EPJ Web of Conferences **288**, 04021 (2023) https://doi.org/10.1051/epjconf/202328804021
ANIMMA 2023

Reactivity modulation experiments for nuclear data in CROCUS within a CEA-EPFL collaboration

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***Abstract*—In nuclear research reactors, integral experiments are powerful tools to measure integral core parameters, such as the delayed neutron fraction. Within the scope of the point kinetic approximation, reactivity modulation experiments can be used for probing the reactor transfer function and then infer integral parameters of the core.**

In this context, Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) and Ecole Polytechnique Fédérale de Lausanne (EPFL) have been collaborating for developing a probe device (PISTIL) and measurement setup adapted to the CROCUS zero power research reactor operated by EPFL (Lausanne, Switzerland).

Despite some mechanical limitations of PISTIL, its maximum reactivity worth was measured with a good precision and repeatability using different methods (8.82 ± 0.07 pcm), and its value is found rather close to the simulated one using TRIPOLI-4 (9.4 ± 0.4 pcm with JEFF-3.3). Above 1 Hz, the shape of the used modulation is pseudo-sinusoidal, with only a few well defined harmonics of excitation. The strongest harmonic only was analyzed using standard signal processing algorithms such as the Fourier transform and the Bartlett estimator. Twelve data points were produced in the range 0.5 Hz to 200 Hz, with uncertainty ranging from 1 % to 15 %. The prompt decay constant was measured at 150 ± 3 rad/s. Below 1 Hz, step-wise modulations were used with pseudo-random time sequences, which allowed exciting at once a large number of frequencies. Around 150 data points were produced in this particularly interesting frequency domain, between 1.6 mHz and 0.75 Hz, thanks to the use of three distinctive sequences with different base frequencies and overlapping ranges. The amplitude and phase of the RTF were measured satisfactorily, with uncertainties below 1 % for the strongest harmonics. The shape of the RTF was found consistent with the predictions of both JEFF-3.3 and ENDF/B-VII.1 libraries.

***Keywords* —Reactor physics, reactor transfer function, CROCUS, delayed neutron groups**

I. INTRODUCTION

INTEGRAL measurements in nuclear research reactors are used to provide information on core integral parameters, such as the delayed neutron fraction, as well as to probe the kinetics of delayed neutrons (DN). For this purpose, reactivity modulation experiments are employed to excite the kinetic response of the core, which is then recorded by neutron detectors. This method allows obtaining precise information on the reactor transfer function (RTF). In the point kinetic approximation, the amplitude and phase of the RTF are dependent on the DN kinetic parameters.

The Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) and Ecole Polytechnique Fédérale de Lausanne (EPFL) have been collaborating towards conducting modulation experiments in the CROCUS zero power research reactor operated by EPFL (Lausanne, Switzerland). The objective was to measure the RTF of CROCUS, its power and phase, on a broad frequency range and with the same device in order to acquire information on the DN (range 1 mHz - 1 Hz) but also on prompt neutrons (range 1 Hz - 100 Hz).

The study was conducted within a PhD work [1], which focused first on designing the modulation device, named PISTIL [2]. An experimental campaign was performed in CROCUS in June 2021. A significant part of the experiment was dedicated to characterizing the reactivity modulation profile.

This article gives an overview of the experimental setup and results obtained so far and gives an outlook onto the comparison with the point kinetic predictions using TRIPOLI-4 with JEFF-3.3 and ENDF/B-VII.1 libraries [3]–[5]. Conclusions are drawn for further experiments on RTF and specifically DN to be scheduled in CROCUS.

II. PROBING THE REACTOR TRANSFER FUNCTION WITH REACTIVITY MODULATION EXPERIMENTS

A. Expression of the point kinetic transfer function

In the framework of the point kinetics model [6], the neutron population in the reactor can be treated as a group, without taking into account the energy and position of each neutron. Only the kinetic behavior of the neutron population is considered $n(t)$. The neutron population is related to several integral parameters, namely the core's reactivity ρ, the effective delayed neutron fraction β_{eff}, the prompt neutron generation time Λ. By "effective", one refers to the fact that all fissile actinides in the core account for a part of the delayed neutron fraction. The production of neutrons is also related to the concentrations of the DN groups of precursors $Ci(t)$, where i is the index of the group, and i=1 refers to the longest lived DN precursors.

For discussing reactivity modulation, it is convenient to express the model in the frequency domain. By considering a small modulation of reactivity $\rho(t) = \rho_0 + \delta\rho(t)$ which gives rise to a modulation in the neutron population $N(t) = N_0 + \delta N(t)$, one can express the reactor transfer function (RTF) of the reactor by the following equation :

$$H(j\omega_0) = \frac{1}{N_0}\frac{\delta N(j\omega_0)}{\delta\rho(j\omega_0)}$$
$$= \left(j\Lambda\omega_0 + \beta_{eff}\sum_i^G \frac{j\omega_0 a_i}{j\omega_0 + \lambda_i} - \rho_0\right)^{-1}$$

In the previous equation, the notations are the following:

- j is the unit imaginary number;
- ω_0 is the pulsation (in radian);
- ρ_0 and N_0 are the time-averaged values of reactivity and neutron population
- a_i and λ_i are the delayed neutron abundance and time constant of the ith DN group. The sum of abundances is normalized to unit (i.e. $\sum_i^G a_i = 1$)
- G is the number of DN groups.

The RTF is a complex function which can be represented by calculating its modulus $\|H\|$ and argument *arg*(H) as a function of the modulation frequency. The kinetic parameters of the CROCUS reactor were calculated using TRIPOLI-4 associated to two nuclear data libraries: JEFF-3.3 and ENDF/B-VII.1 (see table I) and then fed into the RTF model described above. The results are plotted in figure 1. In the range of the prompt neutrons (frequency above 1 Hz), a good agreement is observed with a difference as low as a 2 % between the predictions. This is not the case below 1 Hz, in the frequency range of DN, where a difference of around 15% can be observed between predictions with JEFF-3.3 and ENDF/B-VII.1.

TABLE I
CROCUS KINETIC PARAMETERS COMPUTED WITH TRIPOLI-4

Parameter	JEFF-3.3	ENDF/B-VII.1
Effective DN fraction (pcm)	758.7 ± 1.4	737.2 ± 1.1
Generation time (μs)	47.703 ± 0.001	47.502 ± 0.001
DN average period (s)	12.3 ± 0.24	10.55 ± 0.13
Prompt neutron decay constant (s^{-1})	159.03 ± 0.29	155.20 ± 0.23

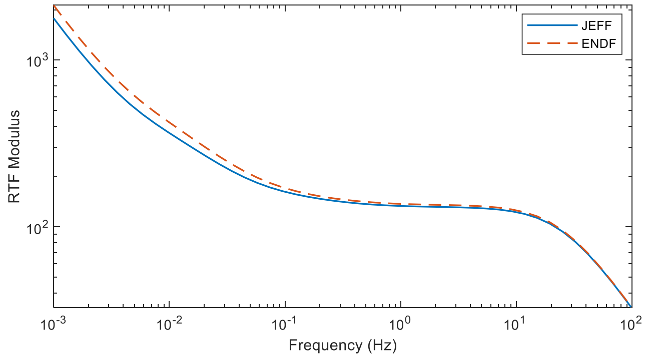

Fig. 1. Modulus of CROCUS RTF calculated with TRIPOLI-4 associated to JEFF-3.3 or ENDF/B-VII.1 nuclear data libraries.

B. *PISTIL, a device for reactivity modulation in CROCUS.*

CEA and EPFL co-developed a reactivity modulation device to meet the purpose to provide feedback on kinetic parameters [7] and the constraints of the CROCUS environment. PISTIL (*Periodic reactivity Injection System for Transients Induced Locally*) is an in-core fixture made of a thin aluminum tube in which a rotary modulator is inserted (see figure 2). The modulator is made of a stator and a rotor. The stator is an aluminum tube with two rectangular cadmium foils stuck on its outer surface with mirror symmetry. Inside of it is the rotor: a polyethylene rod with two cadmium foils facing the ones of the stator. The distance between the rotor and the stator is 0.1 mm.

The rotor is attached to a brushless motor thanks to a thin metallic string. When the motor is rotating, the cadmium foils are alternatively put face to face (when the motor angle is 0° or 180°) and at perpendicular directions (when the motor angle is 90° or 270°).

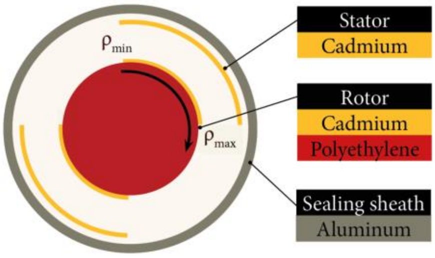

Fig. 2. Principle of PISTIL. Two cadmium sheets are fixed on a stator and a rotor, respectively. The reactivity worth depends on the respective positions of the foils, i.e. the rotation angle.

Because of the high cross sections ^{113}Cd(n,γ) with thermal neutrons, the local thermal neutron flux is depleted around the cadmium foils. The total reactivity worth of PISTIL, which was calculated with TRIPOLI-4 around -100 pcm, is loosely dependent on the position of the foils. The flux depletion is minimized when the foils are facing each others and maximized otherwise. The maximum modulation was calculated at 8.3 pcm, with an uncertainty of 4 pcm (at 1 sigma).

III. ENDF/B-VII.1 CROCUS REACTOR TRANSFER FUNCTION: RESULTS AND DISCUSSION

A. *The CROCUS experimental nuclear reactor*

CROCUS is a zero-power teaching and research reactor operated by EPFL. This pool-type reactor has a maximum nominal power of 100 W, but it is standardly operated around 1 W [8], [9]. Its core is 1 m in height and about 60 cm in diameter. It consists of two interlocked fuel zones of UO_2 (1.806 wt.% enriched) and metallic uranium (0.947 wt.%) rods, with square lattices of different pitches. The reactor is operated at atmospheric pressure and the moderator temperature is controlled. The power is adjusted either by changing the water level in the reactor vessel, or by moving two optional B_4C control rods. It has been used for numerous studies on neutron noise in recent years, both intrinsic and modulation [10], [11].

B. *Experimental setup*

For the purpose of the modulation experimental campaign that took place in June 2021, PISTIL was installed in the core center position. It was operated thanks to a numerical command (TrioMotion) linked to a servo-controller (XtrapulsePac) to command the brushless motor’s position. A National Instruments Labview program communicates with the numerical command through Ethercat connection. The acquisition frequency was set to 1 kHz.

For monitoring the reactivity modulation experiments, four fission chambers were installed in the reflector (Photonis CFUL-01, thermal neutron sensitivity around 1 c/s/(cm²/s), bias voltage 600 V). Their signals were fed to four EPFL-developed current-to-voltage amplifiers [12]. A National Instruments c-RIO mini-crate with a NI-9223 acquisition card was used to record the fission chambers signals.

The PISTIL monitoring software allowed for two operating modes: rotation at constant angular velocity or step-by-step motion. The first mode was used for modulation experiments above 1 Hz. In this mode, the modulation signal contained only a few harmonics, the main one, at the double of the rotation frequency, containing more than 90% of the signal power. For these experiments, the main harmonic (at a frequency twice the rotation frequency) was analyzed and produced one estimate of the RTF.

In the second operating mode of PISTIL, a time sequence of 90 ° angular steps was fed to the monitor software. The initial angular position was chosen so that the reactivity change between two steps is maximum. The time intervals between steps were chosen according to a modified 5-bits Maximum Length Sequence (MLS) given in reference [13]. In theory, by generating reactivity steps according to this pseudo-random series samples in time, ones can induce a pseudo-random signal associated to numerous harmonics of modulation. The length of the 5-bits sequence is equal to $2^{5+1} - 2 = 62$, which corresponds to a sequence of 62 s if the sampling time *dt* is chosen equal to 1 s. The first harmonics of the modulation signal is then 1/62 = 16 mHz. In practice, three time series were used by choosing *dt* equal to 1 s, 2 s and 10 s. The first harmonic of these series are respectively at 16 mHz, 8 mHz and 1.6 mHz. During the experiments, the modulation was repeated multiple times in order to acquire sufficient data for Fourier analysis and peak estimation.

C. Differential reactivity worth calibration

The estimation of the shape and intensity of the reactivity modulation is crucial to correctly analyze data and produce correct estimates of the RTF. Indeed, the power spectrum of the modulation signal is needed to get $\delta\rho(\omega_0)$.

The differential reactivity worth is a function that links the induced reactivity versus PISTIL angular position. By construction, the average of the differential reactivity worth is zero. Its peak amplitude gives the maximum reactivity worth achievable with PISTIL and the shape of the function allows calculating its power distribution, i.e. the power in each significant modulation harmonic.

A specific experiment was conducted to estimate the differential reactivity worth by rotating PISTIL at an angular speed of 4°/s (~11 mHz). First, by applying an inverse kinetics algorithm on the fission chamber signals, the reactivity versus time was obtained. Second, by using the angular position of PISTIL, it was possible to cut and average the many of the time signal into portions of 360° each, then average them to produce the experimental differential reactivity worth function.

From the shape of the curve (Fig. 4), one can see that the modulation signals are not perfectly sinus and not even symmetrical: the positive peaks are narrower than negative ones. This is possibly because of slight differences in the mass of the cadmium foils (the relative difference is about 1 %). Because of this characteristic, the power spectrum of the modulation is associated with several odd harmonics. A five harmonics ARMA model was used to fit the reactivity worth and obtain the power distribution in the harmonics.

From the peak amplitude of the curve, a maximum reactivity worth of about 1.1 ¢ was estimated (1 ¢ = β_{eff}/100 pcm). As expected, there is a significant difference between the JEFF and ENDF predictions (cf. table II). This can be explained by the gap between the predicted RTF at the modulation frequency, as illustrated in figure 1).

One conclusion to be drawn is that estimated reactivity worth by this method cannot be used to normalize the experimental RTF. On the contrary, the shape of the reactivity modulation, which is independent on the reactivity scale, can indeed be used in order to predict the power spectrum and the distribution of harmonics induced by PISTIL. Based on the assumption that the power distribution does not change with the rotation frequency, the modulation experiments at any frequency was analyzed and rescaled using the reactivity spectrum. The authors refer to [1] for more explanations on the data processing.

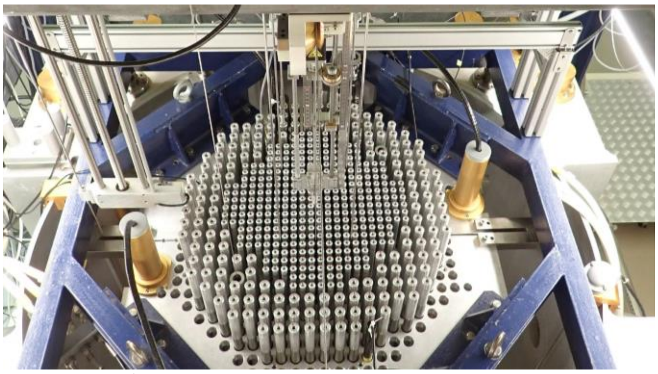

Fig. 3. View of PISTIL inserted in the central channel the CROCUS reactor.

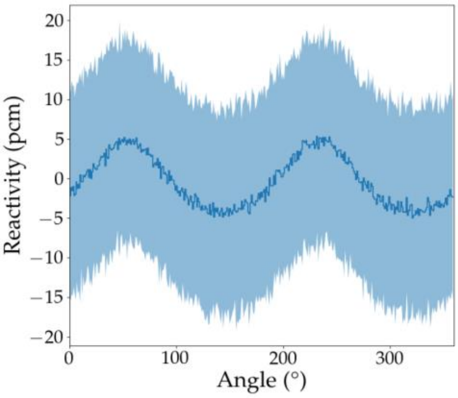

Fig. 4. Differential reactivity worth of PISTIL using an inverse kinetics method. The solid blue line is the curve obtained by averaging the many repetitions (background grey line).

TABLE II
PISTIL REACTIVITY WORTH OBTAINED WITH JEFF-3.3 AND ENDF/B-VII,1.

	ENDF/B-VII	JEFF3.3	Difference
Reactivity worth in ¢	1.06	1.15	7.8 %
Reactivity worth in pcm	7.84	8.76	10.5 %

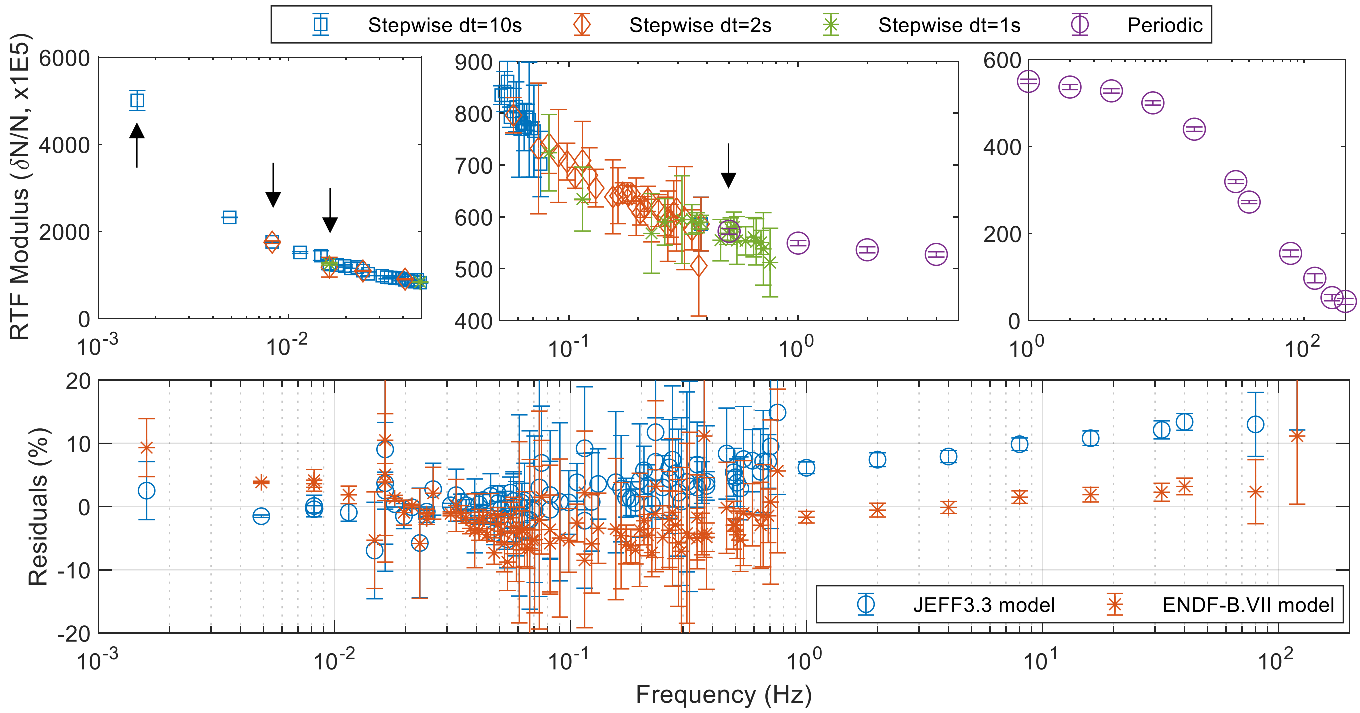

Fig. 5. Experimental estimates of CROCUS modulus on three frequency ranges (upper graphs). Relative residuals from the comparison with models (bottom).

D. Experimental estimates of CROCUS reactor transfer function.

The experimental estimates of CROCUS RTF are presented in Fig. 5 (upper graphs). Because the scale of the data is large, it was split into three sub-graphs.

In the prompt neutron range (right, above 1 Hz), each data point corresponds to an experiment with periodic modulation. In the low frequency range (left, below 50 mHz), three stepwise experiments are represented. The data point of the first harmonic of each experiment is pointed by an arrow. In the intermediate range (middle, between 50 mHz and 5 Hz), the four experiments are represented. One can see that there is an excellent agreement between the various estimates. This is especially the case at 0.5 Hz with a difference of less than 0.1 % between the periodic and stepwise modulations.

E. First comparison with point kinetics models.

To compare the experimental data points with JEFF-3.3 and ENDF/B-VII.1 models, it was necessary to rescale the models. This is because it was not possible to calibrate the reactivity worth of PISTIL independently of a nuclear data library (see section III.C). Rescaling the models was done by multiplying the prediction by the reactivity worth of PISTIL, expressed in $, estimated by inverse kinetics with each nuclear data library. This step has the drawback of possibly introducing a bias coming from the reactivity estimate at low frequency.

The difference between data and models was computed and then divided by the data to obtain relative residuals. They are plotted on figure 5 (bottom graph). One can see that there the two models exhibit different behaviors at low and high frequency. On the one hand, the 6-groups model associated to ENDF/B-VII.1 show a better agreement with the data in the prompt neutrons energy range (above 1 Hz). This tends to indicate that the DN fraction of CROCUS is best predicted by ENDF/B-VII.1.

On the other hand, the 8-groups model associated to JEFF-3.3 show a better agreement with the data in the DN neutron frequency range (below 0.1 Hz). This is particularly the case below 0.01 Hz, which tends to indicate that JEFF-3.3 predicts the behavior of the DNs better than ENDF/B-VII.1.

F. Least square fit of the prompt decay constant.

We chose to analyze the periodic modulation experiments on the frequency range between 2 Hz and 120 Hz, with a simplified RTF model, which has often been used to analyze branching noise experiments [10]:

$$\|H\| = \frac{\delta\rho}{\beta}\frac{1}{\left|1 + j\omega/\alpha_p\right|}$$

Using a weighted non-linear least square fit, the objective was first to obtain an estimate of the prompt decay constant:

$$\alpha_p = 147.2 \pm 3.4 \text{ s}^{-1}.$$

This value compares rather well with the calculated values (see table I), with a relative difference of -5 % as compared to ENDF/B-VII.1, as well as with the reference value previously published [12].

From the amplitude factor, it was also possible to estimate the reactivity worth of PISTIL, expressed in $: $\delta\rho / \beta = 1.07\times10^{-2} \pm 10^{-4}$. It is interesting to note that this estimate is independent from the nuclear data libraries and falls in the very middle of the interval of values from inverse kinetics (see section III.C and table II), but with a much lower uncertainty.

IV. CONCLUSIONS AND OUTLOOK

In the context of improving DN nuclear data, CEA and EPFL have collaborated towards measuring the RTF of the CROCUS reactor by making use of reactivity modulation. PISTIL, a dedicated reactivity modulation device was co-developed for that purpose and used for a first campaign in June 2021. The RTF was estimated over a wide frequency range, from 1.6 mHz to 200 Hz. More than 150 data points were produced, most of them in the DN frequency range. These data can be used to estimate integral parameters of CROCUS, such as the prompt decay constant and the DN abundances.

Based on the results presented here, it is envisaged to go further in estimating the RTF of CROCUS. Indeed, more precise measurements are needed to estimate the DN abundances, within the frame of the point kinetics equation. In the future, and following the CORTEX European project [14], PISTIL could also be used for improving the detection and localization of spurious perturbations in nuclear reactors.

ACKNOWLEDGMENT

This work was funded by the French research institute regrouping CEA, EDF and Framatome. The authors would like to thank the EPFL and the operating team of CROCUS for their support.

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