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VALIDATION OF LWR REACTIVITY VERSUS REACTOR PERIOD. FEEDBACK ON THE DELAYED NEUTRON DATA (β_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. Reactivity worth are measured in experimental reactors by the Doubling Time technique. In both cases, the reactivities are computed from the kinetics equations based on delayed neutron (DN) data (β_i, λ_i). Currently, there is no direct experimental validation of the relationship between the measured flux variation and the core reactivity. The uncertainty on the reactivity, obtained by propagation of the uncertainty of the DN data, amounts to ±6% (1σ) mainly linked to the DN average lifetime τ. This paper presents the direct validation of the kinetics relationship between the reactivity and the flux variation through EOLE integral experiments. This work allows the bias calibration of the deduced LWR reactivity using various DN data: -10% and +2.7% ± 1.1% (1σ) using respectively ENDF/B-VII.0 and JEFF3. A recommendation is finally proposed for improvement of DN data in international libraries.

KEYWORDS: Kinetics, core reactivity, delayed neutrons data, integral experiments, EOLE

1. INTRODUCTION

The reactivity of power 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 (β_i, λ_i, $\chi_{d,i}(E)$, i=6 or 8 time groups) for each fissile nuclide.

Currently, <u>there is no direct experimental validation</u> 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 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 amounts to ±6% (1σ) in the relevant reactivity range {0 - 200pcm} [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-UO_2 reactivity associated with the same doubling time differs by more than 16% [4]. This strong disagreement is mainly due to the average lifetime $\tau = \sum \alpha_i/\lambda_i$ of delayed neutron from ^{235}U fissions (τ^{JEFF3} = 13.0s compared to τ^{B-VII} =10.8s). While the total delayed neutron fraction β can be validated within 2% accuracy thanks to core noise measurements [5], it will be very difficult to reduce τ uncertainty below 6% (1σ) [6], 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%.

This paper presents the direct validation of the kinetics relationship between the reactivity and the flux variation through integral experiments in the EOLE zero-power reactor (CEA Cadarache research center). In these LWR-type experiments, some well-defined reactivity worth, such as water temperature worth and absorber worth, are measured both by doubling time method and by equivalence to soluble boron or driver fuel pins worth. The reference Monte-Carlo calculationTRIPOLI4 of these measurements enhances the correct DN data : these data allow consistency between the reactivity measurement deduced from the doubling time and the equivalence measurements. From this validation work, a recommendation is finally proposed for improvement of the delayed neutron 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 two main reasons for adopting this new DN group structure are :

- The need for a more consistent description of the delayed neutron emission from the longest lived precursors to avoid distortions in the kinetics relationship and reactivity analysis.
- The advantage of using a single set of precursor half lives (for all fissile isotopes and incident neutron energies) in calculations of reactor kinetics.

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. This time dependence was later measured by Piksaikin and the systematics of DN average lifetime τ was investigated [9] : the Keepin relative abundance sets were comforted, therefore 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 [10] and MASURCA, FCA, SNEAK, ZPR for fast spectra [11]. Table I summarizes the comparison of DN data in international libraries and Keepin measured values, as well as Tuttle recommendations [12].

Table I. Delayed neutron Yields ν_d and average Lifetime τ for ^{235}U and ^{238}U fissions.

		Keepin [8]	Tuttle [12]	JEFF3.1.1	ENDF/B-VII.0
^{235}U thermal	ν_d	0.0158 ±3.2%	0.0162	0.0162	0.0159
	τ (s)	13.0	12.8	13.0	10.8
^{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 ^{235}U, Table I shows a consistent agreement among the ν_d^{235} evaluations. On the contrary, the time dependence in B-VII.0 library seems badly represented: the corresponding DN average lifetime τ is lower than recommendations by -16%. 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.

Moreover, the neutron-energy dependence of these DN yields is poorly known that increases the uncertainty for intermediate and fast spectra [13]. Total DN yield measurements seem to indicate a slight increase of ν_d^{235} from thermal value to E_n = 3 MeV, and a strong decrease by -30% between 3 MeV and 7 MeV. The linear fit of the Krick and Evans measurements in the range 0.05-1.75 MeV [14] gives the following ν_d^{235} increase per MeV : +0.6% ± 1.0%. However, Tuttle proposed a higher difference between fast and thermal spectrum : +3.2% ± 3.7%.

3. β_{eff} EXPERIMENTAL VALIDATION

The effective delayed neutron fraction β_{eff} of LWR-type UO2 cores was accurately measured by neutron noise in EOLE-MISTRAL1 [5] and IPEN/MB-01 [6] experiments.

IPEN/MB-01 is a zero power research reactor located in São Paulo, Brazil. The core configuration is a 28x26 lattice of stainless steel cladded fuel pins made of 4.35 wt% enriched uranium oxide. The reactor is fully flooded with light water when it is operated, the critically being adjusted by the insertion of 2 groups of 12 Ag-In-Cd control rods. The core square pitch is close to the optimum moderation ratio. Macroscopic noise experiments are used to solve the low frequency range (<1 Hz) of the auto-power spectral density (APSD) and cross-power spectral density (CPSD). Moreover, microscopic noise experiments were used to obtain β_{eff} and the prompt neutron generation time Λ. The experimental methodology uses a combination of Rossi-α and Feynman-α techniques.

MISTRAL-1 in EOLE is a regular UO_2 (3.7 wt% ^{235}U) core with about 750 PWR-type fuel pins, in a square pitch of 1.32 cm. The moderation ratio is V_{mod}/V_{fuel} = 1.7. The criticality was obtained by adjusting the soluble boron concentration.

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

$$\beta_l = \frac{\int d\vec{r} \int dE\ \Phi^\dagger(\vec{r},E) \sum_j \chi^d_{l,j}(E) \int dE'\ \nu^d_{l,j}(E')\Sigma_{f,j}(E')\Phi(\vec{r},E')}{\int d\vec{r} \int dE\ \Phi^\dagger(\vec{r},E) \sum_j \chi_j(E) \int dE'\ \nu\Sigma_{f,j}(E')\Phi(\vec{r},E')} \tag{1}$$

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*
$\chi^d_{l,j}$: delayed neutron emission spectrum for time-group *l* and isotope *j*
$\nu^d_{l,j}$: fractional delayed neutron yield for the time-group *l* and isotope *j*
$\nu\Sigma_{f,j}$: total production cross section for isotope *j*

Reference calculations of the 3D cores and β_{eff} values were performed by the continuous-energy Monte-Carlo code TRIPOLI4, using the IFP method for the neutron Importance Φ^+ [15]. The deterministic analysis of β_{eff} measurement in the experimental cores was performed by APOLLO2.8 [16], using the 2D-exact MOC method [17] and the refined energy mesh SHEM [18]. 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 the MISTRAL1 experiment, but indicates a β_{eff} overestimation of +3% ± 1% in the accurate IPEN experiment. The use of ENDF/B-VII.0 DN data leads to a significant improvement in the prediction of IPEN β_{eff} measurement, thanks to the lower ν_d^{235} and ν_d^{238} values.

Table II. Calculated vs Experimental β_{eff} values in LWR-UO_2 cores : (C-E)/E in %

Experiment	Measurement β_{eff} in pcm	TRIPOLI-4 JEFF-3.1.1	APOLLO2.8 JEFF-3.1.1	APOLLO2.8 ENDF/B-VII.0
MISTRAL-1	β_{eff} = 788 ± 12(1σ)	+1.1 ± 1.5%	+0.5 ± 1.5%	-2.3 ± 1.5%
IPEN/MB-01	β_{eff} = 750 ± 7(1σ)	+3.2 ± 1.0%	+3.3 ± 1.0%	+0.5 ± 1.0%

This β_{eff} calculation trend in MISTRAL-1 and IPEN/MB-01 experiments was confirmed by the CROCUS [19] and AMMON experiment in EOLE [20]. The Calculation-Experiment comparison presented in Table III is still satisfactory for the two DN international libraries.
Since total DN yields ν_d show small variation between thermal energy and 3 MeV, it becomes useful to analyze also β_{eff} measurement in several U-fueled fast cores. To summarize the TRIPOLI-4 results of β_{eff} measurements [15], Table III presents the C/E comparison in the BIGTEN experiment : in this fast core, the calculation based on JEFF3.1.1 DN data also shows a slight β_{eff} overestimation.

Table III. β_{eff} measured values and C/E comparison in U cores : (C-E)/E in %

Experiment	β_{eff} in pcm	JEFF-3.1.1	ENDF/B-VII.0
AMMON	β_{eff} = 754 ± 19(1σ)	+1.4 ± 2.5%	-1.4 ± 2.5%
CROCUS	β_{eff} = 756 ± 20(1σ)	+0.4 ± 2.7%	-2.6 ± 2.7%
BIGTEN	β_{eff} = 720 ± 7(1σ)	+2.6 ± 1.0%	+0.5 ± 1.0%

4. DETERMINATION OF THE REACTIVITY FROM CORE FLUX VARIATION

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

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta_{eff}}{\Lambda} n(t) + \sum_i \lambda_i C_i(t) + S(t)$$
$$\frac{dC_i(t)}{dt} = \frac{\beta_{eff,i}}{\Lambda} n(t) - \lambda_i C_i(t) \qquad (2)$$

Core reactivity can be deduced from the variation of the flux :

$$\rho(t) = \frac{\Lambda}{n(t)} \left(\frac{dn(t)}{dt} + \sum_i \frac{dC_i(t)}{dt} \right) \qquad (3)$$

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

$$\rho(k) = \frac{\Lambda}{\bar{n}(k)}\left(\frac{\bar{n}(k) - \bar{n}(k-1)}{T_e} + \sum_i \frac{C_i(k) - C_i(k-1)}{T_e}\right)$$
$$k = \frac{t}{T_e} \tag{4}$$
$$C_i(k) = \left(1 - e^{-\lambda_i T_e}\right)\frac{\beta_{eff,i}}{\Lambda\lambda_i}\bar{n}(k-1) + e^{-\lambda_i T_e} C_i(k-1)$$

In experimental reactors, the inhour equation is used :

$$\rho = \omega\left(\Lambda + \sum_{i=1}^{n} \frac{\beta_{\text{eff,i}}}{\omega + \lambda_i}\right) \tag{5}$$

After the cancellation of transients, the doubling time T_d = Ln2/ω_0 is measured and the reactivity can be derived by the kinetics relationship :

$$\rho = \frac{\ln 2}{T_d}\left(\Lambda + \sum_{i=1}^{n} \frac{\beta_{\text{eff,i}}}{\frac{Ln2}{T_d} + \lambda_i}\right) \tag{6}$$

In experimental reactors, only small reactivities are measured and T_D/Ln2 ≥ τ_i, (i=2,n). Thus, the kinetics relationship (6) 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.

5. VALIDATION OF KINETICS RELATIONSHIP IN THE CAMELEON EXPERIMENT

The CAMELEON experimental program, collaboration between CEA and AREVA-NP to answer the global qualification of absorbers and burnable poisons in PWR configurations, has been conducted in the EOLE critical facility between 1982 and 1984 [21]. Reactivity worth of absorber clusters such as Ag-In-Cd, B_4C, Hf, stainless steel, and burnable poisons such as UO_2-Gd_2O_3 and Pyrex have been extensively measured in the central 17x17 assembly of the CAMELEON core. The PWR-type lattice is built with 1739 UO_2 fuel pins (3.5 wt% ^{235}U) in a 1.26cm square pitch. The worth measurements have been performed by equivalence with soluble boron poisoning.

The 3D geometry of the TRIPOLI-4 Monte-Carlo calculation is shown in Figure 1. The Calculation-Experiment comparison on both configurations with 17 and 24 Ag-In-Cd (AIC) rods, compared to B_4C clusters, shows that TRIPOLI4-JEFF3.1.1 prediction of the AIC worth is satisfactory : (C-E)/E = +0.9% ± 0.8%(1σ) [22]. In the EPICURE experiment in EOLE [23], the C/E bias on a 24 AIC cluster worth measurement by soluble boron equivalence is negligible : (C-E)/E = +0.2% ± 1.2%. These analysis results of various AIC worth experiments allow the conclusion that TRIPOLI4/JEFF3.1.1 prediction of AIC rod worth is within 1.5% accuracy.

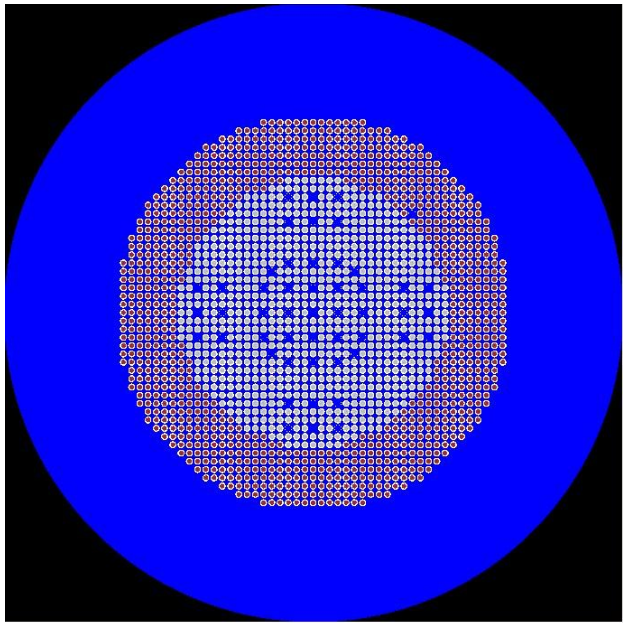

Figure 1. TRIPOLI-4 radial cut-off of the CAMELEON PWR-type core.

1/ In the CAMELEON experiment the reactivity worth of a supplementary 25th AIC rod, introduced at the center of the 24-AIC cluster, was measured by variation of the doubling time T_d, associated with the variation of the core residual reactivity. Thanks to the previous experimental validation, TRIPOLI4/JEFF3 calculation of this AIC rod worth can be considered as the reliable worth value : $\Delta\rho^{AIC}_{Ref}$ = -226.9 ± 4.0 pcm. This value is obtained by CAMELEON core calculations using 10 billions of neutron histories : K_{eff}^{T4} = 1.003334 for the 24-AIC configuration vs K_{eff}^{T4} = 1.001055 for the 25-AIC configuration. The total uncertainty ±4.0 pcm combines the TRIPOLI4 statistical uncertainty ±1.5 pcm, the AIC worth uncertainty from previous equivalence measurements ±3.0 pcm, and the technological experimental uncertainty ±2.2 pcm (mainly due to alloy composition). Table IV compares the $\Delta\rho^{AIC}_{Ref}$ value to the $\Delta\rho^{AIC}_{Td}$ value deduced from T_d doubling time measurement (β_{eff}^{JEFF3} = 770 pcm for this CAMELEON core). These results show that the $\Delta\rho^{AIC}_{Td}$ value deduced from ENDF/B-VII.0 DN data underestimates strongly the AIC rod worth (-9.1%±1.9%), due to the too small DN average lifetime $\tau_{B\text{-}VII}$ = 10.5s ; on the contrary, JEFF3 DN data tends to slightly overestimate the AIC rod worth. Keepin and Tuttle data allow the consistency between $\Delta\rho^{AIC}_{Td}$ worth deduced from doubling time measurement and the $\Delta\rho^{AIC}_{Ref}$ value.

Table IV. Ag-In-Cd rod worth at the center of the CAMELEON core.

		Reactivity deduced from T_d measurement			
		Keepin	Tuttle	JEFF3.1.1	B-VII.0
Experimental Core with 24 AIC	T_d = 7.24±0.1 s	279.9	283.0	291.2	251.6
Experimental Core with 25 AIC	T_d = 97.6±0.2 s	52.9	53.4	55.1	45.3
AIC Worth ($\Delta\rho^{AIC}$ in pcm)	$\Delta\rho^{AIC}_{Ref}$=-226.9±4	-227.0	-229.6	-236.1	-206.3
$(\Delta\rho^{AIC}_{Td}-\Delta\rho^{AIC}_{Ref})/\Delta\rho_{Ref}$	-	0.0±1.9%*	1.2±1.9%	4.0±1.9%	-9.1±1.9%

* Total uncertainty combining both uncertainty on $\Delta\rho^{AIC}_{Ref}$ and uncertainty on $\Delta\rho^{AIC}_{Td}$ due to T_d measurement

2/ Various measurements of Hf worth have emphasized 1% overestimation by TRIPOLI4/JEFF3.1.1:
- (C-E)/E = +1.0% ± 1.7% for a Hf control rod in AMMON experiment (measurement by additive UO_2 driver rods) [20]
- (C-E)/E = +2.0% ± 1.0% for 17 and 24 Hf rod clusters in CAMELEON (measurement vs B_4C) [22]
- (C-E)/E = +1.0% ± 1.0% for a Hf control cross in BASALA (additive MOX driver rods) [24].

In the same way that AIC, the reactivity worth of a 25th Hf rod, introduced at the center of a 24-Hf cluster, was measured in CAMELEON by variation of the doubling time T_d. The TRIPOLI4/JEFF3 calculation of this Hf rod worth, (corrected by -1.4% from the previous experimental validation) can be considered as the reliable worth value : $\Delta\rho^{Hf}_{Ref}$ = -226.7 ± 4.0 pcm. Analysis results confirm the trends obtained in the AIC experiment : using ENDF/B-VII.0 DN data in the kinetics relationship (6), the Hf worth is underestimated by -10.3% ± 2.0%, meanwhile JEFF3.1.1 library induces a $\Delta\rho^{Hf}_{Ref}$ worth greater by +2.6% ± 2.0% than the $\Delta\rho^{Hf}_{Ref}$ worth.

3/ Moreover, the reactivity worth of 8 peripheral UO_2 fuel pins of the CAMELEON core was measured by the doubling time technique. The analysis of this measurement is summarized in Table V. The results confirm that JEFF3.1.1, Keepin and Tuttle data are satisfactory : $\Delta\rho^{UO2}_{Td}$ worth deduced from doubling time measurement is consistent with the $\Delta\rho^{UO2}_{Ref}$ value within 1σ uncertainty. The $\Delta\rho^{UO2}_{Td}$ worth deduced from ENDF/B-VII.0 DN data is once again underestimated (-8.2%±2.9%).

Table V. Reactivity worth of 8 UO_2 fuel rods at the periphery of the CAMELEON core.

		Reactivity deduced from T_d measurement			
		Keepin	Tuttle	JEFF3.1.1	B-VII.0
Experimental Core with 1739 UO_2 fuel rods	T_d = 7.29±0.1 s	279.1	282.1	290.4	250.8
Experimental Core with 1731 UO_2 fuel rods	T_d = 15.4±0.2 s	191.5	193.2	199.3	168.4
8-UO_2 Worth ($\Delta\rho^{UO2}$ in pcm)	$\Delta\rho^{UO2}_{Ref}$=89.8±1.5	87.6	88.9	91.1	82.4
$(\Delta\rho^{UO2}_{Td}-\Delta\rho^{UO2}_{Ref})/\Delta\rho_{Ref}$	-	-2.5±2.9%*	-1.0±2.9%	1.5±2.9%	-8.2±2.9%

6. VALIDATION OF KINETICS RELATIONSHIP IN THE CREOLE EXPERIMENT

The CREOLE (*C*oefficients of *R*eactivity in *EOLE*) experimental program was conceived to supply accurate differential information on the Reactivity Temperature Coefficient (RTC) in the whole temperature range 20°C - 300°C of a PWR power reactor [25]. The experimental facility consists of a pressurized central test loop with 200 PWR fuel pins in a 1.26 cm square pitch, a large vacuum-gap separation zone and a peripheral UO_2 driver core surrounded by a water reflector (Fig. 2).

The RTC of UO_2 (as well as UO_2-PuO_2) lattice was measured from 20°C up to 300°C in the central pressurized loop. The core residual reactivity was measured every +10°C by the doubling time technique. Moreover, the integral temperature reactivity worth between 20°C and 274°C was also measured by equivalence :

- With the soluble-boron poisoning of the central loop (from C_b^{equiv} = 454 ± 2 ppm to 0 ppm)
- With the increase of the driver-zone critical-loading (from 1620 to 1680 UO_2 driver rods).

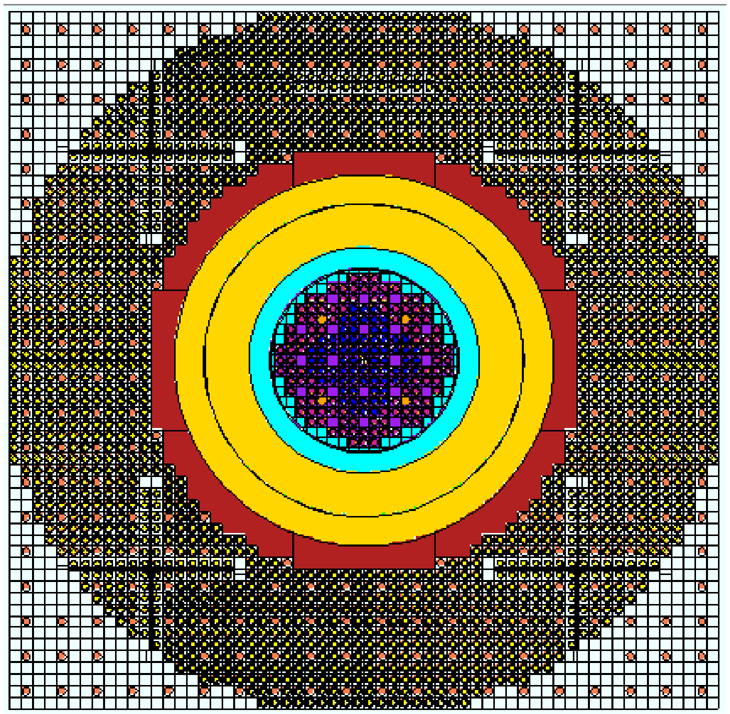

Figure 2. Radial cut-off of the CREOLE core.

Thus, the Temperature reactivity worth deduced from T_d measurements, using relevant (β_i, λ_i) DN data, should be consistent with the equivalent reactivity worth measured through additive driver UO_2 rods and through soluble boron.

APOLLO2.8 calculation supplied the core kinetics parameters, λ_i, α_i and β_{eff}=772 pcm, that allowed the derivation of core reactivities from measured doubling times [25]. Therefore, the temperature reactivity worth from 20°C to 274°C amounts to -930 pcm using JEFF3 DN data (corresponding to a mean RTC α = -3.7 pcm/°C), instead of -894 pcm using Keepin DN data.

The analysis of these experiments was performed using TRIPOLI4/JEFF3.1.1 calculation of the CREOLE cores [26]. The results are summarized in Table VI. From the temperature worth measured by soluble boron and by additive peripheral UO_2 rods, we can conclude that the TRIPOLI4 average C/E bias on the integral RTC is +1.5% ± 1.1% ; this satisfactory PWR-UO_2 RTC prediction by TRIPOLI4 is perfectly consistent with the calculation result of the isothermal RTC measurement in the MISTRAL1 core [27]. Table VI also presents the C/E comparison for the RTC experimental value based on T_d measurement : the TRIPOLI4 bias based on JEFF3.1.1 DN data is -1.4±1.8%. Compared with the results obtained from the two different RTC measurement (Boron and additive UO_2), we can conclude that the reactivity worth value based on T_d measurement using JEFF3.1.1 DN data is overestimated by +2.9% ± 2.1%. On the contrary, the RTC worth based on T_d measurement using ENDF/B-VII.0 DN data is underestimated by -9.5% ± 2.1%. Both reactivity temperature worth based on Keepin and Tuttle DN data are satisfactory.

Table VI. TRIPOLI/Exp bias on Integrated RTC measurement by various experimental techniques

T_d exp. technique	Keepin	Tuttle	JEFF3.1.1	B-VII.0
	+2.6±1.8%[a]	+1.2±1.8%	-1.4±1.8%	+11±1.8%
Boron equivalence	+3.9% ± 2.0%[b]			
UO_2 driver rods	+0.5% ± 1.3%[c]			

a Total uncertainty (1σ) combining the uncertainty due to T_d measurement (1.6%), and technological uncertainties (0.8%) due mainly to loop lattice pitch and UO_2 fuel (pellet radius, density, enrichment, clad radius) [25].
b Total uncertainty combining the Boron concentration uncertainty (1.5%), the boron worth uncertainty (1.0%) and technological uncertainties mainly linked to clad outer diameter and lattice pitch (0.9%).
c Total uncertainty combining the 1.0% uncertainty on additive UO_2 rod worth and 0.8% technological uncertainties

7. VALIDATION OF KINETICS RELATIONSHIP IN THE MIRTE EXPERIMENT

Within the MISTRAL program in EOLE [5], the MIRTE experiment was implemented to validate the reactivity worth of UO_2-Er_2O_3 burnable poison. A reference UO_2 3.7%wt^{235}U fuel pin was first introduced at the center of the MISTRAL1 core and the residual reactivity was measured by the doubling time technique. In a second step, the UO_2-Er_2O_3 pin (1.0 wt% Er, manufactured with the same UO_2 powder) was substituted to the previous reference UO_2 pin, and the new residual core reactivity was also measured by doubling time. The 3D geometry of the TRIPOLI4 Monte-Carlo calculation is shown in Figure 3.

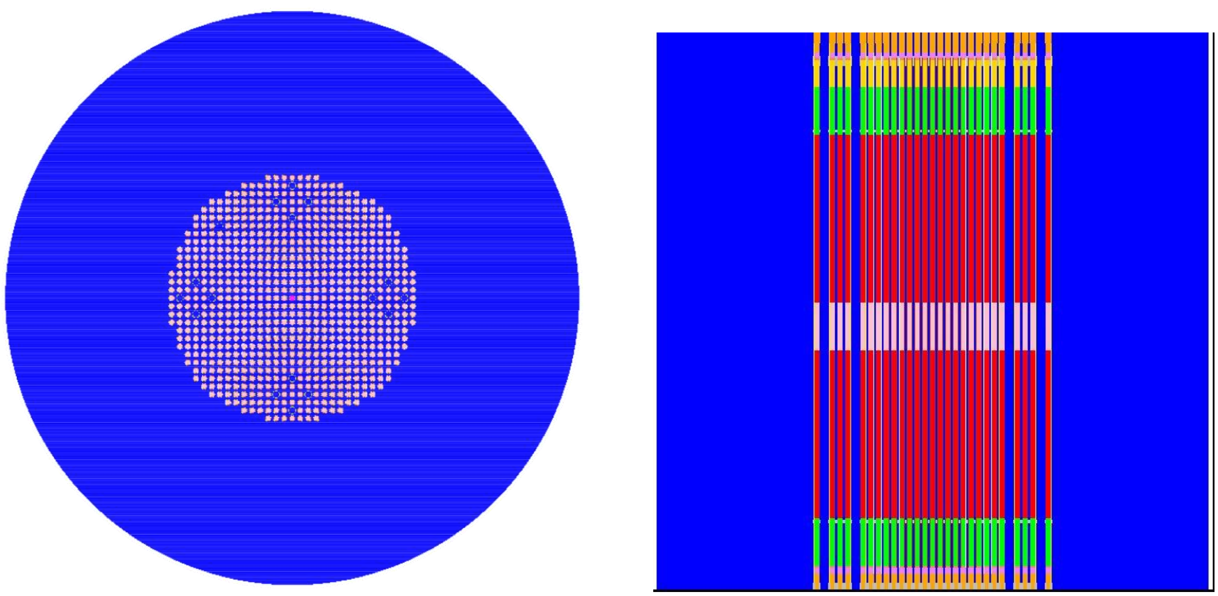

Figure 3. TRIPOLI-4 radial and axial cut-off of the MISTRAL1-MIRTE core

Although the Erbium absorption in various LWR spectra was already investigated in the MINERVE reactor by oscillation of ^{nat}Er, ^{166}Er, ^{167}Er, ^{168}Er and ^{170}Er samples, the uncertainty on the TRIPOLI4 /JEFF3 prediction of UO_2-Er_2O_3 worth was obtained by propagation of cross-section uncertainties. The main uncertainty component is linked to Er(n,γ) cross-section (2.2% in the thermal range [28]). The predominant indirect component is due to ^{235}U absorption : the 0.2% uncertainty in the thermal range induces a 0.16% uncertainty component on the Er pin worth. The TRIPOLI4/JEFF3.1.1 calculation of the UO_2-Er_2O_3 fuel pin worth in MIRTE $\Delta\rho^{Er}_{Ref}$ = 91.3 pcm was obtained both by direct calculation (10 billions of neutron histories) and by the exact perturbation theory using the IFP method. The total uncertainty ±2.2 pcm to be associated with this $\Delta\rho^{Er}_{Ref}$ value combines the TRIPOLI4 statistical uncertainty (±0.4 pcm), the nuclear data uncertainty (±2.0 pcm), and the technological experimental uncertainty ±0.8 pcm (mainly due to ^{i}Er concentrations, diameter and mass of UO_2-Er_2O_3 pellets).

Table VII summarizes the analysis of the MIRTE experiment : $\Delta\rho^{Er}_{Ref}$ value is compared to $\Delta\rho^{Er}_{Td}$ value deduced from T_d doubling time measurement (β_{eff}^{JEFF3} = 792 pcm for the MIRTE core). These results show that the $\Delta\rho^{Er}_{Td}$ value deduced from the ENDF/B-VII.0 DN data underestimates strongly (-13.4% ± 2.9%) the UO_2-Er_2O_3 rod worth. On the contrary, Keepin, Tuttle and JEFF3 DN data allow the consistency between $\Delta\rho^{Er}_{Td}$ worth from doubling time measurement and $\Delta\rho^{Er}_{Ref}$.

Table VII. UO_2-Er_2O_3 reactivity worth at the center of MISTRAL1-MIRTE core

		Reactivity deduced from T_d measurement			
		Keepin	Tuttle	JEFF3.1.1	B-VII.0
Core with central UO_2	T_d = 15.5±0.2 s	196.0	198.4	204.4	172.4
Core with UO_2-Er_2O_3	T_d = 40.0±0.3 s	107.9	109.1	112.6	93.3
UO_2-Er_2O_3 Worth ($\Delta\rho^{Er}$ in pcm)	$\Delta\rho^{Er}_{Ref}$=-91.3±2.2	-88.1	-89.3	-91.8	-79.1
$(\Delta\rho^{Er}_{Td}-\Delta\rho^{Er}_{Ref})/\Delta\rho^{Er}_{Ref}$	-	-3.5±2.9%*	-2.2±2.9%	+0.5±2.9%	-13.4±2.9%

* Total uncertainty combining the uncertainty on $\Delta\rho^{Er}_{Ref}$ and the uncertainty on $\Delta\rho^{Er}_{Td}$ due to T_d measurement

8. SUMMARY OF WORTH RESULTS AND DN DATA RECOMMENDATION

The synthesis of the analysis of independent worth measurements in several EOLE experiments is presented in Table VIII. Consistent trends are obtained for these various worth types (from 90 pcm of additive peripheral UO_2 rods up to 227 pcm for AIC and Hf absorber rod). Table VIII points out that Tuttle and Keepin DN data are satisfactory. Using ENDF/B-VII.0 DN data leads to a strong under-prediction by 10% of UO_2 core reactivity : this poor kinetics relationship is linked to the large underestimation of the average delayed-neutron lifetime τ^{U235}. Using JEFF3.1.1 DN data leads to a reactivity over-prediction by +2.7% ± 1.1%.

Table VIII. Reactivity worth analysis using various DN data

Exp. / measured worth	Keepin	Tuttle	JEFF3.1.1	B-VII.0
CAMELEON / AIC	0.0 ± 1.9%	1.2 ± 1.9%	4.0 ± 1.9%	-9.1 ± 1.9%
CAMELEON / Hf	-1.4 ± 2.0%	-0.1 ± 2.0%	2.6 ± 2.0%	-10.3 ± 2.0%
CAMELEON/periph. UO_2	-2.5 ± 2.9%	-1.0 ± 2.9%	1.5 ± 2.9%	-8.2 ± 2.9%
CREOLE / Temperature	-1.1 ± 2.1%	0.2 ± 2.1%	2.9 ± 2.1%	-9.5 ± 2.1%
MIRTE / UO_2-Er_2O_3	-3.5 ± 2.9%	-2.2 ±2.9%	0.5 ± 2.9%	-13.4 ± 2.9%
Average bias ± 1σ	**-1.3 ± 1.1%***	**0.1 ± 1.1%**	**2.7 ± 1.1%**	**-9.9 ± 1.1%**

* Total uncertainty accounting for correlated technological uncertainties in CAMELEON measurements

The reactivity overestimation using JEFF3 DN data is probably due to too high yields ν_d^{U235} and particularly ν_d^{U238}. Recent and accurate β_{eff} measurement in the IPEN UO_2 core confirms this assumption. Therefore, we recommend to preserve the (α_i, λ_i) of the 8 time-groups used in JEFF3, and to introduce improved total yields : ν_d^{U235} = 0.0159 (in agreement with Parish [29]) and ν_d^{U238} = 0.044 (in agreement with Tuttle). These proposed DN data fit perfectly the reactivity measured in EOLE cores.

9. CONCLUSIONS

The validation work based on reactivity worth measurements in various EOLE experiments has enabled the bias calibration of the LWR core reactivity deduced from the flux variation. The kinetics relationship based on Tuttle or Keepin DN data is satisfactory. On the contrary, using B-VII.0 DN data leads to a strong under-prediction by -10% of UO_2 core reactivity, and JEFF3.1.1 DN data leads to a reactivity over-prediction by +2.7% ± 1.1% (1σ). Thus the best DN data, which fit perfectly the EOLE measured reactivities, are the (α_i, λ_i) of the 8 time-groups used in JEFF3, and the following total yields : ν_d^{U235} = 0.0159 and ν_d^{U238} = 0.044.

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