Analysis of the CREOLE Experiment Using MCNP6.1 Code and ENDF/B-VII.1 Library

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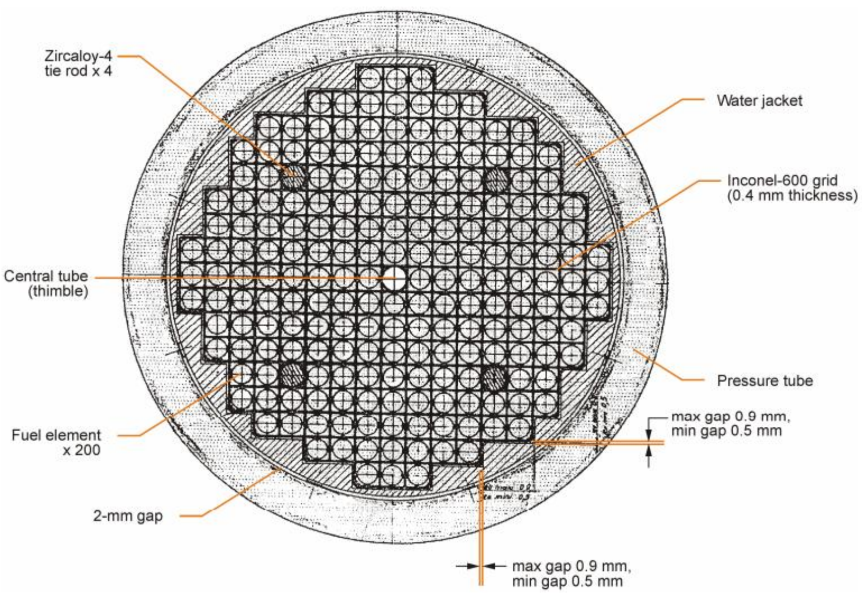
Introduction

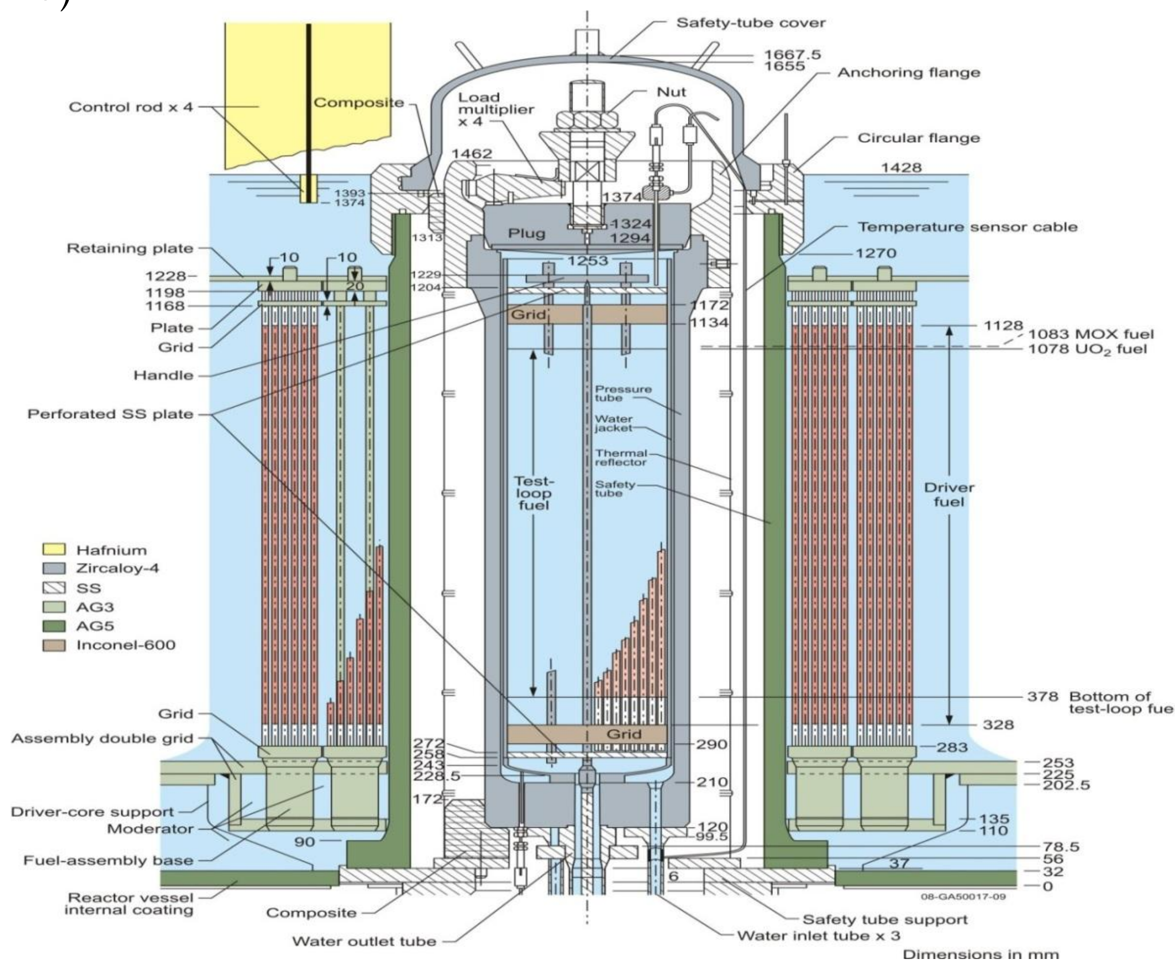
- ✓ The reactivity Temperature Coefficient (RTC) is an important parameter in design, control and safety of Light Water Reactors.
- ✓ For safety considerations, the RTC is desired to be negative throughout the core life.
- ✓ The calculation of the RTC is rather a complicated problem because it results from the combination of several negative and positive contributions from different physical phenomena related to the temperature change.
- ✓ it is important to validate any reactor calculation tool and any nuclear data library for an accurate prediction of this parameter.
- ✓ The objective of the present work is to perform the analysis of the CREOLE experiment using the Monte Carlo code in new version MCNP6.1 and its associated ENDF/B-VII.1 cross section library, in order to check the accuracy of new cross section library for the RTC calculations.

CREOLE Experiment

CREOLE performed in the EOLE facility at CEA-Cadarache during the two last years of the seventies, this experiment is the most representative of the operating conditions of a large PWR power reactor; Water moderated UO_2 lattices was investigated for the temperature range starting from room temperature up to (300°C).



Radial cross section of the central loop



Axial cross section of CREOLE reactor

CREOLE Experiment

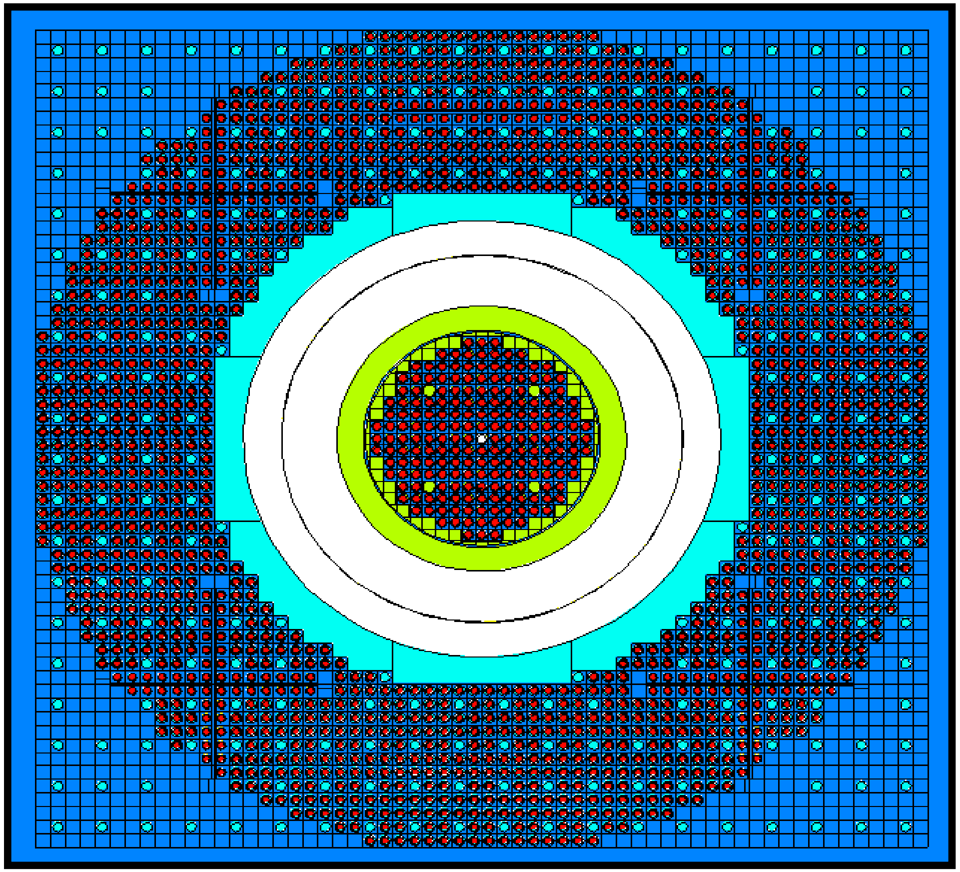
Fuel rod compositions for the central loop and the driver core at room temperature.

Paramètres	Central loop	Driver core
Fuel material	UO_2	UO_2
Fuel density (g/cm^3)	10.28 ± 0.02	10.25
^{234}U (wt.%)	0.0304	3.04633E-02
^{238}U (wt.%)	96.8696	85.0305
^{235}U (wt.%)	3.10 ± 0.01	3,5
Fuel pellet radius (cm)	0.4098	0.3524
Pitch (cm)	1.260 ± 0.003	1.430 ± 0.005
Fuel colomn height (cm)	70.0	80.0
Clad material	Zircolloy-2	AG3 or stainless steel (304L)
Clad tickness (cm)	0,06	0,074
Cladding outer radius (cm)	0.478	0,535

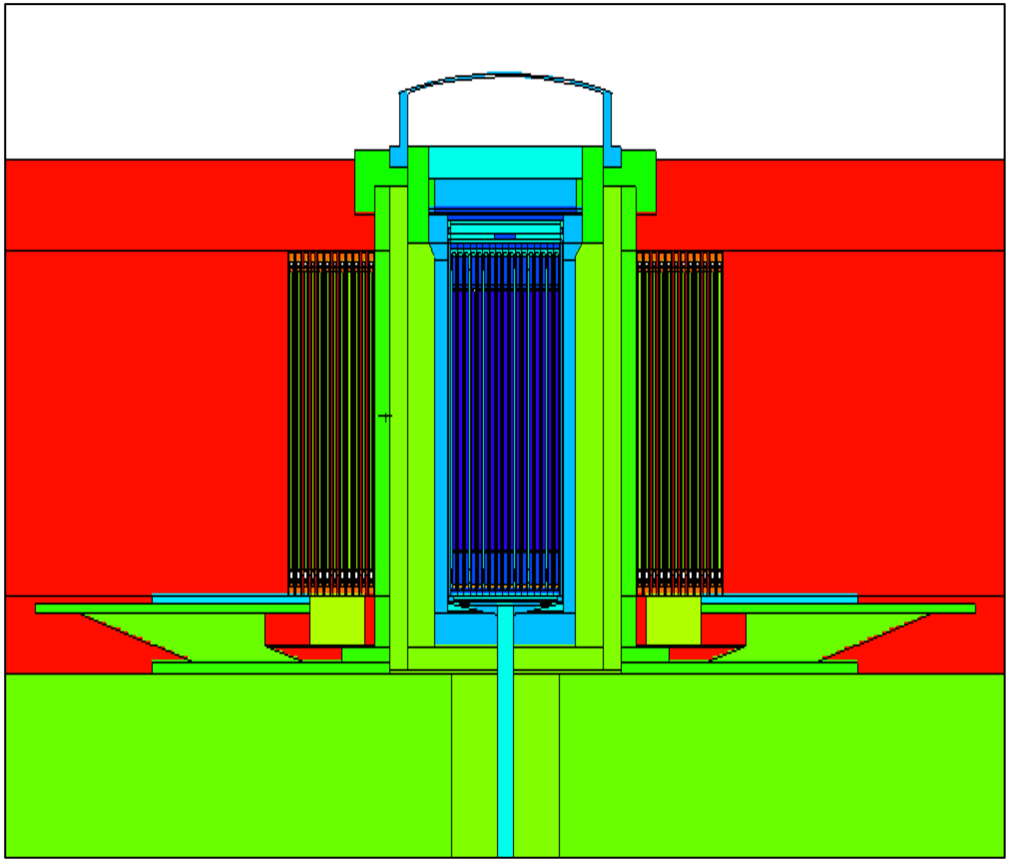
Critical sizes at room temperature

Core configuration	Driver-core temperature (°C)	Central-loop temperature (°C)	Central-loop pressure (bar)	Doubling time (s)	Residual Reactivity (pcm)	Driver-core size (fuel rods)
UO_2 1166 ppm boron	19.6 ± 0.2	21.83 ± 0.2	66.5 ± 0.5	6.86 ± 0.2	316 ± 13	1772

MCNP Model of EOLE



Radial cross section of the CREOLE model using MCNP6.1.



Axial cross section of the CREOLE model using MCNP6.1 .

MCNP Model of EOLE

Experimental reactivity measurements (UO_2 lattice with 1166 ppm of boron)

Driver-core size	Driver-core temperature. (°C)	Central-loop Temperature (°C)	Central-loop pressure (bar)	Doubling time (s)	Reactivity (pcm)
1772 éléments	19.6	21.83	66.5	6.86	298.30
	19.6	33.83	66.5	6.83	298.90
	19.7	44.03	66.5	6.81	299.26
	19.7	63.87	67.0	6.77	300.05
	19.7	86.83	67.7	6.74	300.63
	19.7	116.61	69.0	6.77	300.04
	19.75	146.37	78.7	6.90	297.53
	19.75	175.60	72.9	7.13	293.21
	19.8	206.73	75.7	7.57	285.38
	19.8	237.46	79.2	8.28	273.80
	19.85	269.30	84.4	9.54	255.91
	19.85	296.68	91.6	11.51	233.01

Theoretical Considerations

Decomposition and analysis of the temperature effets on the effectif multiplication factor:

$$k_{eff} = k_{\infty}.P_{nL}$$

$$k_{\infty} = \chi \cdot \varepsilon \cdot p \cdot f \cdot \eta$$

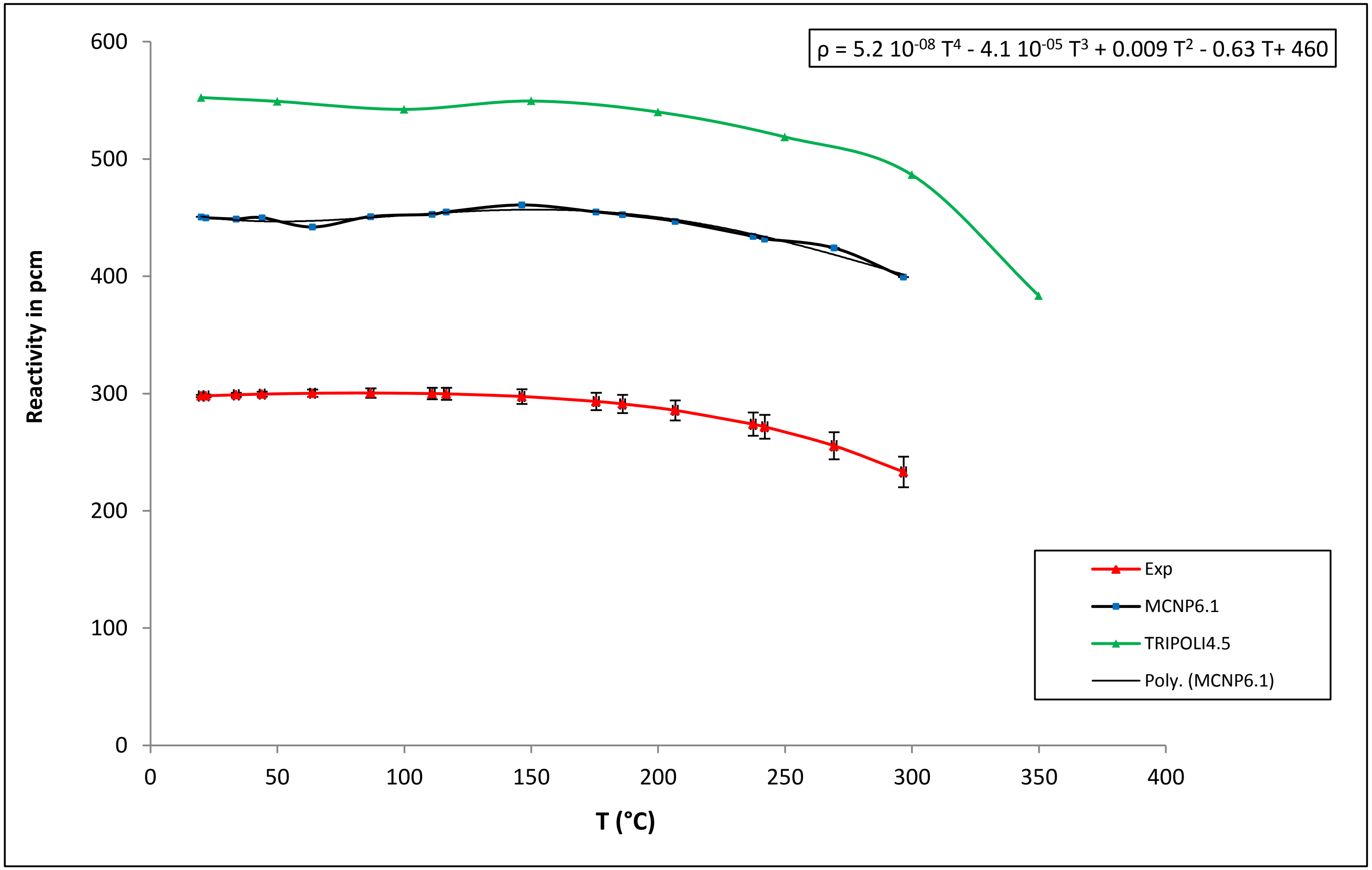
$$\alpha = \frac{1}{k_{eff}(T_1).k_{eff}(T_2)} \frac{k_{eff}(T_2) - k_{eff}(T_1)}{T_2 - T_1} \Rightarrow \alpha_T = \frac{1}{k_{eff}} \frac{dk_{eff}}{dT} = \frac{1}{k_{\infty}} \frac{dk_{\infty}}{dT} + \frac{1}{P_{nL}} \frac{dP_{nL}}{dT}$$

$$\alpha_T = \alpha_{k_{\infty}} + \alpha_{nL}$$

$$\alpha_{k_{\infty}} = \frac{1}{(\chi \cdot \varepsilon \cdot p \cdot f \cdot \eta)} \frac{d(\chi \cdot \varepsilon \cdot p \cdot f \cdot \eta)}{dT}$$

$$\alpha_{k_{\infty}} = \frac{1}{\chi}\frac{d\chi}{dT} + \frac{1}{\varepsilon}\frac{d\varepsilon}{dT} + \frac{1}{p}\frac{dp}{dT} + \frac{1}{f}\frac{df}{dT} + \frac{1}{\eta}\frac{d\eta}{dT}$$

Results and Interpretations



Reactivity variation with temperature for the UO_2 configuration with the 1166 ppm boron.

Results and Interpretations

The infinite multiplication components for a pin cell simulation

Température de la boucle (°C)	χ ±Std	ε ±Std	p ±Std	f ±Std	η ±Std	k_∞(f.f.f) ±Std	k_∞(MCNP) ±Std
21.83	1.00142 ± 125	1.23305 ± 25	0.68102 ± 83	0.77976 ± 97	1.83663 ± 37	1.20433 ± 495	1.2061 ± 8
33.83	1.00142 ± 124	1.23374 ± 25	0.68 ± 83	0.78046 ± 97	1.83626 ± 37	1.20405 ± 494	1.20581 ± 7
44.03	1.00142 ± 124	1.23446 ± 25	0.67898 ± 83	0.78123 ± 97	1.83592 ± 37	1.2039 ± 494	1.20559 ± 7
63.87	1.00143 ± 124	1.23622 ± 25	0.67657 ± 83	0.78306 ± 97	1.83519 ± 37	1.20369 ± 494	1.20549 ± 7
86.83	1.00144 ± 125	1.239 ± 25	0.6731 ± 82	0.78557 ± 98	1.83426 ± 37	1.20344 ± 494	1.20516 ± 6
116.61	1.00145 ± 125	1.24335 ± 25	0.66784 ± 82	0.78948 ± 98	1.83296 ± 37	1.20338 ± 494	1.20511 ± 6
146.37	1.00147 ± 125	1.24874 ± 25	0.66162 ± 81	0.79393 ± 99	1.83159 ± 37	1.20321 ± 494	1.20507 ± 7
175.60	1.00149 ± 125	1.25533 ± 25	0.65422 ± 80	0.7991 ± 99	1.83015 ± 37	1.20288 ± 495	1.20468 ± 7
206.73	1.00152 ± 125	1.2638 ± 25	0.64513 ± 79	0.80535 ± 100	1.82859 ± 37	1.20253 ± 495	1.20431 ± 7
237.46	1.00155 ± 125	1.27453 ± 25	0.63405 ± 78	0.81252 ± 101	1.82697 ± 37	1.20148 ± 495	1.20335 ± 6
269.30	1.00159 ± 126	1.28951 ± 26	0.61938 ± 76	0.82159 ± 102	1.82523 ± 37	1.19965 ± 495	1.20152 ± 7
296.68	1.00164 ± 126	1.30782 ± 26	0.60242 ± 74	0.83145 ± 104	1.82365 ± 36	1.19659 ± 495	1.19859 ± 6

*: Formule des cinq facteurs
±Std: déviation Standard (pcm).

Results and Interpretations

Analytical formes for the k_∞ components calculated in the central loop

Component	Analytique Forme (T in (°C))
χ	$3.9\ 10^{-14}\ T^4 - 2\ 10^{-11}\ T^3 + 5.4\ 10^{-09}\ T^2 - 1.4\ 10^{-07}\ T + 1$
ε	$1.7\ 10^{-11}\ T^4 - 7.6\ 10^{-09}\ T^3 + 1.8\ 10^{-06}\ T^2 - 4.2\ 10^{-05}\ T + 1.2$
p	$-1.3\ 10^{-11}\ T^4 + 6.4\ 10^{-09}\ T^3 - 1.5\ 10^{-06}\ T^2 - 1.7\ 10^{-06}\ T + 0.68$
f	$6.7\ 10^{-12}\ T^4 - 3.4\ 10^{-09}\ T^3 + 9.7\ 10^{-07}\ T^2 + 1.2\ 10^{-05}\ T + 0.78$
η	$-5.7\ 10^{-13}\ T^4 + 4.3\ 10^{-10}\ T^3 - 1.5\ 10^{-07}\ T^2 - 2.4\ 10^{-05}\ T + 1.8$

Results and Interpretations

CREOLE experiment calculation results of the temperature coefficient of k_∞ components in (/°C)

T (°C)	α_χ	α_ε	α_f	α_p	α_η
21.83	6.8696E-03	2.1435	6.3825	-8.6020	-1.6311
33.83	1.6251E-02	4.5655	8.5839	-12.240	-1.7841
44.03	2.3219E-02	6.3276	10.232	-14.876	-1.9011
63.87	3.4519E-02	9.1116	12.934	-18.998	-2.0975
86.83	4.4688E-02	11.558	15.415	-22.504	-2.2797
116.61	5.5008E-02	14.122	17.989	-25.890	-2.4582
146.37	6.4359E-02	16.793	20.338	-29.100	-2.5892
175.6	7.4993E-02	20.338	22.933	-33.326	-2.6909
206.73	9.0534E-02	26.001	26.562	-40.419	-2.7908
237.46	1.1284E-01	34.344	31.552	-51.685	-2.9025
269.3	1.4615E-01	46.687	38.721	-69.867	-3.0552
296.68	1.8537E-01	60.783	46.859	-92.905	-3.2352

Results and Interpretations

Measured value and (C-E) for the core RTC

α and C-E (pcm/°C)	20 °C – 111 °C	111 °C – 186 °C	186 °C – 242 °C	242 °C – 296 °C
EXPERIENCE (α) [1]	+ 0.02 ± 0.04	- 0.12 ± 0.04	- 0.35 ± 0.05	- 0.67 ± 0.06
MCNP6.1 (ENDF/B7.1) (C – E)	+ 0.003 ± 0.128	+ 0.117 ± 0.146	- 0.019 ± 0.191	+ 0.041 ± 0.205
TRIPOLI4 (JEFF3.1.1) (C -E) [1]	- 0.10 ± 0.06 (0.04)*	+ 0.08 ± 0.06 (0.05)*	- 0.01 ± 0.09 (0.07)*	+ 0.05 ± 0.10 (0.08)*
APOLLO2 (JEFF3.1.1) (C – E) [1]	- 0.01 ± 0.04	+ 0.01 ± 0.04	+ 0.05 ± 0.05	+ 0.12 ± 0.06

C-E on the central loop RTC for the UO_2 with the 1166 ppm of boron (integration of the differential measurements)

C-E (pcm/°C)	UO_2 (1166 ppm de bore) 20°C – 296°C
EXPERIENCE (a) [1]	- 0.22 ± 0.02
MCNP6.1 (ENDF/B-VII.1)	0.036 ± 0.02
APOLLO2 (JEFF3.1.1)	0.03 ± 0.05
TRIPOLI4 (JEFF3.1.1)	- 0.004 ± 0.01

Conclusion

In the present work, we have analyzed the CREOLE experiment of a PWR lattice type on the reactivity temperature coefficient of UO_2 boron poisoned lattice. The analysis of this experiment has been carried out using the Monte Carlo code MCNP6.1 with the ENDF/B-VII.1 library.

The discrepancies between calculations and experiment on the Reactivity temperature Coefficient for the boron poisoned UO_2 LWR lattices is relatively small.

In this study, we could quantify the contribution of each infinite multiplication factor‘s components separately in the reactivity temperature coefficient.

Thank you