2 pcm	49.6 ± 1.2 pcm
Reference boron worth $\Delta\rho^{B}_{Ref}$	54.1 ± 0.8 pcm	
$(\Delta\rho^{B}_{Td} - \Delta\rho^{B}_{Ref}) / \Delta\rho^{B}_{Ref}$	-3.3% ± 2.7%*	-8.3% ± 2.7%*

* Total uncertainty combining both $\Delta\rho^{B}_{Ref}$ uncertainty and $\Delta\rho^{B}_{Td}$ uncertainty

6. CONCLUSIONS

The validation work based on boron reactivity worth measurements in MISTRAL2 experiment has enabled the bias calibration of LWR MOX core reactivity deduced from the flux variation. The kinetics relationship based on JEFF3 DN data is satisfactory. On the contrary, using B-VII DN data leads to an under-prediction by -8.3% ± 2.7% of MOX core reactivity. Considering the satisfactory prediction within 2% of the measured β_{eff} value, we can conclude that this large boron worth bias is mainly due the DN time dependence in BVII data (too small average lifetime τ^{Pu239} and τ^{U238}).

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