ANALYSIS OF THE CREOLE EXPERIMENT ON THE REACTIVITY TEMPERATURE COEFFICIENT USING THE APOLLO2 CODE AND THE JEF2.2 NUCLEAR DATA FILE

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ABSTRACT

In the framework of the validation of the French APOLLO2 code, we have analysed the CREOLE experiment on the LWR reactivity temperature coefficient (RTC). In this experiment performed in the EOLE critical facility located at CEA-Cadarache, the RTC has been measured in UO_2 and UO_2-PuO_2 PWR type lattices. Both clean and Boron poisoned water moderated lattices were investigated for the temperature range starting from room temperature up to PWR power plant operating conditions (300C). In addition to the measurements of the global reactivity temperature coefficient, the water expansion effects were also estimated using Aluminium over-cladding tubes to remove moderator. The measurements were carried out in a PWR fuel type zone contained in a pressurised cylindrical loop located in the centre of the zero power reactor EOLE. In this work we have used the APOLLO2 code to analyse selected experimental configurations from the CREOLE experimental programme. In addition to the standard CEA-93 cross sections library based on JEF2.2 nuclear data file, the U-235 cross sections from the new JEFF3 evaluation have also been used in our analysis.

1. INTRODUCTION

The analysis of several experimental benchmarks on the reactivity temperature coefficient including the CREOLE experiment [1] and the start up experiments in French PWRs using the APOLLO1 code with the early CEA-1979 cross section library [2] (mainly based on ENDF/B4 and UKNDL data) had shown a large discrepancy between calculation and measurements. The calculation overestimated the absolute value of the reactivity temperature coefficient by about:

(5 ± 2) pcm/C (1 pcm $= 10^{-5}$ in $\Delta k/k$) for the clean (without boron) PWR type UO_2 lattices from room temperature up to 90C.
(3 ± 2) pcm/C for the operating conditions of a large PWR power reactor (temperature around 300C)

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Similar results were reported by different authors from other European countries where similar data libraries were used, especially from U. K. and Sweden [3] and [4]. It is important to point out that among the large number of available experimental benchmarks on the reactivity temperature coefficient, only the CREOLE experiment is representative of the operating conditions of a large PWR power plant.

Our analysis showed that most of this error can be linked to the shift of the thermal spectrum with temperature [5]. Therefore, it was suggested to change the thermal shape of Eta ($\nu\sigma_f / \sigma_a$) for U-235 below 0.1 eV. Experiments performed later on, in the European Linear Accelerator at Geel [6] and in the ILL high flux reactor at Grenoble [7] confirmed this proposal which is presently widely accepted and already introduced in the main basic nuclear data files especially JEF2.2 and ENDF/B6 (starting from release 2).

Since 1987, the version 2 of the transport lattice code APOLLO has been developed in France [8], with enhanced capabilities compared to the earlier version APOLLO1 used in our original work. The main advantages of the APOLLO2 code are : accurate space dependent resonance self shielding by the use of the Background Matrix model, cross sections collapsing and homogenisation are performed with the SPH equivalence method in order to preserve reaction rates, P_{ij} and S_n methods capabilities (classical finite differences and nodal numerical schemes) and the use of the Xmas 172 group structure. In addition to the modelling enhancement, the APOLLO2 uses the CEA-93 cross sections library based on the European JEF2.2 nuclear data file, containing the most recent and reliable evaluations available. It is important to mention that the current APOLLO2 library does not have any cross section adjustments, contrarily to the previous libraries used in our previous work with APOLLO1 code (CEA-1979 and CEA-1986).

With the high level of accuracy reached by modern codes it is now possible to minimise the discrepancies between experiment and calculation due to the theoretical modelling and consequently to highlight the errors related to nuclear data. It is then considered that the target accuracy for the reactivity temperature coefficient should not exceed 1 pcm/C for a water moderated lattice, including both UO2 and MOX fuels.

The objective of the present work is to perform the analysis of the CREOLE experiment using the APOLLO2 code with the CEA-93 cross sections library in order to assess the reactivity temperature coefficient calculation by APOLLO2. The impact on the RTC calculation, using the U-235 cross sections from the new JEFF3 evaluation [9], will also be evaluated.

2. THE CREOLE EXPERIMENT

The CREOLE experimental program was conceived to supply accurate RTC differential information in the whole temperature range of interest in a large PWR (from room temperature up to 300C).

The measurements were performed in the EOLE facility at CEA-Cadarache during the two last years of the seventies. Among the large number of experiments carried out in the framework of the CREOLE programme, the following will be considered in the present work :

- continuous differential measurements of the RTC in UO2 and UO2-PuO2 typical PWR clean lattices from room temperature up to 300C.
- measurements of the contribution of water expansion effects on the RTC by the use of Aluminium over cladding tubes.
- measurements of fission rates distributions for different temperatures.

The measurements were carried out in a PWR fuel type zone contained in a pressurised cylindrical loop located in the centre of the zero power reactor EOLE.

2.1 DESCRIPTION OF THE CREOLE FACILITY

The CREOLE experimental facility consists of a pressurised central test loop in which it is possible to achieve operating conditions of a large PWR power reactor in terms of pressure and moderator temperature, a large air gap separation zone and a peripheral driver core surrounded by a water reflector. Starting from the centre, the experimental loop contains the following concentric zones (see Fig. 1):

– a central tube made of Zircaloy (9.8 mm i.d. ; 1mm thickness), intended for axial distribution of fission rates measurements by fission chambers.

– a PWR type assembly of 200 UO2 or UO2-PuO2 fuel pins with Zircaloy cladding. The fuel rods were arranged in a 1.26 cm square lattice pitch. The main characteristics of the fuel rods are summarised below :

- pellet diameter : 8 mm
- o. d. of cladding : 9.4 mm
- Uranium enrichment : 3.1% for UO2 fuel rods and natural Uranium for UO2-PuO2 fuel rods.
- Plutonium characteristics : 80 fuel rods with 3.2% of fissile Pu
  120 fuel rods with 2% of fissile Pu

– a Zirconium alloy filler to prevent water gaps next to the peripheral cells of the studied lattices in the central loop.

– an annular tube made of Zirconium alloy, designed in such a way that it can withstand the maximum pressure conditions in the experimental zone (120 bar).

The driver core was loaded with UO2 (3.5% enrichment) fuel pins with Aluminium cladding. The fuel rods were arranged in a 1.43 cm square lattice pitch. The criticality was obtained by raising the moderator (light water) level in the reactor tank. For safety reasons the driver core was isolated from the experimental loop by a tank made of Aluminium alloy and a large air gap zone which contains a stainless-steel heat reflector intended to prevent the heat leakage from the central loop to the

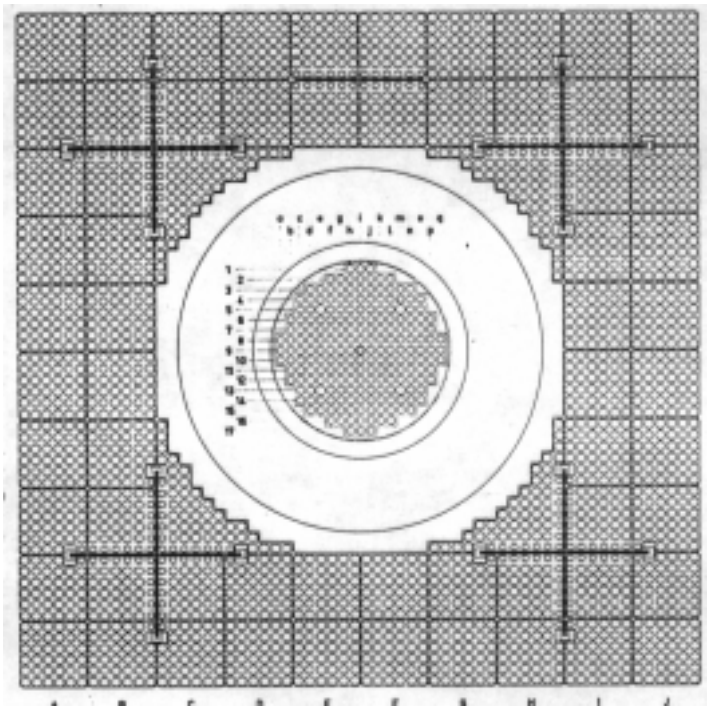

Figure 1. Radial cross section of the core in the CREOLE facility

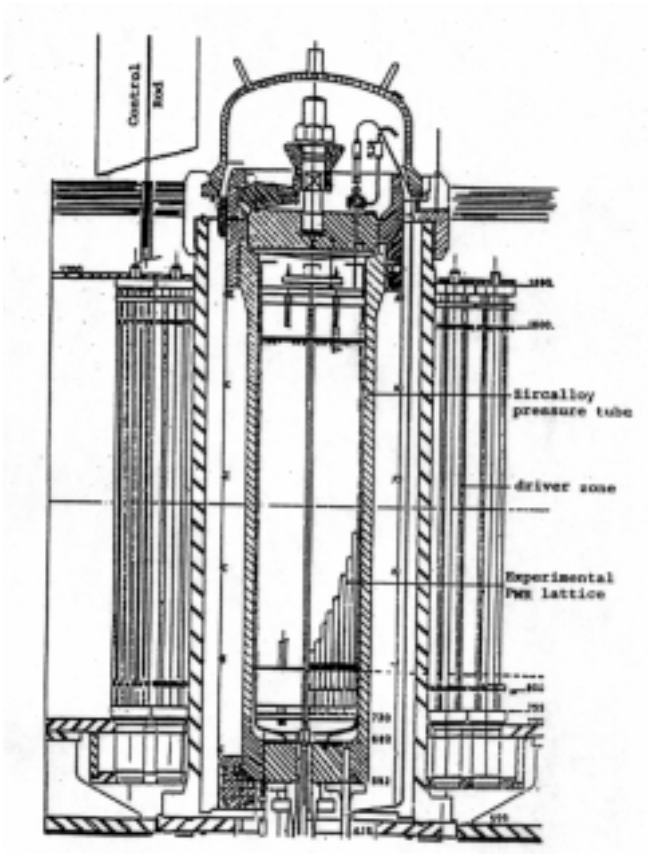

Figure 2. Longitudinal cross section of the CREOLE core

driver core. The driver core sizes were adjustable according to the investigated lattice type and the operating conditions in the central loop.

The driver core was surrounded by a radial reflector made of water. Except for the control rods driving system which was located above the reactor core, all other auxiliary systems intended either for operating the reactor or for safety purposes were located under the reactor tank. Fig. 2 shows a longitudinal section of the CREOLE experiment.

2.2 MEASUREMENTS TECHNIQUES AND EXPERIMENTAL RESULTS

A. Reactivity and temperature measurements :

Starting from a core with a reactivity excess of about 300 pcm, the moderator temperature in the experimental loop was raised using an electrical heater placed in a water storage tank located below the reactor tank. The resultant reactivity change was measured by the usual doubling time method.

The temperature was measured with a platinum resistor thermometer located in the top, just under the cover, of the experimental loop. The temperature homogeneity has been proved experimentally using the indications given by 7 thermocouples located in different spot levels inside the experimental loop. The relative uncertainty in the measured temperatures was estimated at 0.2 C.

In the studied configurations, the reactivity loss due to the temperature change from 20 C to 300 C was much greater than the core reactivity excess (300 pcm). It was then necessary to perform the reactivity measurements for these configurations in four temperature ranges, with their corresponding driver core loading :

- 1^{t} range : 20 C - 120 C
- 2^{d} range : 110 C - 200 C
- 3^{d} range : 190 C - 250 C
- 4^{th} range : 245 C - 300 C

To pass from one to the next range it was necessary to increase the driver core loading in order to restore a core reactivity excess of about 300 pcm. The reactivity measurements were carried out by steps of $\Delta T = 5$ C in each temperature range.

B. Fission rate distribution measurements :

The main purpose of these measurements is to achieve the validation of the 3D reactor core calculation. Several measurements of radial power distribution have been carried out in both experimental loop and driver core. For the experimental loop the measurements have been performed at room temperature and at 300 C. Various techniques were used in carrying out these measurements, including gamma spectrometry on the fuel rods, fission chambers and activation foils. Axial fission rate profile was obtained in the central thimble using miniature fission chambers.

2.3 EXPERIMENTAL DATA PROCESSING

In order to reduce the experimental fluctuations of the measured core reactivity, a least-squares polynomial fitting of the core reactivity, versus moderator temperature, was applied in each temperature range. By using the analytical representation of the core reactivity in each region, it was possible to join the four sets of experimental results and to obtain a single continuous set of reactivity variation with temperature in the overall range from 20C up to 300C. We then applied a polynomial fitting to the connected values in order to condense the experimental results in a practical form and to enhance their accuracy. To take into account precisely the experimental variation of the core reactivity and the RTC with the temperature, a fourth degree polynomial fit should be used for the core reactivity. A typical example of the core reactivity is shown in Fig. 3 for the UO2 clean lattice. The differentiation of this core reactivity fit supplies the measured core differential reactivity temperature coefficient ; these analytical forms of the measured RTC for UO_2 and UO_2-PuO_2 clean lattices are presented in table 1.

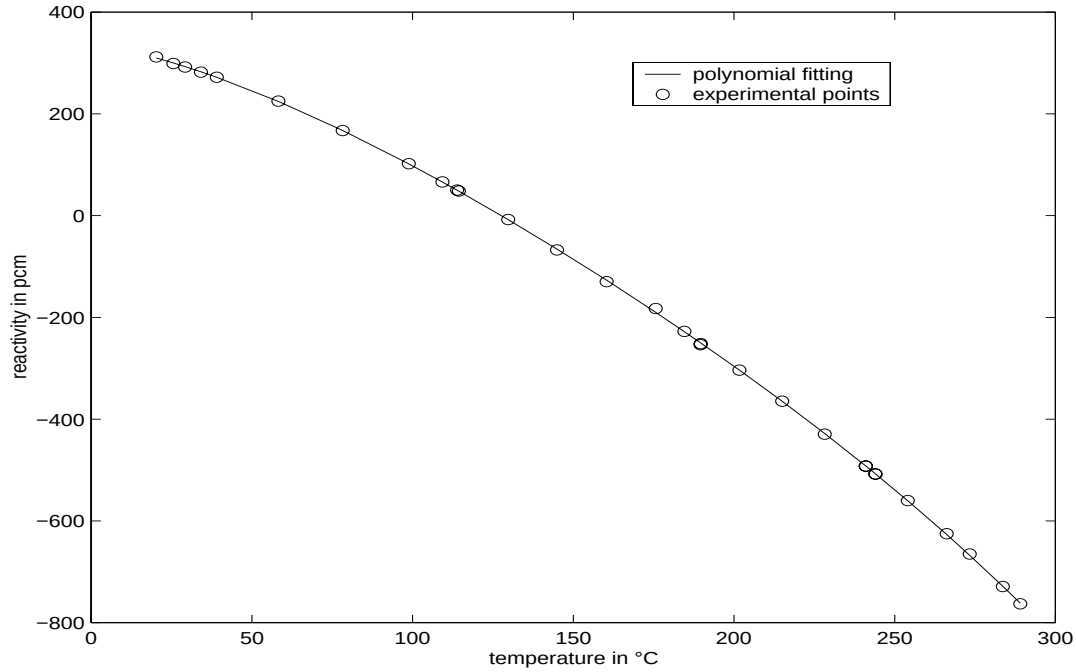

Figure 3. The 4th degree polynomial fitting for the core reactivity in the UO_2 lattice

Table I : Analytical forms of the measured core reactivity temperature coefficient

	$RTC_{core} = \frac{d\rho_{core}}{dT}$ (in pcm/°C) fot $20°C \le T \le 300°C$
UO_2 lattice	$-3.385\times10^{-7}\cdot T^3 + 1.577\times10^{-4}\cdot T^2 - 3.493\times10^{-2}\cdot T - 1.108$
UO_2-PuO_2 lattice	$-3.448\times10^{-7}\cdot T^3 + 1.549\times10^{-4}\cdot T^2 - 3.174\times10^{-2}\cdot T - 0.429$

In Figure 4 we present the variation of the measured core RTC with the temperature for the UO_2 clean lattice configuration. As seen from the figure, the core RTC for the UO_2 clean lattice is negative for the whole temperature range and it increases almost linearly with the temperature. A similar shape was also obtained for the UO_2-PuO_2 lattice.

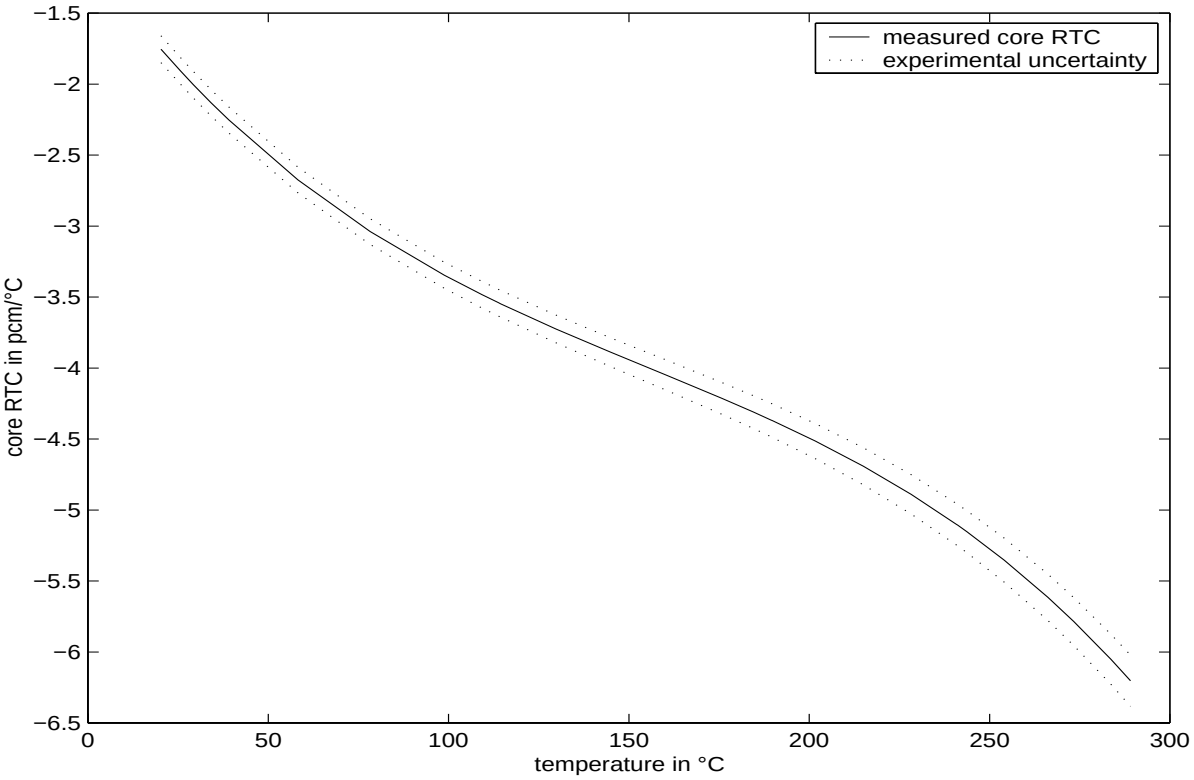

Figure 4. The experimental core RTC as a function of the loop temperature in the UO_2 clean lattice

The experimental uncertainties (1σ) shown in Fig. 4, were estimated from the fitting errors and the uncertainty associated with β_{eff} of the core for which a relative error of 2% was adopted.

3. APOLLO2 CORE CALCULATIONS

3.1 CALCULATION PROCEDURES AND MODELLING :

In order to analyse the CREOLE experiment, it is necessary to compute the core reactivity as a function of the temperature of the experimental loop. The specific characteristics of the CREOLE experiment (high level of leakage, axial void streaming effect due to the presence of a large air gap inside the core and the presence of two multiplying zones with different temperatures), require the use of transport theory in the core calculations. The outstanding capabilities of the APOLLO2 code allow us to perform the whole analysis of the experimental set up, including the basic cell and multicell calculations for fuel and non fuel regions and the whole core calculation.

To account precisely for the high level of the core leakage, the actual 3D geometry of the core should be used and this was achieved by using the RZ geometry of the APOLLO2 S_N module. In order to prepare the group constants for the S_N calculations, the space homogenisation and cross sections collapsing were performed using the most accurate current interface formalism of the APOLLO2 code (P1 anisotropic angular flux) in the P_{ij} cell or multicell calculations. We should also mention that the thermal expansion effects in the fuel pellet, the cladding material and lattice pitch, were accounted for in our calculations at both multicell level and core level.

To minimise the biases associated with the core S_N calculation, an extensive study was carried out to optimise the core modelling and the conclusions are summarised below :

- S_8 quadrature was selected for the S_N approximation : comparison of S4, S8 and S16 calculations has shown that the error on the RTC associated with S4 approximation is 0.2 pcm/C in comparison with the reference S16 calculation, whereas this error is only 0.03 pcm/C for the S8 calculation.

- 20 energy groups for the multigroup approximation : It has been proved by different preliminary tests that 20 groups (12 fast and 8 thermal) is adequate for the modelling of the CREOLE core.

- P1 anisotropic scattering was used : Comparison to a reference S8/P3 core calculation pointed out an error of 0.01 pcm/C on the averaged RTC (20C - 300C temperature range).

- refined spatial mesh in both radial and axial directions : the preliminary tests allowed us to optimise the spatial mesh ($\cong$ 0.5 cm in the asymptotic spectrum regions of the core).

3.2 EXPERIMENTAL VALIDATION OF THE CORE CALCULATION MODEL :

The core calculation model developed to analyse the CREOLE experiment was validated through 3D fission rate measurements and critical loading prediction.
Concerning the fission rate distributions, it should be noted that the cylindrical model of the core used in our calculations is not suitable to reproduce accurately the radial fission rates associated with individual fuel rods. Typical examples of the experimental-calculation comparisons of the radial power maps are presented in Figs. 5 and 6. As it can be seen from these figures, our calculation model reproduces the experimental shapes except near the boundaries where the effects of cylindrisation are important. The relatively good agreement between calculation and the measured radial fission rate distribution in the experimental loop as well as in the driver core means that the mutual interaction between neutron spectra from the two multiplying regions of the core was accounted for correctly by calculation. The agreement between calculation and the measured axial distribution of the fission rates presented in Fig. 7, demonstrate the ability of our calculation model to handle accurately the axial leakage in the experimental loop.

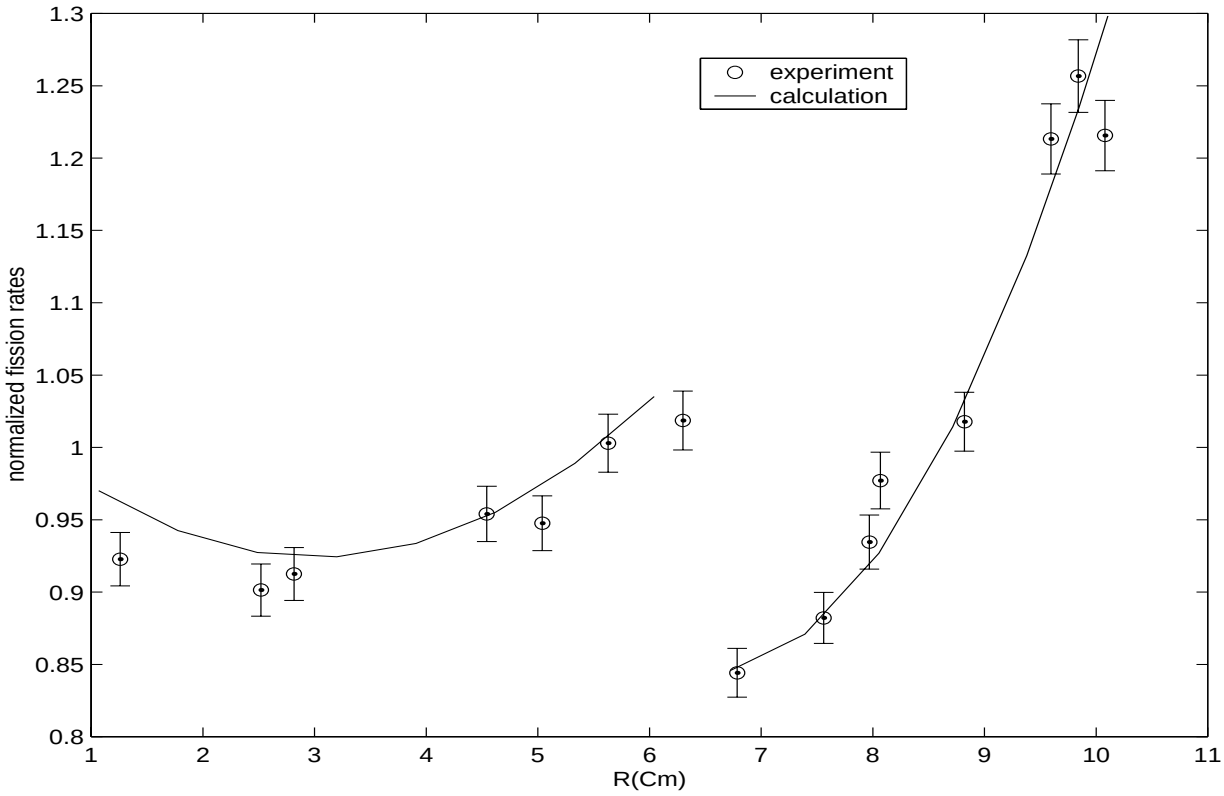

Figure 5. Radial fission rates distributions in the experimental loop
UO_2-PuO_2 clean lattice configuration T = 300 C

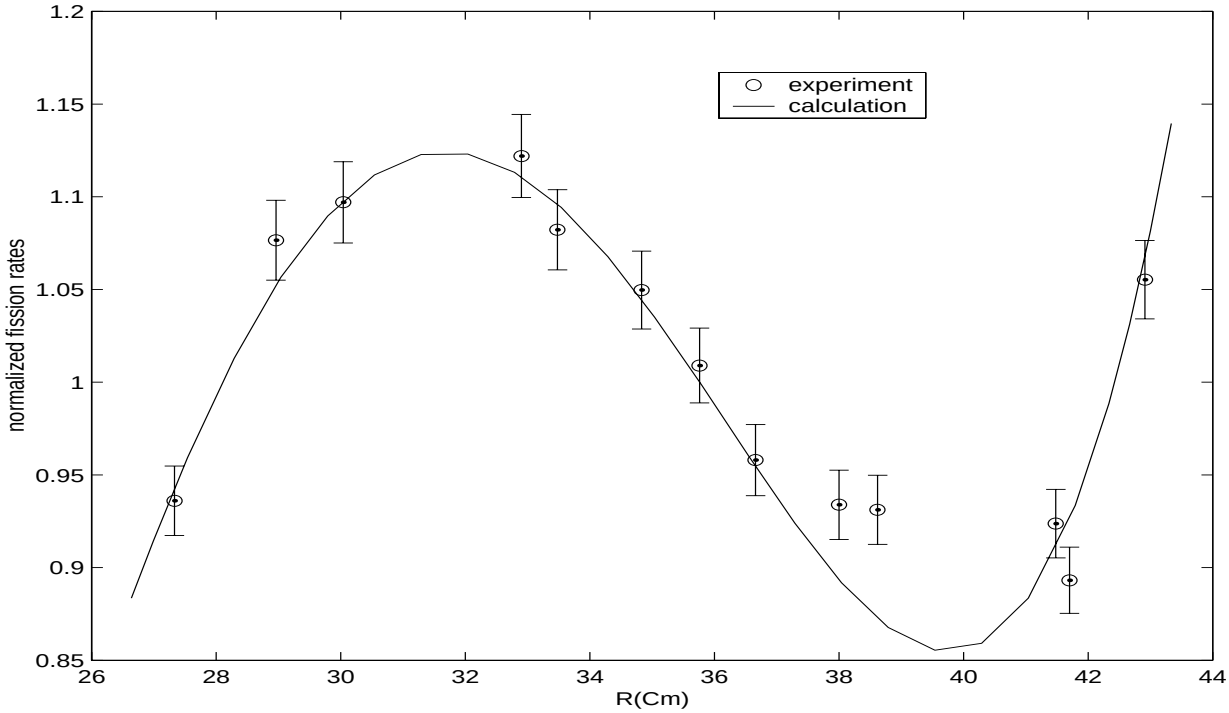

Figure 6. Radial fission rates distributions in the driver core

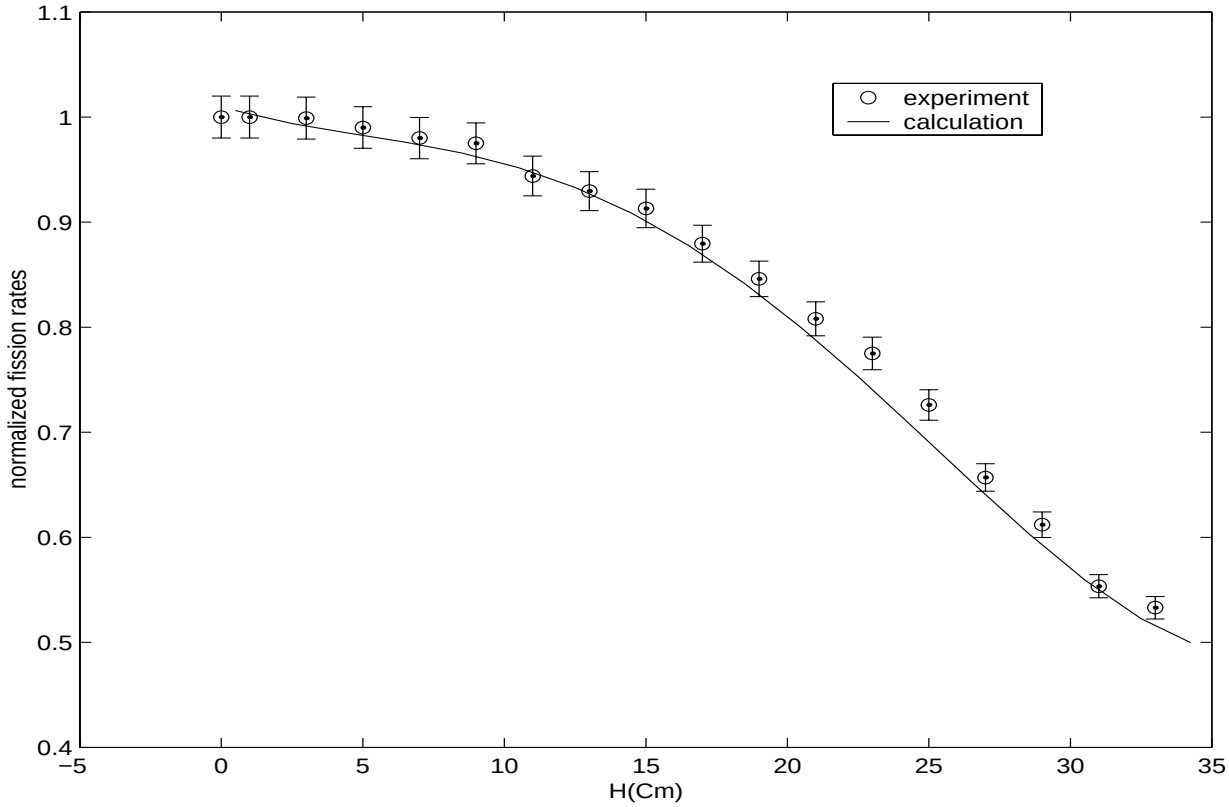

Figure 7. Axial fission distribution in the experimental loop
UO_2 clean lattice configuration T = 20 C

For the core reactivity effects, our calculation model over-predicts the core k_{eff} in room temperature with :

+500 pcm for the UO_2 clean lattice
+400 pcm for the UO_2-PuO_2 clean lattice

These values are fully consistent with the usual trend observed when using the APOLLO2 code with the cross sections library CEA93. Different investigations and analysis have shown that this trend to overestimate the LWR reactivity in cold conditions is linked to the epithermal capture of U-235, which is underestimated by about 10% in JEF2.2 based cross sections libraries [9].

4. COMPARISON OF THE EXPERIMENTAL RESULTS WITH APOLLO2 CALCULATIONS

4.1 REACTIVITY TEMPERATURE COEFFICIENT ANALYSIS:

Calculations of the CREOLE core have been carried out at all the whole measured temperatures from 20C up to 300C in both UO_2 and UO_2-PuO_2 clean lattices configurations. A least-squares fitting, similar to that used with the measured core

reactivity, was applied to the calculation results. This procedure will assure a total consistency between the calculated and the measured values. The differential forms obtained for the measured and calculated core RTC in the two investigated lattices are shown in Figs. 8 and 9. As seen from these figures, the experimental temperature dependence of the core RTC is quite well reproduced by calculation. The discrepancies between the experimental results and calculation for the core RTC are presented in Figs. 10 and 11 for UO_2 and UO_2-PuO_2 lattices respectively. For the UO_2 clean lattice, the discrepancies are within the experimental uncertainties and consequently no significant error can be associated with calculation for the whole temperature range; whereas, for the UO_2-PuO_2 lattice there is a clear tendency to underestimate the absolute value of the core RTC for the temperature range beyond 250C.

Several physical effects contribute to the core RTC in a reactor system. The main contributions are the thermal spectrum shift effects and the water expansion effects. In the room temperature region (below 100C), there is a small contribution of the water expansion effects to the Temperature Coefficient and this contribution becomes predominant around 300C. The absence of a significant error on the RTC for low temperatures means that the thermal spectrum shift effect, which is mainly linked to the shape of the thermal cross sections of the heavy isotopes, is correctly accounted for. The positive and significant error observed in the high temperature region, especially for the UO_2-PuO_2 lattice is probably linked to the water expansion effects.

4.2 THE WATER EXPANSION EFFECTS ANALYSIS:

The water expansion effects measurements enables the uncoupling of the spectral shift component of the error from the water density component. The lattice parameters which are the most sensitive to the water expansion effects are the resonance escape factor, the thermal utilisation factor and the migration area. In order to evaluate the contribution of the water expansion effects to the total temperature coefficient, measurements were performed in the CREOLE experiment using Aluminium over-cladding tubes to remove moderator and simulate the water density change. The simulated value of the water density was 0.6 g/cm^3 for both UO_2 and UO_2-PuO_2 lattices.

The core reactivity loss associated with the introduction of these Aluminium over-cladding in the experimental loop was compensated by increasing the driver core loading. The analysis of these experiments with our core calculation model based on APOLLO2 code and CEA93 library leads to the results presented in Table II.

The temperature dependence of the calculation error associated with the water expansion effects can be deduced from the integral error and the shape of the function $(d\rho_{H2O}/dT)$ with the temperature. The obtained results for the two investigated lattices are presented in Fig. 12. From this figure it can be concluded that the positive error on the RTC observed in the high temperature range for the UO_2-PuO_2 lattice is mainly linked to the water expansion effects.

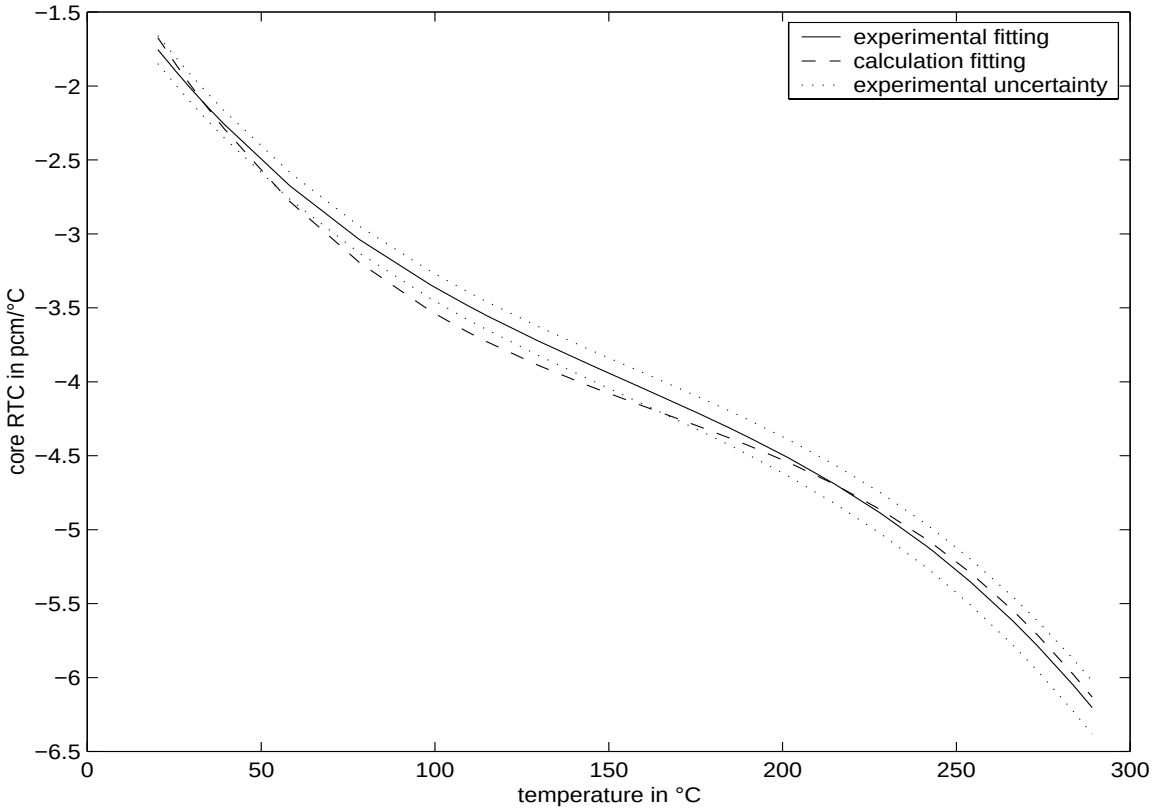

Figure 8. Comparison of the measured and calculated differential core RTC UO_2 clean lattice configuration

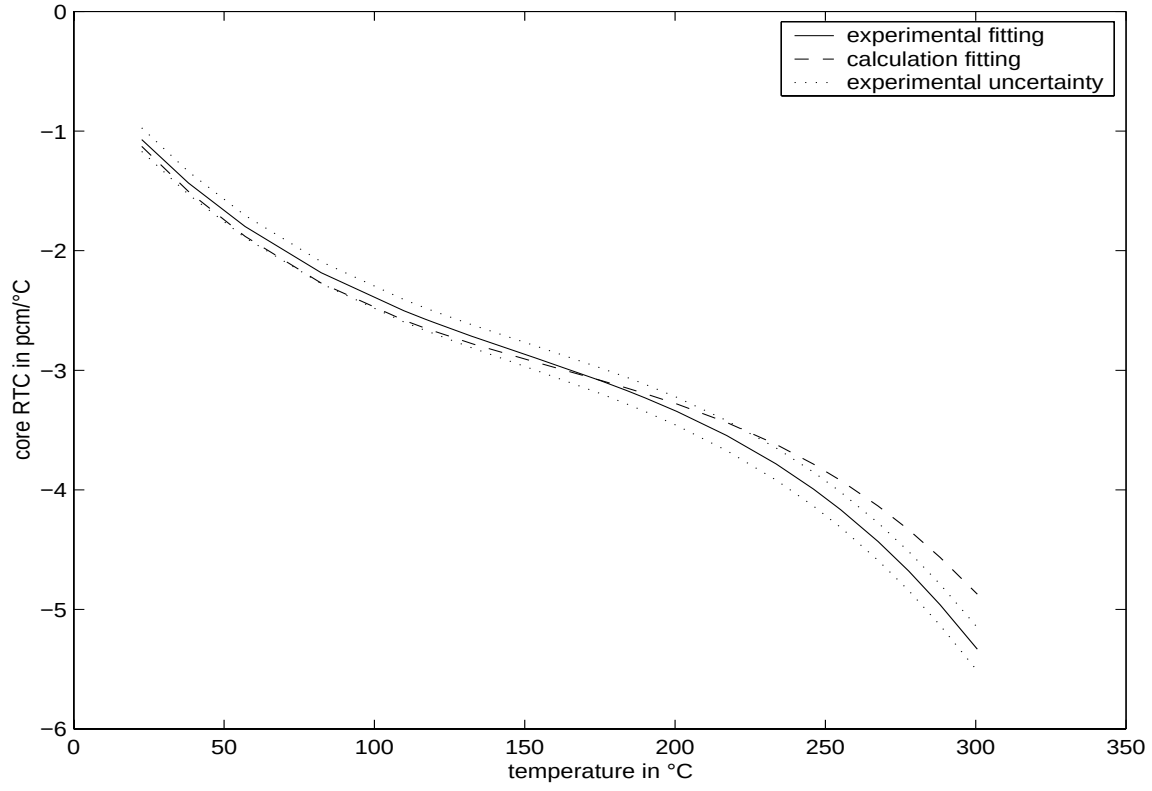

Figure 9. Comparison of the measured and calculated differential core RTC UO_2-PuO_2 clean lattice configuration

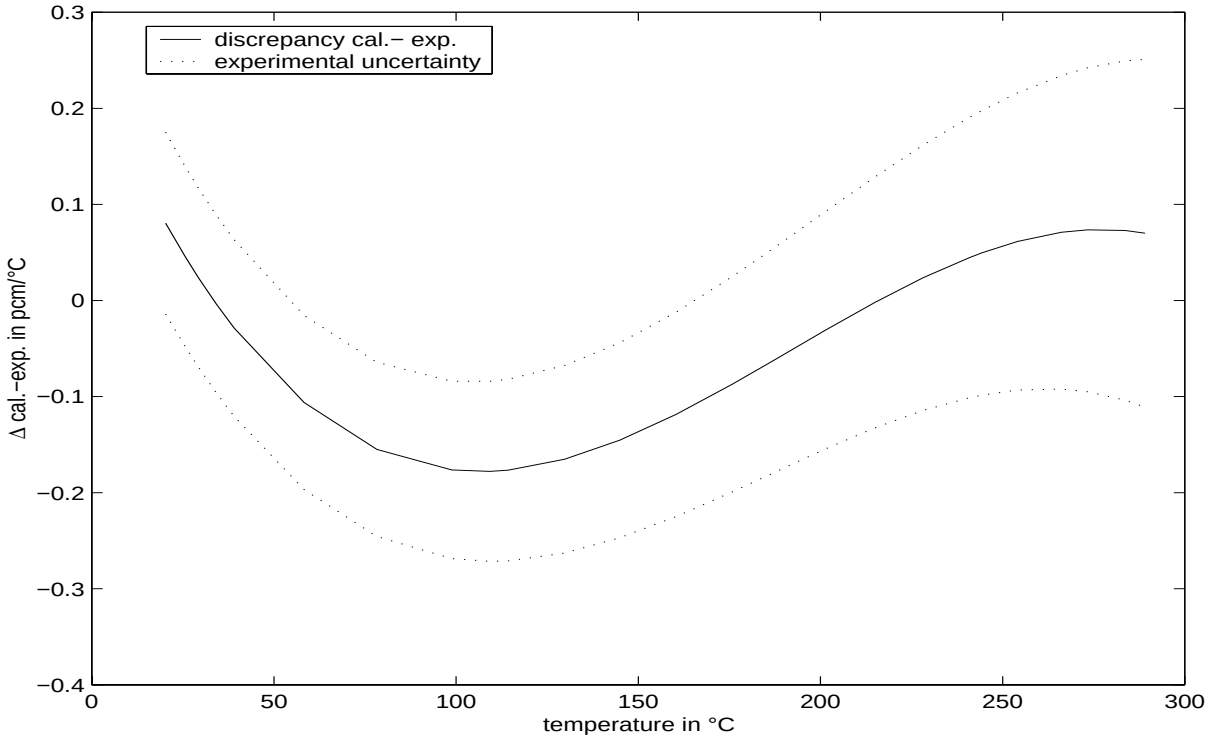

Figure 10. Discrepancy between measured and calculated core RTC
UO_2 clean lattice configuration

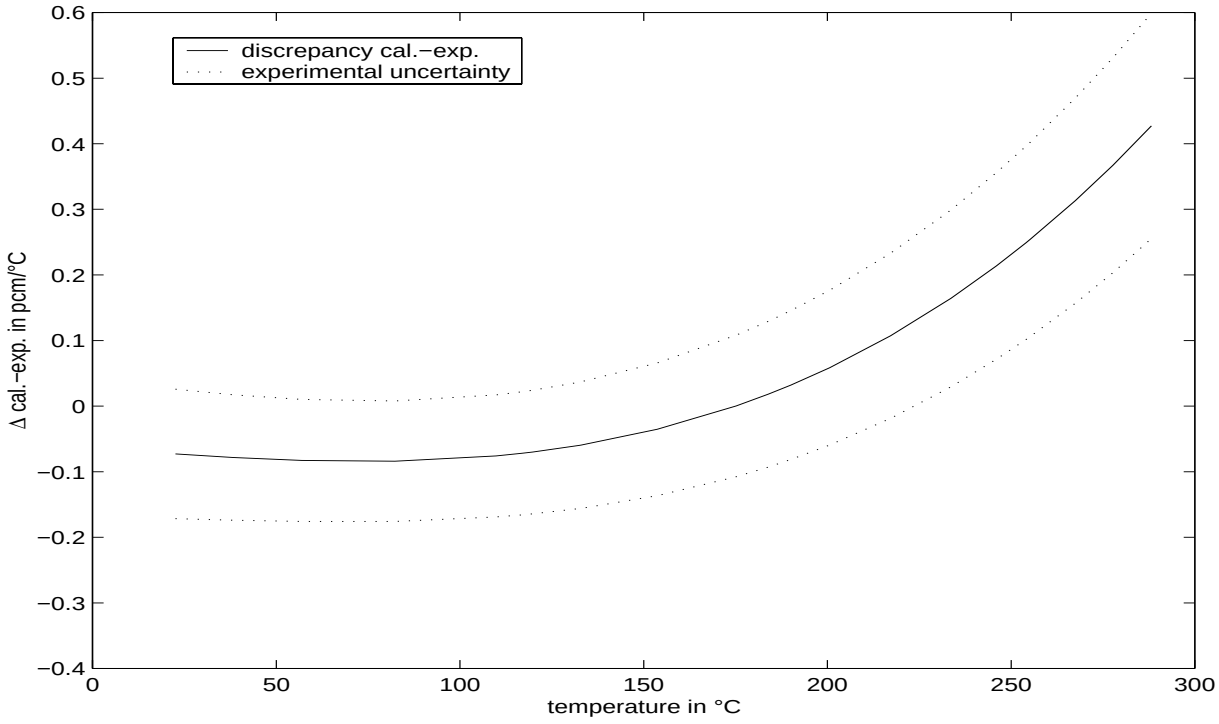

Figure 11. Discrepancy between measured and calculated core RTC
UO_2-PuO_2 clean lattice configuration

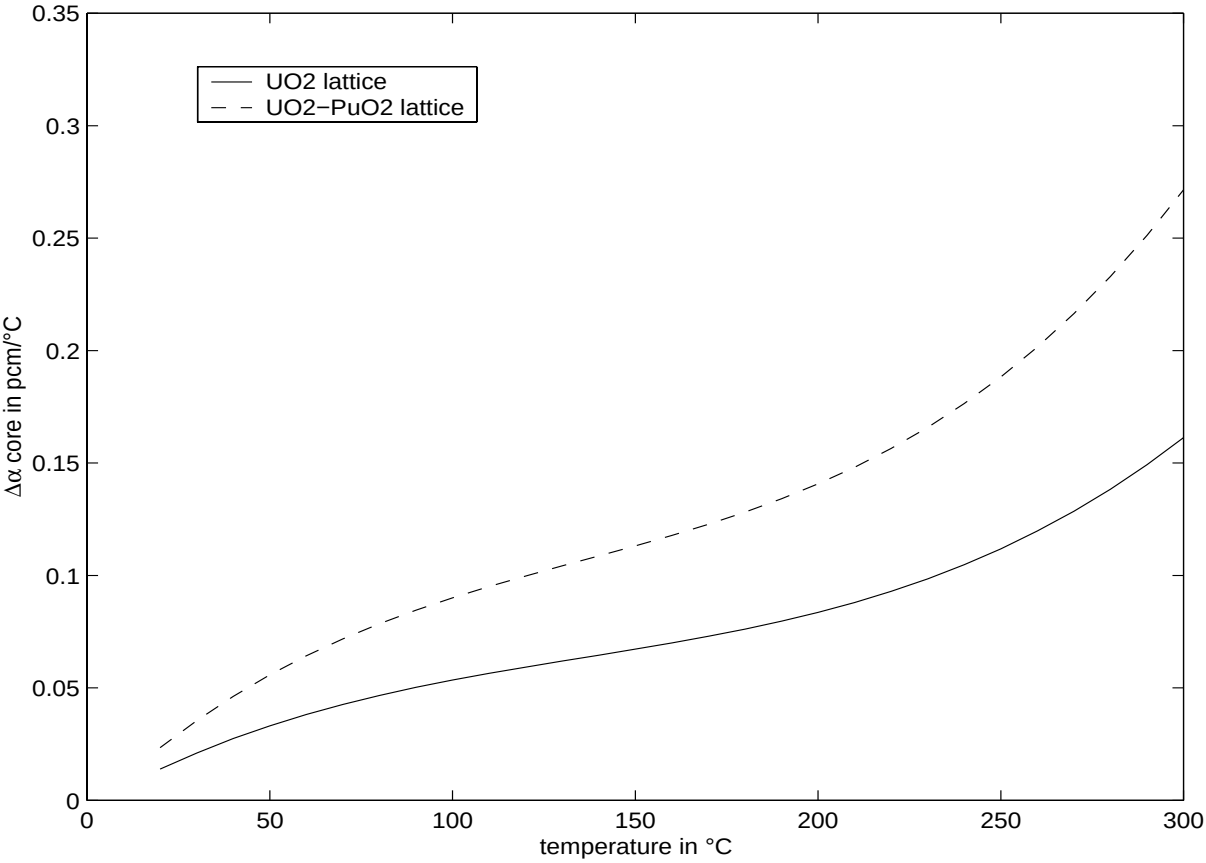

Figure 12. Temperature dependence of the water density error in the UO_2 and UO_2-PuO_2 lattices

Table II. Comparison of experimental and calculation results for the water density effects

	UO_2 lattice	UO_2-PuO_2 lattice
Experimental $\Delta\rho$ (pcm)	1420	1080
(C-E)/E (%)	2.1	4.6
Average contribution to RTC calc. bias	+0.07 pcm/C	+0.15 pcm/C

5. THE IMPACT OF THE RECENT L-D-L EVALUATION (JEF3) FOR U-235 ON THE RTC CALCULATION

A new APOLLO2 cross sections library is under preparation using the new JEFF-3 evaluation. One of the most important changes in comparison with the current JEF2.2 library concerns the U-235 isotope for which the most recent evaluation LDL will be used [10] (Notice that the LDL evaluation has already been implemented in the ENDF/B6 file, since the release 5). In this new evaluation proposed by Leal, Derrien and Larson, the U-235 resonant capture, which is underestimated in the current JEF2.2 library, has been increased by about 10%. The objective of this study is to assure that the expected library upgrade will not affect negatively the RTC calculation.

This impact was evaluated by performing a complete analysis of the core RTC measurements in the UO_2 clean lattice with a modified library which includes the LDL evaluation. The temperature dependence of the calculation error on the core RTC associated with the current and the modified libraries are presented in Fig. 13.

As seen from this figure, there is no significant discrepancy between these two calculations. Then, we can conclude that the impact on the reactivity temperature coefficient of using the new LDL evaluation for U-235 is not important.

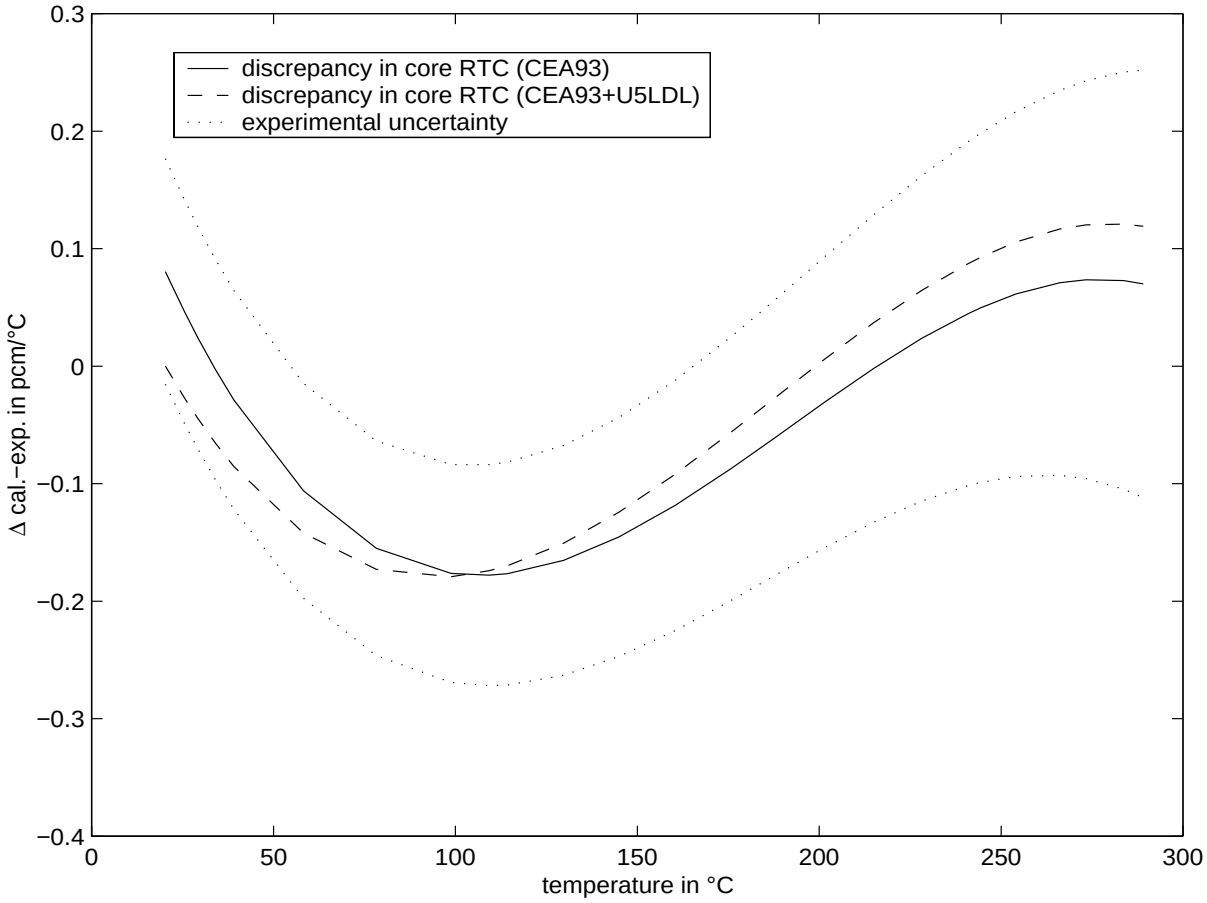

Figure 13. The impact on the RTC calculation of using the LDL evaluation for U-235

6. TRANSPOSITION OF THE CREOLE RESULTS TO A TYPICAL PWR LATTICE

The results of our analysis presented in the previous sections are specific to the CREOLE experiment. In this form, these results are not directly comparable to other published results on the reactivity temperature coefficient of light water lattices. In order to make these results more useful for the whole scientific community, it is important to present them in the context of a PWR lattice situation.

The transposition from the core situation to a PWR lattice situation is performed by using the relative reactivity worth of the experimental loop calculated by the reference core calculation. More details on the formalism used in this transposition can be found in reference [1]. The results for both temperature and water expansion effects are summarised in three temperature ranges and presented in Table III. In this table, the previous results obtained by APOLLO1 code with CEA79 and CEA86 [11] libraries, are presented. The C/E improvement observed with CEA86 library is mainly linked to the use of a non flat thermal shape of Eta for U-235. Table III also compares the APOLLO2 results with JEF2.2 and JEFF3 (for U-235) libraries.

In addition to the cross sections improvement, the more accurate calculation route based on APOLLO2 allows the observed satisfactory calculation-experiment.

Table III. Summary of the reactivity coefficient analysis in CREOLE experiment transposed to the PWR lattice situation

RTC (water density effects contribution) $\Delta\alpha_{C\text{-}E}$ (in pcm/°C)						
	UO_2 lattice			UO_2-PuO_2 lattice		
	20C - 90C	90C-250C	250C-300C	20C - 90C	90C-250C	250C-300C
APOLLO1 (CEA79)	- 4.2 ± 1.5 (+0.5)	- 1.9 ± 1.7 (+1.4)	+ 1.1 ± 2.0 (+2.0)	- 2.3 ± 1.8 (+0.4)	- 0.4 ± 2.0 (+1.1)	+ 2.2 ± 2.2 (+2.1)
APOLLO1 (CEA86)	- 1.7 ± 1.5	- 0.6 ± 1.7	+ 0.8 ± 2.0	-	-	-
APOLLO2 (CEA93)	- 0.8 ± 1.5 (+0.3)	- 0.7 ± 1.7 (+0.7)	+ 0.7 ± 2.0 (+1.2)	- 0.7 ± 1.8 (+0.7)	+ 0.5 ± 2.0 (+1.5)	+ 3.0 ± 2.2 (+2.5)
APOLLO2 (CEA93/LDL)	- 1.4 ± 1.5	- 0.6 ± 1.7	+ 1.1 ± 2.0	-	-	-

SUMMARY AND CONCLUSIONS

The Reactivity Temperature Coefficient measurements for light water moderated lattices performed in CREOLE experiment have been analysed using the French APOLLO2 code with the standard cross section library CEA93-172 groups. The main conclusions of this analysis are summarised below :

- For the standard PWR UO_2 clean lattices, the calculation error on the temperature coefficient is within the experimental accuracy and its magnitude in the whole temperature range is less than 1 pcm/C which corresponds to the current target accuracy in LWR design calculations. So, the large negative error associated with the temperature range below 100C is now cancelled, which means that our proposed drooping ETA-U235 shape (used in JEF2 and ENDF/B6.1) is validated.

- For the MOX clean lattices, the calculation error on the temperature reactivity coefficient is within the experimental uncertainties in the whole temperature range. However, the magnitude of the error for temperatures higher than 250C reaches +3 pcm/C $\pm$ 2 pcm/C (1σ).

- The water expansion effect measurements enabled us to split the calculation error between the spectral shift component and the water density component. The experiment analysis has shown that the calculation error associated with the water density effects is more significant in the high temperature range, particularly for MOX lattices. Furthermore, the error level on the water density effects for MOX lattices is consistent with the relatively large positive error on the RTC which remains in the high temperature range.

In this analysis we have also assessed the impact of the new LDL evaluation of U235 cross sections, used in the starter File of the next European nuclear data Library JEFF3 and implemented in the release 5 of ENDF/B6. We have shown that the conclusions on the RTC calculation will not change significantly.

This analysis has also allowed us to check the capability of the APOLLO2 code to predict with reasonable accuracy, the criticality of a small critical facility with strong heterogeneities and high level of leakage.

From this analysis, we can conclude that the residual error on the temperature reactivity coefficient in high temperature range, especially in MOX fuel lattices, is most probably linked to water expansion effects. The thermal spectrum effects seem to be correctly accounted for, when using modern codes with the more recent nuclear data evaluations.

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