DE LA RECHERCHE À L'INDUSTRIE

cea den

New analysis of experimental measures of $\boldsymbol{\beta_{eff}}$ from BERENICE program

Authors | Paul Dufay and Gérald Rimpault
Presented by : Cyrille De Saint Jean

CEA-Cadarache
LEPh

MAI 2016, WPEC, SG39

DE LA RECHERCHE À L'INDUSTRIE

cea den

PRESENTATION PLAN

1. The experimental β_{eff}: delayed effective neutron fraction
   1. How can we measure the β_{eff}?
   2. Three existing methods

2. New evaluation and calculations with TRIPOLI-4®
   1. The three studied cores from the BERENICE program.
   2. Calculated β_{eff} with TRIPOLI-4®
   3. Experimental β_{eff} and C/E

3. Uncertainties evaluation
   1. Uncertainties due to nuclear data
   2. Experimental uncertainties
   3. Statistical uncertainties

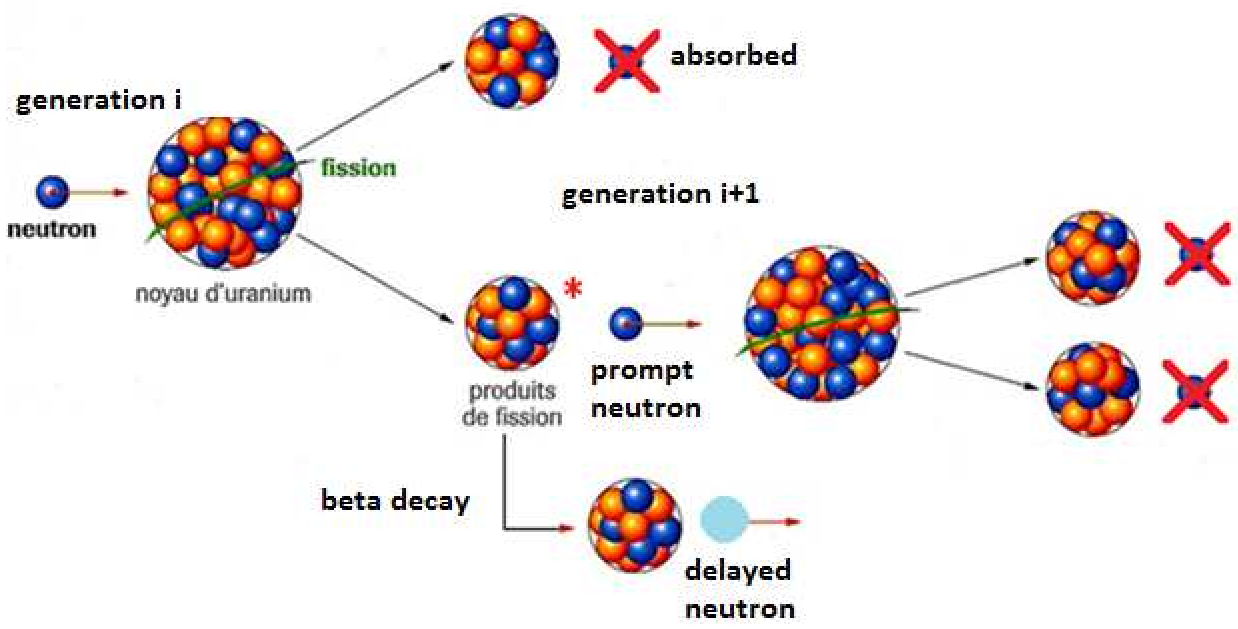
4. Conclusion & Perspectives

1-EXPERIMENTAL β_{eff} :
THE EFFECTIVE DELAYED NEUTRON FRACTION

PHYSICS OF DELAYED NEUTRONS

- In the core of a nuclear reactor a chain reaction of fission has to be controlled, by absorbing prompt neutrons in order to obtain the equilibrium :

  1 fission => 1-β fission



- The missing β neutrons are produced by the fission product's decay which are called « precursors ». These precursors are classified in 8 families depending on their half-life which is the duration between the fission and the emission of the delayed neutrons.

HOW CAN WE MEASURE THIS β_{eff} ?

- Main equations which describe the neutron flux and the delayed neutron production by beta decay of the precursors : C_i.

$$\begin{cases} \frac{1}{v}\frac{\partial \Psi}{\partial t} + \mathbf{A}\Psi = \mathbf{F_p}\Psi + \sum_{i=1}^{I} \lambda_i \chi_{di} C_i + S \\ \frac{\partial C_i}{\partial t} + \lambda_i C_i = \beta_i \mathbf{P}\Psi \qquad \mathrm{k} = 1, \dots, \mathrm{I} \end{cases}$$

- The reactivity can be written as a ratio of « importance » and by using the dollar reactivity which is normalized by the effective delayed

$$\rho = \beta_{eff} \cdot \rho_{\$} = -\frac{< \Phi^{+}, S >}{< \Phi^{+}, \mathbf{F}\Phi >} \qquad \text{E1}$$

- The β_{eff} defined by this ratio of two integrals of adjoint flux cannot be only deduced of experimental measures indeed numerical simulation are mandatory to know the adjoint flux.

METHOD WITH THE CF252 SOURCE

- The first method to measure the β_{eff} imply to introduce the Cf 252 source in the core.
  - The following perturbation will give information about the β_{eff}.
  - Two fission chambers are in the core : one is called « reference » and located at the core center (noted « ref ») and the other for counting rate (noted « d »)
  - The formula E1 can be decomposed in the following way, with S_1 the Cf 252 source and S_0 the one related to the fuel.

$$-\rho \frac{<\Sigma_{réf},\Phi_1>}{<\Sigma_{réf},(\Phi_1+\Phi_0)>} = \frac{<\Phi^+,S_1>}{<\Phi^+,\chi_r>\cdot<S_1>} \frac{<S_1>}{<\Sigma_d,(\Phi_1+\Phi_0)>} \frac{<\Sigma_d,(\Phi_1+\Phi_0)>}{<\Sigma_{réf},(\Phi_1+\Phi_0)>} \frac{<\Sigma_{réf},\Phi_1><\Phi^+,\chi_r>}{<\Phi^+,\mathbf{F}\Phi_1>}$$

- So we have :

$$\beta_{eff} = \frac{\varphi_{sc}}{K_c} \frac{S_{sc}}{N.K_e.|\Delta\rho_\$|}$$

$$\beta_{eff} = P_c.P_m$$

Avec

$$P_c = \frac{\varphi_{sc}}{K_c}$$

$$P_m = \frac{S_{sc}}{N.K_e.|\Delta\rho_\$|}$$

- With P_m the measured part and P_c the calculated part.

THE NOISE METHOD

- This method considers that in a sub-critical and « stationary » state the absorption and production of neutrons are random phenomena ruled by a Poisson distribution.

- With Fourier transformation and after some easy calculation steps, we can write this simple formula :

$$\beta_{eff}{}^2 = 2\frac{<\Sigma_d,\Phi>.<\Sigma_{réf},\Phi>.D.V_1.V_2}{<\Sigma_d,\Phi>.<\Sigma_{réf},\Phi>.<\Sigma_f,\Phi>.\ DSPI.(1+|\rho_\$|)^2}$$

$$\beta_{eff}{}^2 = \frac{2D}{K_c}\frac{V_1.V_2}{N.K_e.DSPI.(1+|\rho_\$|)^2}$$

  - With the DSPI : the power spectral density inter-compared of 2 measurement chains.

- So we have :

$$\beta_{eff}{}^2 = P_c.P_m$$

with :

$$P_c = {2D}/{K_c}$$

$$P_m = {V_1.V_2}/{N.K_e.DSPI(1+|\rho_\$|)^2}$$

- With P_m the measured part and P_c the calculated part.

THE α-ROSSI METHOD

- This method is very similar to the noise method, the difference is the time measure which is short (less than 1 millisecond). The counting rate of the second detector is triggered by the first one.

$$\beta_{eff} = \frac{1}{1 + (1 + |\rho_\$|) . \sqrt{\frac{2 < \Sigma_d, \Phi >}{D} . \frac{< \Sigma_{réf}, \Phi >}{< \Sigma_d, \Phi >} \frac{< \Sigma_f, \Phi >}{< \Sigma_{réf}, \Phi >} . \frac{N_0 . \Delta t}{N_2} . \frac{\alpha + C}{\alpha}}}$$

$$\beta_{eff}{}^2 = \frac{D}{2 K_c} \frac{1}{(1 + \rho_\$)^2 . N\, K_e} \frac{N_2}{N_0 . \Delta t} \frac{\alpha}{\alpha + C}$$

  - With the α : the decay constant associated with prompt neutrons.
  - N_2 non-correlated counting during the time window Δt triggered by all initial impulsions C
  - N_0 correlated counting during all the time windows
- So we have :

$$\beta_{eff}{}^2 = P_c . P_m$$

with :

$$P_c = {}^{D}/_{2K_c}$$

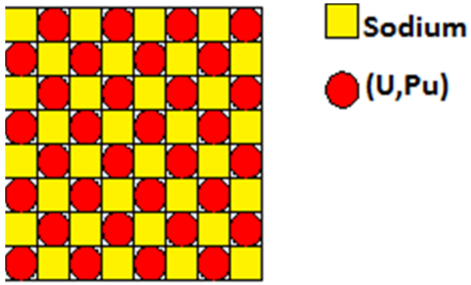
$$P_m = {}^{\alpha . N_2}/_{N_0 . \Delta t (\alpha + C)(1 + \rho_\$)^2}$$

- With P_m the measured part and P_c the calculated part.

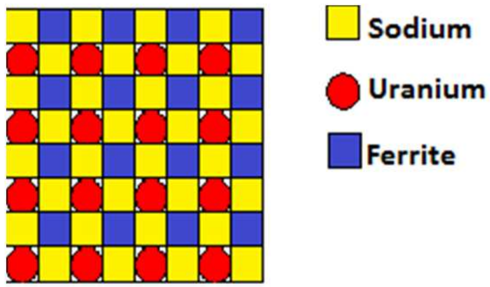
2-NEW EVALUATION AND CALCULATIONS WITH TRIPOLI-4®

THE 3 STUDIED CORES

View of the under core of MASURCA



Basic cell of ZONA2 core



Basic cell of R2 cores

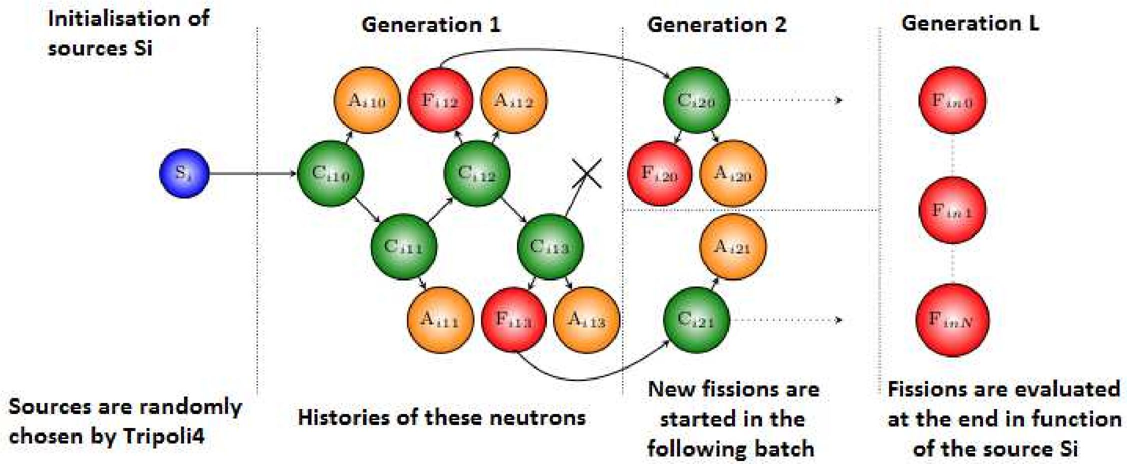
- The MASURCA assemblies are composed of steel tubes of 10.6x10.6 cm^2 .
- These 3 cores are surrounded by fertile blanket composed of depleted uranium.

	ZONA2	R2 réf	R2 exp
Fuel	$UPuO_2$	UO_2	UO_2
Diluant	Na	Na-Fe_2O_3	Na-Fe_2O_3

CALCULATED β_{eff}

- The best method to estimate the β_{eff} with TRIPOLI-4® is the Iterated Fission Probability (IFP).

- This method uses the definition of the adjoint flux as an importance of a neutron ie the number of fissions induced by this neutron after L cycles (generation)



TRIPOLI4 IFP (JEFF-3.2)	β_{eff} (pcm)	$d\beta_{eff}$ (pcm)
ZONA2	349,9	0,9
R2 réf	742,4	3,2
R2 exp	740,1	5,0

EXPERIMENTAL β_{eff} WITH THE CF 252 SOURCE

- The calculated part P_c was evaluated twice by CEA, once using an old code and once by using ERANOS but these codes have used approximations in the representation of the cores geometries. That is why a new evaluation using the IFP method with TRIPOLI-4® has been done.

	ZONA2		R2 réf		R2 exp	
Codes	$P_c\ (10^{-6})$	$\beta_{eff}\ (pcm)$	$P_c\ (10^{-6})$	$\beta_{eff}\ (pcm)$	$P_c\ (10^{-6})$	$\beta_{eff}\ (pcm)$
Old code	2,3060	354,95	1,9800	761,78	1,9099	780,13
ERANOS	2,3282	358,36	2,0564	791,16	2,0195	825,31
TRIPOLI-4®	2,2393	344,81	1,9586	756,55	1,8282	747,57

- The C/E are calculated by comparison with TRIPOLI-4® results with IFP method.

C/E	ZONA2	R2 réf	R2 exp
Old code	0,9858	0,9746	0,9487
ERANOS	0,9765	0,9384	0,8970
TRIPOLI-4®	1,0148	0,9813	0,9900

EXPERIMENTAL β_{eff} WITH THE NOISE METHOD

- These measurements were only run for ZONA2 and R2 exp.

	ZONA2		R2 exp	
Codes	$P_c\ (10^{-6})$	$\beta_{eff}\ (pcm)$	$P_c\ (10^{-6})$	$\beta_{eff}\ (pcm)$
Old code	7,2699	336,44	4,9268	717,37
ERANOS	7,3845	339,09	5,6414	767,55
TRIPOLI-4®	7,6710	345,61	5,4598	755,18

- The C/E are calculated by comparison with TRIPOLI-4® results with IFP method.

C/E	ZONA2	R2 exp
Old code	1,0400	1,0317
ERANOS	1,0319	0,9642
TRIPOLI-4®	1,0125	0,9800

EXPERIMENTAL β_{eff} WITH THE α-ROSSI METHOD

- These measurements were only run for R2 exp.

	R2 exp	
Codes	$P_c\ (10^{-6})$	$\beta_{eff}\ (pcm)$
Old code	1,2317	769,25
ERANOS	1,3753	812,50
TRIPOLI-4®	1,3650	816,07

- The C/E are calculated by comparison with TRIPOLI-4® results with IFP method.

C/E	R2 exp
Old code	0,9621
ERANOS	0,9109
TRIPOLI-4®	0,9069

- The ratios C/E for the Cf 252 source and noise method have improved with the use of IFP method in TRIPOLI-4®.

3-UNCERTAINTIES

UNCERTAINTIES DUE TO NUCLEAR DATA

- Numerical simulations tools are using nuclear data as inputs, such as cross-sections or fission spectrum, all these data are known with some uncertainties. The uncertainties on the β_{eff} are calculated with a sensitivity analysis and the sandwich formula :

$$\sigma_i = S.B.S^t$$

- To take into account that some of these uncertainties are correlated this calculation has to use a covariance matrix. This work has been lead with ERANOS and the COMAC-DEV for JEFF-3.1 and the COMAC-V1 for JEFF-3.2.

Cores	Relative uncertainties (in %)	
	JEFF-3.1	JEFF-3.2
ZONA2	3.62	2.90
R2 réf	3.56	3.34
R2 exp	3.56	3.34

- The huge difference for ZONA2 between the two libraries comes from a great improvement of the uncertainties on the fission cross-section of Pu239.

UNCERTAINTIES DUE TO NUCLEAR DATA

- The main contributors to the β_{eff} uncertainty with JEFF-3.2 for the ZONA2 core come from the fission of Pu239 and the delayed yield of Pu239 and U238.

Uncertainties on β_{eff} for ZONA2 core

	Capture	Fission	Elastic	Inelastic	n,xn	υ	υd	Total
U235	0,025	0,005	0,003	0,001	0,001	0,003	0,038	0,046
U238	0,261	**0,683**	0,114	0,104	0,036	0,044	**1,506**	1,680
Pu238	0,001	0,001	0,000	0,000	0,000	0,007	0,007	0,010
Pu239	0,188	**1,530**	0,054	0,023	0,005	0,237	**1,706**	2,311
Pu240	0,196	**0,421**	0,010	0,010	0,006	0,013	0,208	0,427
Pu241	0,017	0,043	0,001	0,000	0,001	0,034	0,136	0,148
Pu242	0,002	0,001	0,000	0,000	0,000	0,001	0,028	0,028
Na23	0,024	0,000	0,092	0,033	0,006	0,000	0,000	0,101
Fe56	0,046	0,000	0,085	0,016	0,003	0,000	0,000	0,098
Total	0,262	1,728	0,160	0,113	0,035	0,236	2,290	2,896

- The uncertainty on fission U238 and Pu239 comes from their relative importance in the β_{eff}

EXPERIMENTAL UNCERTAINTIES

- Experimental uncertainties depends of the method used, they have been evaluated in the Veronique Zammit thesis :

Uncertainty source	Method	Relative uncertainty (in %)
S_{sc}	Source Cf 252	$\pm$1,6 (R2)
		$\pm$1,8 (ZONA2)
$\lvert\Delta\rho_{\$}\rvert$	Source Cf 252	$\pm$1,5
$K_e\ (<\Sigma_{f,réf}, \Phi>)$	For the 3 method	$\pm$1,8
DSPI	Noise method	$\pm$2,4
N_2/N_0	α-Rossi	$\pm$1,0
D_υ	Noise and α-Rossi method	$\pm$1,6 (R2)
		$\pm$2,0 (ZONA2)

Method	Cores	Conservative uncertainty
Source Cf 252	R2	$\sqrt{1{,}6^2+1{,}5^2+1{,}8^2}=2{,}8\%$
	ZONA2	$\sqrt{1{,}8^2+1{,}5^2+1{,}8^2}=3{,}0\%$
Noise method	R2	$\frac{1}{2}\sqrt{1{,}8^2+2{,}4^2+1{,}6^2}=1{,}7\%$
	ZONA2	$\frac{1}{2}\sqrt{1{,}8^2+2{,}4^2+2{,}0^2}=1{,}8\%$
α-Rossi method	R2	$\frac{1}{2}\sqrt{1{,}8^2+1{,}0^2+1{,}6^2}=1{,}3\%$

EXPERIMENTAL UNCERTAINTIES

- A series of measurements was performed for each method. Here, the dispersion in the various values of a given series increase the experimental uncertainty. This is calculated as the standard deviation of the series and conservatively added to the previous experimental uncertainties (total in the following table).

Method	Cores	Standard deviation (in %)	Total (in %)
Source Cf 252	R2 réf	1,56	3,21
	R2 exp	3,07	4,15
	ZONA2	2,40	3,84
Noise method	R2 exp	2,27	2,84
	ZONA2	0,85	1,99
α-Rossi	R2 exp	1,98	2,36

STATISTICAL UNCERTAINTIES

- The Monte-Carlo method allows a refined representation of the geometry but it is introducing a statistical bias even if it can be neglected as we can see in the next table :

	Relative uncertainties		
Cœurs	P_c Cf 252	P_c Fréquences	P_c α-Rossi
ZONA2	0,58	0,195	-
R2 réf	0,61	-	-
R2 exp	0,46	0,24	0,24

- This bias can be neglected in regard of the experimental uncertainties and the ones due to nuclear data.

4-CONCLUSION

CONCLUSION & PERSPECTIVES

- The new evaluation using the latest development in TRIPOLI-4® has improved the ratio C/E for the method with the Cf 252 source and for the noise method.

- The uncertainties due to nuclear data have the same magnitude than the experimental ones for the method with the Cf 252 source, the use of the noise method allows to reduce the experimental uncertainties.

- The results obtained with the noise method could be used to improve nuclear data.

Noise method	CFV β_{eff} (pcm)	Uncertainty (%)
Measured Value (with TRIPOLI4 corrections)	345.6	2.0
Calculated Value with TRIPOLI4 IFP	349.9	2.9
C/E	1.012	3.5%

- A new β_{eff} experimental method inspired from the noise method is being developed (using modern electronic able to detect the phase variation between signals of 2 different fission chambers). This technique has the potential to reduce the experimental bias for the next experimental program GENESIS of the MASURCA zero power facility.

Thanks for your attention

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | 13115 Saint-Paul-lès-Durance Cedex
T. +33 (0)4 42 25 70 00

Cadarache
DEN
SPRC

Etablissement public à caractère industriel et commercial | R.C.S Paris B 775 685 019