Study of neutron scattering in light water in the mistral experiments carried out in EOLE Reactor at CEA Cadarache

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STUDY OF NEUTRON SCATTERING IN LIGHT WATER IN THE MISTRAL EXPERIMENTS CARRIED OUT IN EOLE REACTOR AT CEA CADARACHE

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ABSTRACT

The interpretation of the reactivity temperature coefficient measured in the Mistral experiments was performed with the Monte Carlo code TRIPOLI4 from 10°C to 80°C. The nuclear data library JEFF-3.1.1 was used in the calculations. Three different thermal scattering laws of hydrogen in light water were tested in order to evaluate the impact in the Mistral calculations: the thermal scattering laws present in the nuclear data libraries JEFF-3.1.1 and ENDF/B-VII.1, and CAB model. A different approach for creating thermal scattering files, as molecular dynamics simulations (CAB model) was assessed.

Key Words: **light water, thermal scattering law, reactivity temperature coefficient, Mistral.**

1. INTRODUCTION

The Mistral experimental program [1], carried out in EOLE reactor at CEA Cadarache (France), was developed to test the feasibility of charging 100% MOX fuel in nuclear power plants. Among many neutronic parameters, it was measured the reactivity temperature coefficient (RTC) for the configurations Mistral-1 (UOX lattice), Mistral-2 and Mistral-3 (MOX lattices) between 10°C and 80°C.The interpretation of this parameter was performed with the Monte Carlo code TRIPOLI4 [2]. The nuclear data from JEFF-3.1.1 library [3] was used in the calculations.

Three thermal scattering laws (TSL) of hydrogen in light water were tested in order to evaluate the impact: JEFF-3.1.1, ENDF/B-VII.1 [4] and CAB model [5]. The first and second sets derive from the IKE model developed by M. Mattes and J. Keinert [6], based on experimental measures of the frequency spectrum of hydrogen in light water. The third one, obtained by I. Marquez Damian from Centro Atomico Bariloche (CAB), Argentina, is based on molecular dynamic simulations [5].

As CAB model shows a better description of the light water total cross section in the cold neutron energy range, the analysis of the performance of a thermal scattering law computed from molecular dynamics simulation is justified. Readers may refer to the appropriate references to extend the knowledge of both used models.

To calculate the difference in the reactivity temperature coefficient from 10°C to 80°C, evaluated files of hydrogen in light water were obtained for each temperature step and incorporated in the library JEFF-3.1.1. To accomplish this, it was done an interpolation of the IKE model parameters as well as the frequency spectrum of hydrogen in light water (JEFF-3.1.1 and ENDF/B-VII.1 thermal scattering laws). For the case of CAB model, the frequency spectrum was obtained for each temperature step. In all cases, the LEAPR module of the processing tool NJOY [7] was used to calculate the TSL.

2. DESCRIPTION OF THE MISTRAL PROGRAM

The MISTRAL (MOX Investigation of Systems which are technically Relevant of Advanced Light water reactors) experimental program was developed in the late nineties to evaluate the feasibility of charging 100% MOX fuel in light water reactors (LWR). It was carried out in EOLE experimental facility at CEA Cadarache (France). Three different configurations were tested (Mistral-1, Mistral-2, Mistral-3), modifying fuel type (UOX or MOX), number of fuel pins and moderation ratio.

2.1. Mistral-1 Experiment

The Mistral-1 core is a homogenous UO2 configuration that serves as reference set for the rest of the MOX experiments. The cylindrical core consists in a regular lattice using 750 standard PWR fuel pins (enriched UO2, 3.7% w/o U235) in a square pitch of 1.32 cm (figure 1). The moderation ratio is 1.7 (slightly over moderated) and there are 16 clusters dedicated for safety rods.

To compensate the reactivity loss due to temperature increase, soluble boron concentration was adjusted in the moderator.

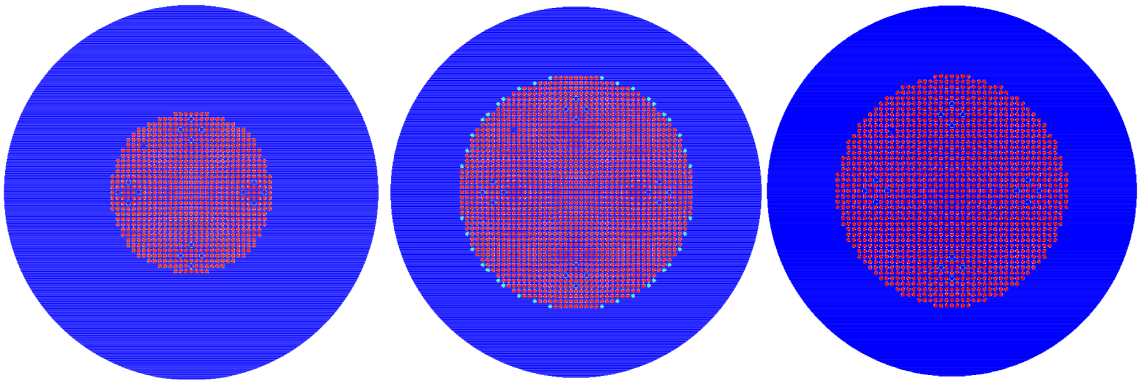


Figure 1. Radial cross sections of the Mistral-1 core, on the left figure, Mistral-2 in the middle (20°C configuration) and Mistral-3 on the right.

2.2. Mistral-2 Experiment

The Mistral-2 core is a homogenous MOX configuration with 1572 MOX fuel pins with a fuel enrichment of 7% Am-PuO2, same number of guide tubes, pitch and moderation ratio as Mistral-1

(figure 1).

MOX pins with enrichment of 8.7% were strategically added, in number and location, at the periphery of the core so as to compensate the reactivity loss with temperature.

2.3. Mistral-3 Experiment

The Mistral-3 core is a homogenous MOX configuration with 1388 MOX fuel pins with a fuel enrichment of 7% Am-PuO2 (figure 1). As Mistral-1 and Mistral-2, the number of guide tubes for absorbers is 16 and 1 pilot rod. The difference between Mistral-2 resides in the moderation ratio: 2.1 with a square pitch of 1.39 cm.

The soluble boron is used to compensate the temperature effect on the core reactivity and to adjust criticality.

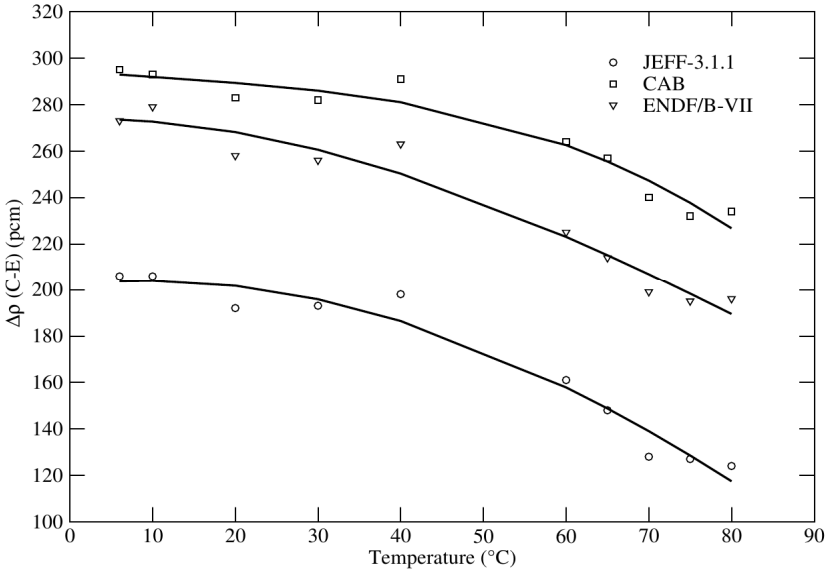
3. RESULTS

3.1. RTC Results for Mistral-1 Experiment

It was calculated the discrepancy between the calculated and measured reactivity $\Delta\rho$ from 5°C to 80°C, and for the three thermal scattering laws. A third order polynomial fitting was done in each case [8] (figure 2).

The TSL of CAB model and ENDF/B-VII overestimate in all temperature range the calculated reactivity of the reference library JEFF-3.1.1. The average difference value between CAB and JEFF-3.1.1 is +100 pcm, and for ENDF/B-VII is +65 pcm.

The difference in the Reactivity Temperature Coefficient $\Delta\alpha$ was obtained derivating the reactivity difference with respect to temperature [8] (table 1). The corresponding expressions are plotted in figure 2.



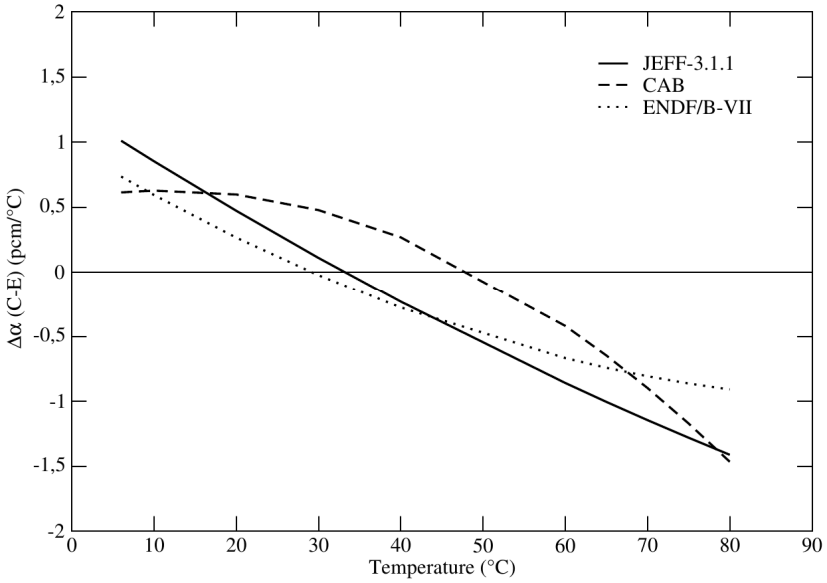


Figure 2. In the upper figure, it is third order polynomial fitting of the difference in reactivity C-E for JEFF-3.1.1, ENDF/B-VII and CAB TSL. In the lower figure, the difference in reactivity temperature coefficient as a function of temperature for the same TSL files, for Mistral-1.

Table 1. Coefficients of the second order polynomial equation for the difference in the RTC of the three thermal scattering laws for Mistral-1.

Parameter	$\Delta\alpha = AT^2 + BT + C$ [pcm/°C]		
	JEFF-3.1.1	CAB	ENDF/B-VII
A	-0.000402	-0.000753	-0.000234
B	0.00852	0.04168	0.00444
C	-0.6388	-0.9710	-0.8141

3.2. RTC Results for Mistral-2 Experiment

For a temperature range of 10°C to 80°C, the difference in reactivity Δρ was calculated for the three thermal scattering laws. Like Mistral-1, a third order polynomial fitting was done (figure 3).

It is seen an overestimation of the thermal scattering files CAB and ENDF/B-VII.1 at all temperature range, compared with the reference JEFF-3.1.1 library. The difference with CAB model is more accentuated for MOX lattices. The average difference is +180 pcm. For ENDF/B-VII.1, the average difference in reactivity is +80 pcm.

The difference in Reactivity Temperature Coefficient Δα was obtained derivating the reactivity difference with respect to temperature (table 2). The corresponding expressions are plotted in figure 3.

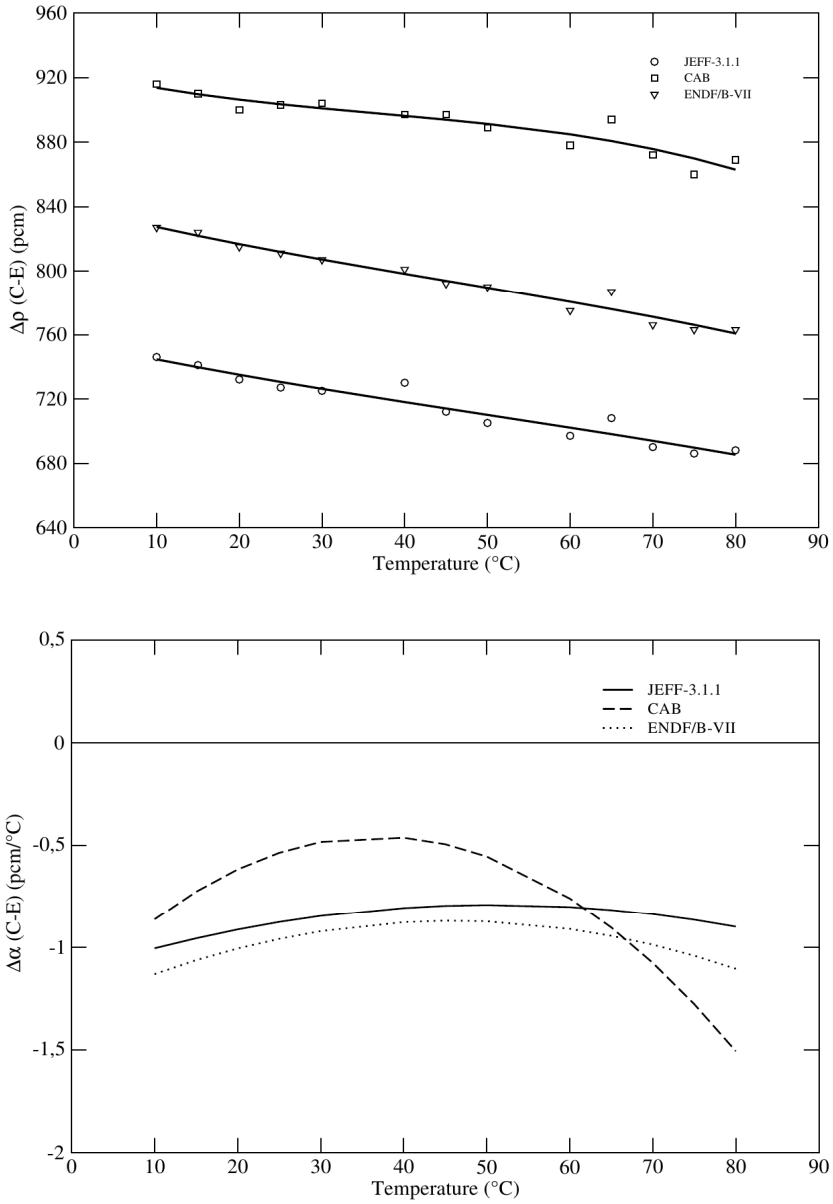


Figure 3. In the upper figure, it is third order polynomial fitting of the difference in reactivity C-E for JEFF-3.1.1, ENDF/B-VII and CAB TSL. In the lower figure, the difference in reactivity temperature coefficient as a function of temperature for the same TSL files, for Mistral-2.

Table 2. Coefficients of the second order polynomial equation for the difference in the RTC of the three thermal scattering laws for Mistral-2.

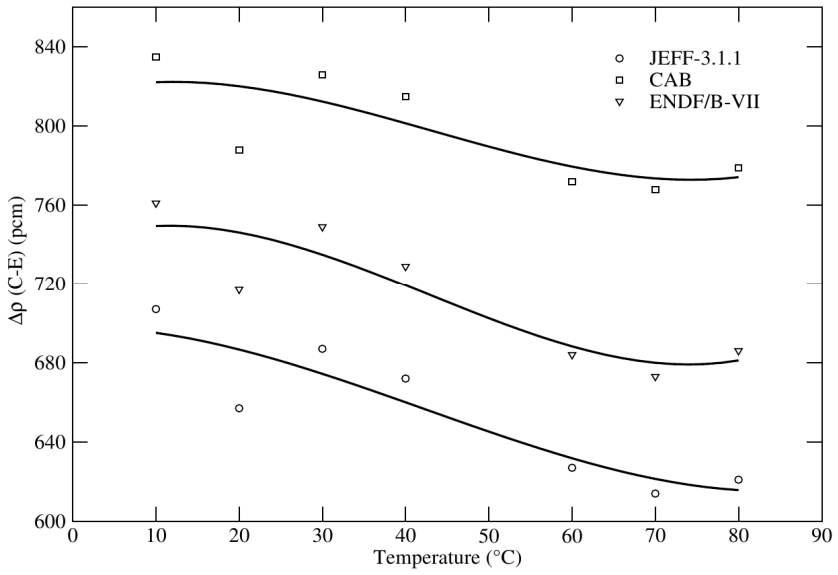
Parameter	$\Delta\alpha = AT^2 + BT + C$ [pcm/°C]		
	JEFF-3.1.1	CAB	ENDF/B-VII
A	-0.000129	-0.000564	-0.000201
B	0.01304	0.0415	0.01854
C	-1.1222	-1.2215	-1.2959

3.3. RTC Results for Mistral-3 Experiment

It was calculated the difference between the calculated and measured reactivity Δρ from 10°C to 80°C, and for the three thermal scattering laws. Like Mistral-1 and M, a third order polynomial fitting was done (figure 4).

Same trend as Mistral-2 is identified for Mistral-3 configuration. The mean difference between CAB and JEFF-3.1.1 is +140 pcm. For ENDF/B-VII.1, is +60 pcm.

The difference in the Reactivity Temperature Coefficient Δα was obtained derivating the reactivity difference with respect to temperature (table 3). The corresponding expressions are plotted in figure 4.



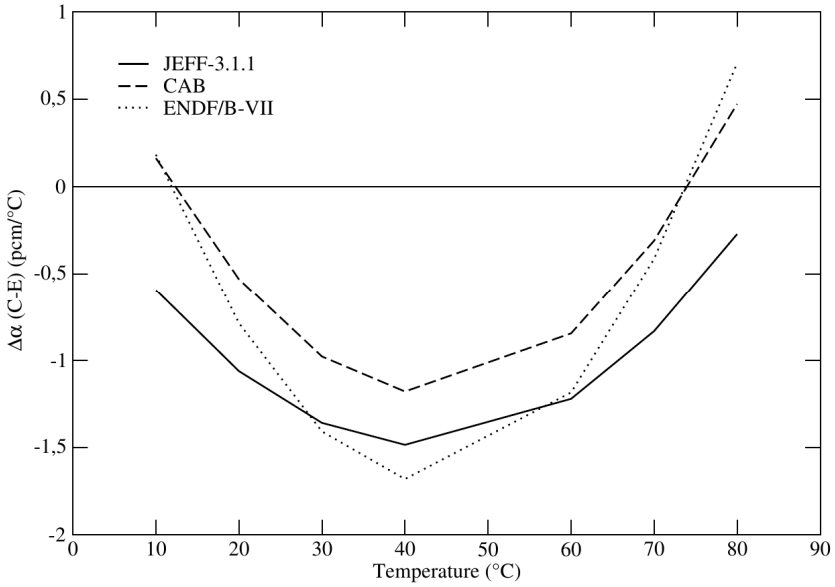


Figure 4. In the upper figure, it is third order polynomial fitting of the difference in reactivity C-E for JEFF-3.1.1, ENDF/B-VII and CAB TSL. In the lower figure, the difference in reactivity temperature coefficient as a function of temperature for the same TSL files, for Mistral-3.

Table 3. Coefficients of the second order polynomial equation for the difference in the RTC of the three thermal scattering laws for Mistral-3.

Parameter	$\Delta\alpha = AT^2 + BT + C$ [pcm/°C]		
	JEFF-3.1.1	CAB	ENDF/B-VII
A	0.000597	0.000921	0.001443
B	-0.05158	-0.0814	-0.12478
C	-0.0659	0.9354	1.3194

5. CONCLUSIONS

It was done the interpretation of the Reactivity Temperature Coefficient of Mistral experiment with the Monte Carlo code TRIPOLI4, using three different thermal scattering laws of hydrogen in light water.

For all tested TSL, similar trends on the RTC were achieved. A different approach for creating thermal scattering law files, like molecular dynamic simulations (CAB model) was assessed.

The main results of the average difference in the RTC in the whole temperature range, for all configurations and the three thermal scattering laws, are shown in table 4.

Table 4. Mean values of the difference in the Reactivity Temperature Coefficient (pcm/°C) between 10°C and 80°C.

TSL H(H2O)	**Mistral - 1**	**Mistral - 2**	**Mistral - 3**
Uncertainty	*±0.3*	*±0.3*	*±0.4*
JEFF - 3.1.1	-0.3	-0.8	-1.1
CAB	+0.0	-0.7	-0.7
ENDF/B-VII.1	-0.3	-1.0	-1.0
AP2.8 + JEFF - 3.1.1 [4]	+0.4	-0.9	-1.0

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