EPJ Nuclear Sci. Technol. **6**, 55 (2020)

https://doi.org/10.1051/epjn/2020017

EPJ Nuclear Sciences & Technologies

Available online at:
https://www.epj-n.org

Regular Article

Open Access

Review of kinetic modulation experiments in low power nuclear reactors

Yifeng Jiang[1,*], Benoit Geslot[1], Vincent Lamirand[2], and Pierre Leconte[3]

[1] DES/IRESNE/DER/SPESI/LP2E, Commissariat à l'Energie Atomique et aux Energies Alternatives, 13108 Saint Paul-lez-Durance, France
[2] Laboratory for Reactor Physics and Systems behaviour, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
[3] DES/IRESNE/DER/SPRC/LEPh, Commissariat à l'Energie Atomique et aux Energies Alternatives, 13108 Saint Paul-lez-Durance, France

Received: 28 April 2020 / Received in final form: 4 August 2020 / Accepted: 21 September 2020

Abstract. The safety improvement of nuclear reactors requires continuous efforts in understanding the fundamental physical quantities related to the fission process. In neutronic models, the reactor dynamics is covered by the kinetic parameters to characterize the temporal behavior of the neutron population subject to perturbations. The reactor transfer function is a frequency domain analogy of this temporal description. It can be measured experimentally through transfer function analysis via noise analysis or kinetic modulation, for the study of reactor stability and kinetic parameters. This paper summarizes the experimental measurements of reactor transfer function through kinetic modulation. Extensive work have been conducted experimentally, starting from the beginning of reactor physics research. An overview is given regarding various experimental designs and conducted analyses. The concepts of the modulation system are also discussed. The current work is limited to online contents and internal archives of CEA Cadarache due to difficulties in accessing references traced back to 1950s.

1 Introduction

The understanding of reactor dynamics, which are governed by the behavior of the in-core neutron population, is crucial for the operation and safety analysis of nuclear reactors. When a reactor is close to criticality, the so-called reactivity and kinetic parameters can be defined as integral properties of the entire core to describe the temporal evolution of the neutron population, referred to as the point kinetics (PK) approximation derived from the neutron transport equation [1]. Inspired by control system engineering, a comprehensive understanding of reactor system stability was developed within the PK framework, known as the reactor transfer function (RTF) analysis [2]. The practical measurement of this transfer function in the reactor core relies on Fourier analysis using either neutron noise methods or modulation methods.

Reactor noise, also known as "pile noise" concerns the reactor power variation subject to statistical fluctuations due to branching in fission processes [3–5] during stable reactor operation. Therefore, few modifications of the core configuration are required to conduct noise measurement. Nevertheless, the interpretation of experimental data is complex due to the presence of parasitic noise sources, e.g., vibration induced effects and noise generated by electronic devices.

The modulation method, by contrast, introduces a controlled modulation of the reactor power. Additionally, the amplitude of the modulation, adjusted by the experimental design, makes it possible to override the uncertainties due to undesired noise sources including the pile noise [6]. The method was used extensively in nuclear data improvement [7] owing to the precision of the data. A periodic modulation system of reactivity or source strength, referred to as a modulator, produces a periodic variation of the reactor power. The measured RTF yields information about the kinetic parameters and the modulation magnitude, as will be shown in the next section. Therefore, by assuming the former as known the reactivity worth of samples is measured. The inverse application as the measurement of kinetic parameters, is investigated in various applications using a known modulation [8].

Experimental studies on the modulation method first appeared in the 1950s. A considerable amount of modulator designs and in-core experiment methodologies are documented. At the present time, much fewer modulation

* e-mail: yifeng.jiang2@hotmail.com

studies can be found in the literature. Nonetheless, the method is being actively used and its new possible applications have been suggested [9]. To the authors' knowledge, multiple modulators have been built, tested [10,11] and operated [12–16] in the last 10 years.

At the experimental physics, instrumentation and safety studies service (SPESI) of CEA Cadarache, a new modulation device is currently under development. Its purpose would be to offer flexible, accurate and high performance modulation capabilities while satisfying the enhanced safety requirements for in-core experiments.

This paper is part of the design studies realized for such a new modulation device. We intend to summarize the experimental work conducted in determining the RTF of low power reactors and designing the associated modulators, for studies ranging from the 1950s to 2020. Considering the span it would be nearly impossible to give an exhaustive review. Therefore, cited work are selected to be representative in the experimental methodology or in the modulator designs. Section 2 introduces the mathematical background of the RTF analysis. Section 3, we then review the applications of the RTF experimental studies. An overview of reactivity or source modulator designs is given in Section 4.

2 Theory

2.1 Point kinetic model

In a nuclear system, the temporal evolution of the neutron population $N(t)$ and that of delayed neutron precursors $C_i(t)$ are described in the PK approximation as [17]:

$$\begin{cases} \dfrac{dN(t)}{dt} = \dfrac{\rho(t) - \sum_i^n \beta_i}{\Lambda} N(t) + \displaystyle\sum_i^n \lambda_i C_i(t) + Q(t) \\ \dfrac{dC_i(t)}{dt} = \dfrac{\beta_i}{\Lambda} N(t) - \lambda_i C_i(t) \quad \text{for } i = 1, 2, ..., n \end{cases} . \tag{1}$$

The involved parameters are the reactivity $\rho(t)$, the source strength $Q(t)$ and the kinetic parameters: the prompt neutron generation time Λ (s), the delayed neutron fractions β_i and the associated decay constants λ_i (s^{-1}) for the precursor group i in a n-group approximation.

The PK model can be represented as a Linear Time Invariant (LTI) system shown in Figure 1. Such a system is characterized in the frequency domain by a transfer function: a ratio between complex amplitude of the output and the input of the system.

The feedback effects will be first considered negligible for the derivation of the Zero Power Transfer Function (ZPTF). This is consistent for reactors operating at low power (amount would be dependent on fuel type) or the Zero Power Reactors (ZPRs).

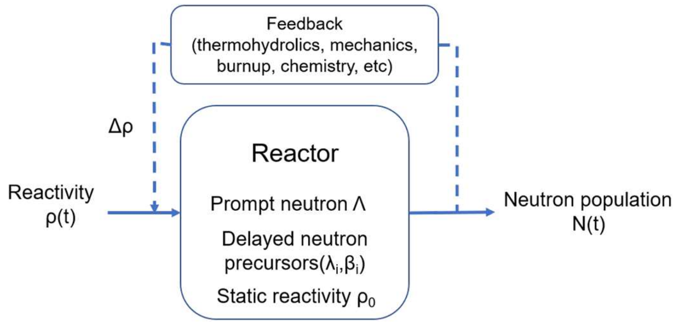


Fig. 1. LTI representation of a nuclear reactor in the framework of PK.

2.2 Derivation of the zero power reactor transfer function

Applying Laplace transform to small perturbations $\rho(t) = \rho_0 + \delta\rho(t)$ of an initial steady state (i.e. critical or subcritical), the ZPTF is obtained [18]:

$$G(s) = \frac{1}{N_0}\frac{\delta N(s)}{\delta\rho(s)} = \frac{1}{\Lambda s + \sum_i^n \frac{\beta_i s}{s+\lambda_i} - \rho_0}. \tag{2}$$

The initial condition $\lim_{t\to 0^+} \delta N(t) = \lim_{t\to 0^+} \delta\rho(t) = 0$ is in accordance to the initial steady state hypothesis. The variable s stands for the complex variable, with units s^{-1}.

A similar derivation for a neutron source perturbation gives the source transfer function [19]. Note that it is different from the ZPTF by a normalization constant Λ/N_0:

$$G_q(s) = \frac{1}{N_0}\frac{\delta N(s)}{\delta Q(s)} = \frac{\Lambda}{N_0} G(s). \tag{3}$$

2.3 Reactor transfer function with feedback effects

The ZPTF characterizes a nuclear system without feedback effects, which is an "open-loop" system in analogy of the control theory. With a proper multiphysics coupling to PK, a power reactor can be considered as a "closed-loop" system and the RTF becomes:

$$G_p(s) = \frac{G(s)}{1 + G(s)H(s)} \tag{4}$$

where $H(s)$ is the power-to-reactivity feedback transfer function to account for temperature related effects.

The closed-loop RTF can be measured with the same or similar modulation experiments (that will be detailed in Sect. 4) as the ZPTF that is determined for a low power configuration. The knowledge of these two transfer functions gives an estimation of $H(s)$ based on experimental results using equation (4). The $H(s)$ is rather determined analytically by thermomechanical modelings than being measured experimentally. Therefore, modulation experiments allow the validation of analytical modelings, so that they can be applied to reactor operation and stability studies, and can be further extended to system analysis

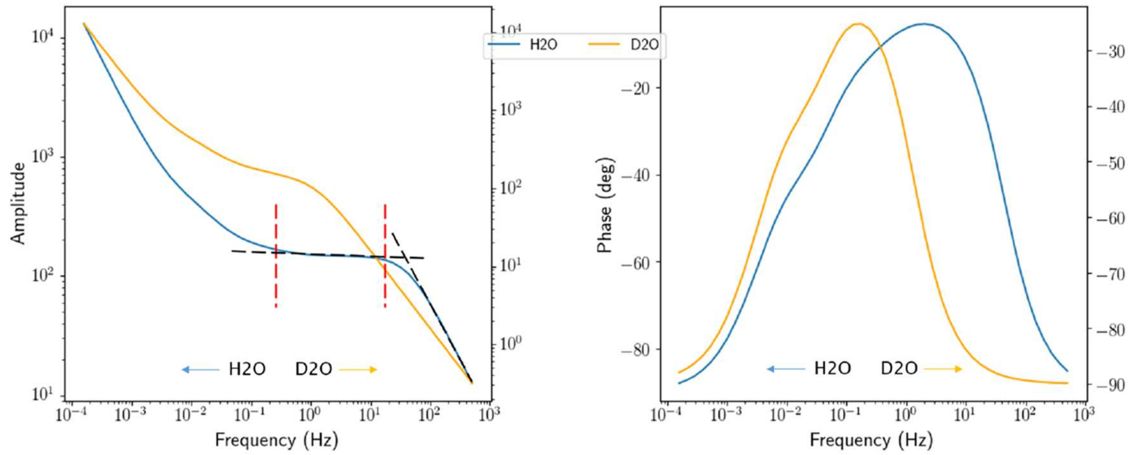


Fig. 2. Typical ZPTF for light and heavy water moderated reactors.

of nuclear power plants. The interested reader is referred to [20–22].

2.4 Experimental consideration

The modulation experiments are conducted with the introduction of a periodic reactivity or source modulation of angular frequency ω (rad s^{-1}). The resulting reactor frequency response is expressed by substituting the complex variable s in $G(s)$ by $j\omega$:

$$G(j\omega) = \frac{1}{a(\omega) + jb(\omega)} \quad (5)$$

where $j^2 = -1$ and

$$a(\omega) = -\rho_0 + \sum_i^n \frac{\beta_i \omega^2}{\lambda_i^2 + \omega^2} \quad (6)$$

$$b(\omega) = (\Lambda + \sum_i^n \frac{\beta_i \lambda_i}{\lambda_i^2 + \omega^2})\omega. \quad (7)$$

The interpretation of the experimental data resorts to the amplitude $\|G(j\omega)\|$ and the phase $arg[G(j\omega)]$ of the ZPTF. An example of their profiles is illustrated in Figure 2, with the delayed neutron data taken from the Keepin data set [23], $\Lambda = 25\ \mu s$ for a light water reactor (LWR) and $\Lambda = 1000\ \mu s$ for a heavy water reactor (HWR). A detailed discussion is given in [24] about the contribution of prompt and delayed neutrons in the amplitude and the phase response.

Experimentally, the observable is the recorded signal of a neutron detector, which allows the inference of the temporal evolution of the in-core neutron flux level. The amplitude and phase of the ZPTF are estimated as:

$$\|G(j\omega)\| = \frac{\|\delta N(j\omega)\|}{N_0} \cdot \frac{1}{\|\delta\rho(j\omega)\|} \quad (8)$$

$$arg[G(j\omega)] = arg\left[\frac{\delta N(j\omega)}{N_0}\right] - arg\left[\frac{\delta\rho(j\omega)}{\|\delta\rho(j\omega)\|}\right]. \quad (9)$$

As shown in equation (8) the analysis of ZPTF amplitude measurement requires a normalization over the initial neutron population and the reactivity modulation amplitude before direct comparison with theoretical values. For this purpose, the amplitude calibration of the modulation is mandatory. By contrast, the phase lag between the input modulation and the output is independent of the amplitude, as indicated by equation (9).

It should be noted that the knowledge of $\delta\rho(j\omega)$ has to be inferred from a parameter $x(j\omega)$, or eventually a combination of multiple ones. $x(j\omega)$ quantifies the perturbation applied to the reactor (such as a mechanical motion, discussed in Sect. 4) that generates a modulation of reactivity effect. $\delta\rho(j\omega)$ and $x(j\omega)$ do not necessarily share the same frequency domain behavior in terms of amplitude or phase. Therefore, a calibration or an estimated relationship (the "transfer function") between them is of importance in the RTF analysis.

The experiment is conventionally done with at least one ex-core neutron detector (e.g., fission chambers, ionization chambers), so that the PK approximation remains valid in measurements. Detectors located at different distances from the modulator could record different frequency responses in the amplitude or the phase. Therefore with a combination of multiple detectors, in-core or ex-core, the investigation can be extended to study spatial kinetic effects.

Some time constants of fluctuating phenomena in light water moderated nuclear reactors are summarized in Table 1. The measurement of ZPTF or RTF in a certain frequency range would yield the reactor dynamic response induced by the corresponding phenomenon, when the perturbation is small so that the reactor can be considered as an LTI system. The differences in the order of magnitude between these phenomena suggest interest in conducting modulation experiments (i) at low frequency ($\sim$ mHz to $\sim$ Hz) to measure the dynamics of delayed neutrons and

Table 1. Time constants of fluctuation phenomena in light water reactors (after [25]).

Phenomena	s^{-1}
Delayed neutron effect	10^{-3} to 1
Thermohydraulic effect	0.1 to 10
Prompt neutron effect	1 to 100
Subcooled boiling effect	10 to 3000
Space-dependent effect	1000 to 10^6

thermohydraulic effects; (ii) at high frequency (up to ~ kHz) for prompt neutron related and spatial effects.

3 Overview of reactor transfer function measurement

The experimental determination of the RTF, to the extent of this work, is based on the detection of reactor power variations during a periodic modulation in reactivity or source strength. In this section, a historical review of modulation experiments for RTF measurement is given.

3.1 Studies before 1980s

The transfer function analysis was extensively applied in the early years (1950–1980) of reactor physics research. A large number of ZPTF determination studies can be found in the literature. They were either conducted on ZPRs or power reactors in a low-power configuration. Conferences exclusively dedicated to the topic, during the 1960s, were found in the literature [8,26,27].

The initial motivation was to investigate reactor stability analysis or anomaly detection, such as feedback effects, flux tilt or boiling. This kind of analysis was first conducted in 1952 through reciprocal movement of a control rod on CP-2 [6] and then applied to different types of research reactors.

A number of studies during this period investigated kinetic parameter measurements at zero power [28–34]. The measured ZPTFs were compared to the analytical one with a chosen set of kinetic parameters, or alternatively used for the estimation of kinetic parameters of interest in the given reactor. Works on fast reactors focused essentially on the prompt neutron generation time and the prompt decay constant $\alpha = \beta/\Lambda$, while in the case of thermal reactors the total delayed neutron fraction or number of groups in the PK model were investigated. Several authors [35–38] addressed the observed discrepancies between experimental data and theoretical values using previously evaluated kinetic parameter sets. However, no clear common conclusion could be drawn due to uncertainties in experimental data, limits in data acquisition systems and computational tools.

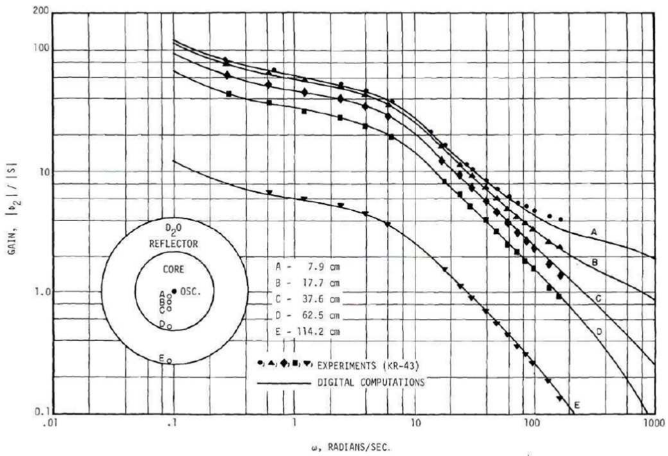
For power reactors the transfer functions were determined using a two-step approach: first, measurements at zero power were conducted and then at successively higher power. This allowed the determination of the ZPTF and the power RTF, and consequently the power-to-reactivity feedback. Therefore the measurements also contributed to analytical modelings in thermohydraulics. These measurements are documented for frequencies from 1 mHz to 8 Hz [29,36,39,40], which is consistent with the frequency range of interest for thermohydraulic parameters (e.g. void fraction, flow velocity).

While the common approach in the measurement transfer function assumes a point-like reactor behavior, several works [41–44] investigated spatially dependent transfer function measurements in comparison with analytical predictions. These studies were based on the code development in spatial reactor kinetics. Spatial and spectral effects are taken into account through a multienergy group neutron diffusion equation in a multi-region reactor model. It was shown that, for large or loosely coupled cores the measured ZPTFs were in accordance with the spatial kinetic models and differed from PK results [17] at high frequency with respect to the prompt decay constant α, as shown in Figure 3. Remarkably, the reported space-dependent transfer function were mainly measured in systems moderated or reflected by heavy water and graphite. A possible explanation is the low values of α in these systems, which makes the spatial effects much easier to observe than LWRs or fast reactors. In the work of [45], two periodic modulations 180° out of phase were generated to emphasize the excitation of spatial mode fluxes in the ZPTF measurement. Nevertheless, the complete suppression of the fundamental mode was nearly impossible due to limitations in the mechanical drives.

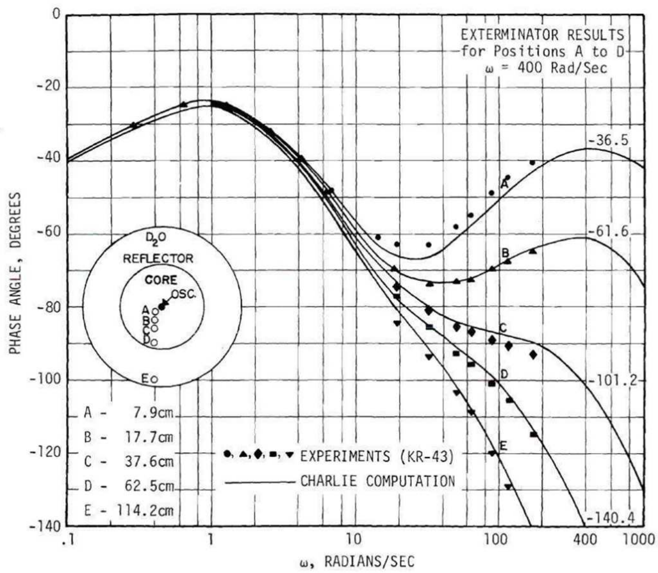
The energy dependence of the transfer function measurement is not only impacted by the reactor behavior itself, but also the detection process. The topic was however rarely addressed in the early literature for modulation experiments. Variations of the neutron spectrum in the near surrounding of the detector influence the neutron detector's efficiency and consequently the ZPTF amplitude, especially when the detector is close to the localized modulation [46]. Several possible methods to consider this impact can be found in the recent literature for low frequency (smaller than α) measurements. One approach is to compare measurements made at different detector positions using the ZPTF phase response, which is independent of the detector efficiency [47]. [16] suggests that the imaginary part of the ZPTF shows few spatial and spectral dependence on the core response. Therefore, for the purpose of comparison, an arbitrary normalization can be chosen so that the imaginary parts of the ZPTF measurements are as close as possible to each other.

3.2 After 1980

The subject seemed to be sidelined between 1980 and the beginning of the twenty-first century. The number of studies on modulation experiments reduced significantly. Only a few references can be cited [48–51] during this period. A possible explanation for this observation can be the decrease in the number of operating ZPRs. Advances in code development for reactor physics simulations may also made the experimental modulation studies less attractive in inferring the core parameters.



(a) Amplitude response



(b) Phase response

Fig. 3. Experimental transfer function of the NORA reactor (Institute for Energy Technology, Norway) compared with computations [42].

Starting from 2000, several modulation studies with a focus on the determination of kinetic parameters, especially for delayed neutron parameters, are found in the literature [13–15,52–54]. The kinetic parameter evaluations in major nuclear data libraries rely essentially on experimental data, and the impact of undocumented uncertainty and experimental conditions of various experiments are difficult to quantify. Discrepancies observed in the libraries led to inconsistency in the computation of reactor kinetic response. The international effort in the improvement of delayed neutron data [55] could be part of the motivation of the new experimental kinetic modulation works.

Since the emphasis was put on the delayed neutron behavior, rather slow modulation (from 0.001 Hz to up to 2 Hz) were performed, which were much lower compared to earlier studies. In order to improve the precision of the acquired data, long time acquisition is required with respect to the modulation period. In accordance, the amplitude of the modulation was observed to be in the order of 1 cent to limit the power drift. Additionally, the digital signal processing methods were extensively used over the recorded modulation input to extract the information contained in a large number of frequency harmonics. A similar approach in the data analysis was adopted in these works: kinetic parameter fittings were conducted on experimental data, and then compared to computed values with kinetic parameter sets from common nuclear data libraries. An example of the comparison is given in Figure 4.

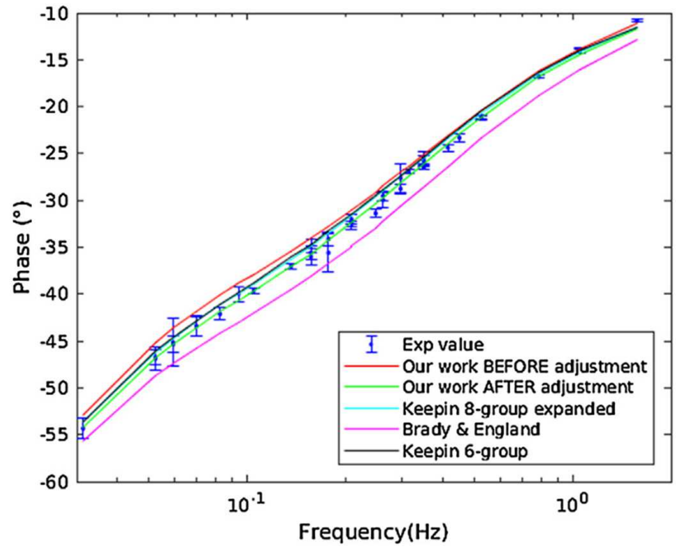


Fig. 4. ZPTF phase measured in the MINERVE reactor [54] compared with equivalent results with the kinetic parameters from Brady & England (ENDF/B-VIII.0β4 [56]), Keepin 6-group (JENDL-4.0 [57]) and Keepin 8-group expanded (JEFF-3.3 [58]).

4 Review of design of modulation systems

4.1 Source modulation

Neutron source modulations were primarily applied to subcritical reactors and accelerator-driven systems, known as the Pulsed Neutron Source (PNS) techniques [17]. In a PNS experiment, periodic neutron pulses are injected into a subcritical system and the resulting power transients are measured. Although the measurements are conventionally analyzed as time series, Fourier analysis of PNS experiments were also found in the literature [59,60]. However, due to the distortion of the PK behavior, spatial corrections are required at high source modulation frequency. Another source modulation approach, as used in the work of [61], consists in a neutron source coupled with a rotating neutron poison disc that modulates the thermal neutron intensity periodically, while the contribution at higher energy remains almost constant. It should be noted that source modulation is not exclusively performed using pulses: continuous modulation (e.g., sinusoidal) is also technologically viable [62]. Thorough discussions and considerable amount of works on the subject are covered in [63–65].

The source intensity in past works varied from 10^3 to 10^{14} $\mathrm{n\,s^{-1}}$, and the source size ranged from several centimeters to meters, covering compact sealed neutron tubes [66–68] and boosters [69,70]. Commercialized miniature neutron sources containing Cf-252 in sealed casings were mentioned in the literature. The spontaneous fission of this isotope produces about 2.3×10^6 $\mathrm{n\,s^{-1}\,\mu g^{-1}}$. Studies conducted in [71–73] used the mechanical oscillation of compact sources for reactivity and kinetic parameter measurements. Specific nuclear reactions can be used to generated mono-energetic neutrons, for instance ^{7}Li(p,n)^{7}Be (keV neutrons), ^{3}H(p,n)^{3}He (MeV neutrons), ^{2}H(d,n)^{3}He (2.5 MeV neutrons) and ^{3}H(d,n)^{4}He (14 MeV neutrons). Neutrons with continuous energy spectra can be generated with electron linear accelerators, as the result of Bremsstrahlung photons interacting with fissile materials.

4.2 Reactivity modulator

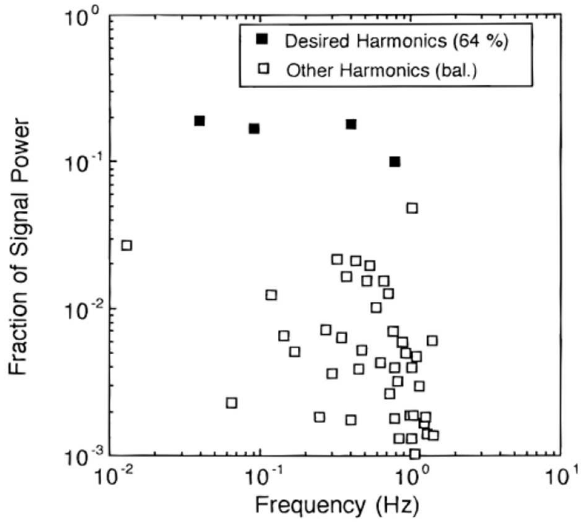
A reactivity modulator generates a periodic reactivity variation of the core. The most widespread modulator concept was the so-called pile oscillator [7]: the reactivity variation is induced by an oscillatory motion (e.g. linear motion or rotation) of a sample material in order to measure its reactivity worth. The same concept was also used for RTF measurements.

4.2.1 Linear modulator

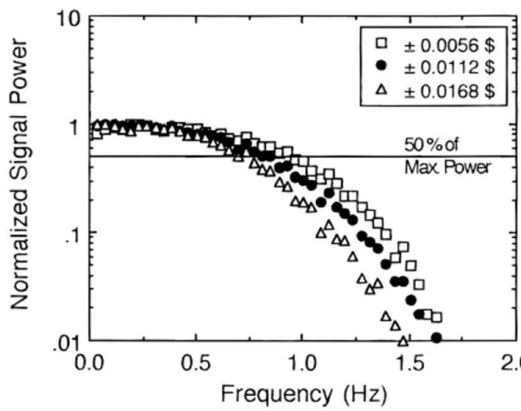
Numerous modulator experiments have been conducted using a linear motion oscillator, in the analogy of vertically positioned fuel rods or control rods. Experiments using existing control rods of the reactor to study its dynamics is relatively simple to implement. The reactivity variation is produced by periodic insertion and extraction of the oscillator. The generated modulation depends on the velocity of the mechanical motion.

The linear motion of control rods or safety rods, however, was usually limited to approximately 5 Hz. The local flux depletion induced by the control rod affects the validity of PK approximation and additional corrections for spatial effects are required for RTF analysis [43,74]. Alternatively, oscillator rods of low reactivity worth were designed to allow fine adjustment of reactivity effects. A popular concept in this aspect is the system containing an outer stationary layer (stator) and an inner movable layer. The stator consists of a neutron poison that screens out efficiently the influence of thermal neutrons to the inner layer. Thus the oscillator reactivity is minimized when the inner layer is nested in the stator. An example of such a system is illustrated in Figure 5, including a moving piston (right) and a stationary sleeve (left). Different relative positions between neutron-absorbing paint (Gadolinium), in white, have variable reactivity worth (up to a maximum of about 5 pcm) due to the screening effects.

Fig. 5. Linear self-shielded reactivity modulator in ZED-2 reactor: a piston (right) and sleeve (left) coupling [15].



(a) MFBS (Multifrequency binary sequence)



(b) QRBS (Quadratic residue binary sequence)

Fig. 6. Power spectra of pseudo-random binary reactivity modulations in Experimental Breeder Reactor-II (Argonne National Laboratory, 1999 [51]).

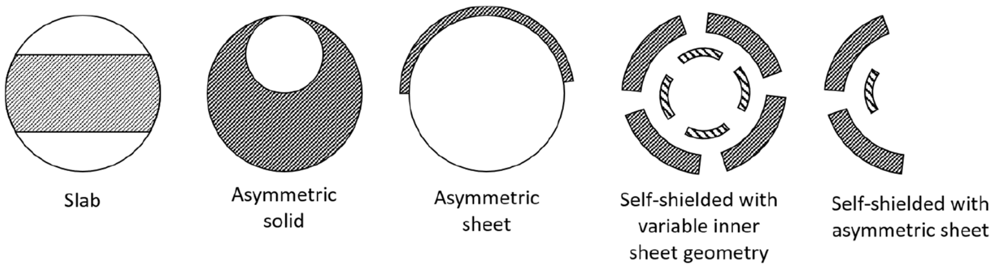


Fig. 7. Typical geometries of rotary modulators (after [78]).

Table 2. Typical rotary rod oscillator in past experimental studies.

Material	Geometry	Reactor	Reactor type	Power	Frequency (Hz)
B4C + Na	Asymmetric	Enrico Fermi [36]	SFR	~0	0.001–10
B4C				100 MW	
Boral poison	Self-shielded	SRE [79]	SFR	~0	0.05–20
Cd+H2O	Self-shielded	KEWB [30]	Thermal, solution fueled	~0	1–260
Enriched and natural Uranium	Asymmetric	Zephyr [29]	Fast ZPR	~0	0.002–3
Cd+H2O/Cd+U	Self-shielded	SPERT-I-B [80]	LWR	1 kW	0.002–18.4
Cd	Self-shielded	LPTR [32]	LWR	Subcritical[1]	0.005–150
		GTRR [42]	HWR	~0	0.1–40
Cd+PE[2]	Asymmetric	OSURR [33]	MTR	1 kW	0.013-60

[1] Critical with photo-neutron source.
[2] Polyethylene.

The driving system of linear oscillator has its capacity reduced for high frequency motion due to structural vibration and limits in the transmission system. Therefore, discontinuous pseudo-random binary motion [15,38,51,75,76] is preferred for the high flexibility it offers to the experimental setup. This kind of motion is driven by a binary sequence generated with a deterministic algorithm and has a similar statistical behavior to true stochastic sequence. Its rich frequency spectra (a large number of harmonics) lead to the possibility to simultaneously measure the RTF at multiple frequencies by a proper design. As shown in Figure 6, dedicated algorithms can be used to generate binary sequences with desired spectral properties [51,77]. The use of a linear actuators were observed to distort the designed signal from square-like to trapezoid-like ones. The practical form of the modulation input had to be taken into account for Fourier analysis.

4.2.2 Rotary modulator

Mechanical vibrations induced by the linear motion also impact inevitably the measured frequency response, which led to the development of rotary modulators. Compared to linear systems, rotary rods offer a much larger range of operational frequencies while the mechanical driving system remains simple and stable. This was of interest for wide frequency band modulation experiments. The reactivity variation can be generated either with an azimuthal asymmetry in the geometry or in the composition, or through a rotor-stator coupling with self-shielding effect. Several representative rotary rod concepts are shown in Figure 7. The reactivity modulation frequency is found in the literature up to 260 Hz [32], thanks to the performance of rotary shafts. Almost all modulation experiments were conducted with a uniform speed continuous rotation, with the exception of the work of [40] in the 10 MW JRR-3 reactor. Remarkably, the authors applied a pseudo-random rotary motion up to 70 rad s^{-1} over a self-shielded modulator. The maximal frequency, which is much lower compared to continuous rotation experiments, might be a choice for compatibility with on-power applications.

In terms of modulator material, the most commonly used poisons were cadmium and boron as shown in Table 2. In several modulator designs, the neutron poison was coupled with moderating material to adapt the modulation efficiency to fast reactor spectrum. Aluminium was mostly chosen as the structural material for its transparency to neutrons.

The coupling of multiple modulators in the same reactor, in order to broaden the measurable frequency range and operational conditions, was also studied in the literature [10,36]. Indeed, separating low/high frequency modulations or low/high power experiments relieves design and safety criteria over the drive system. Figure 8 shows a combination of two modulators that are functional at different frequency ranges, which were recently used in the AKR-2 reactor [11]. It should however be noted that a frequency range overlap was required to analyze experimental data recorded with different modulators (having different moderation strengths) as a whole for RTF determination.

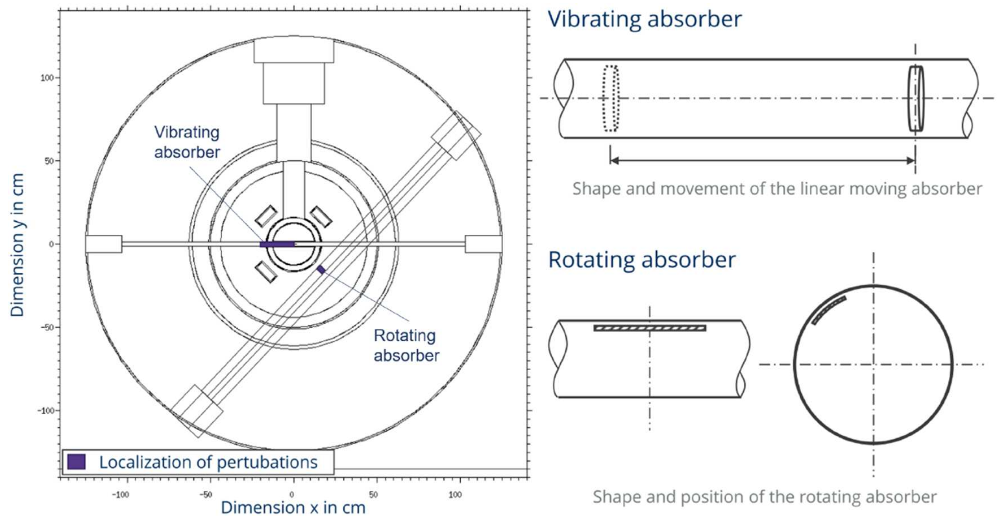


Fig. 8. Vibrating and rotating modulators in the AKR-2 reactor (after [10]).

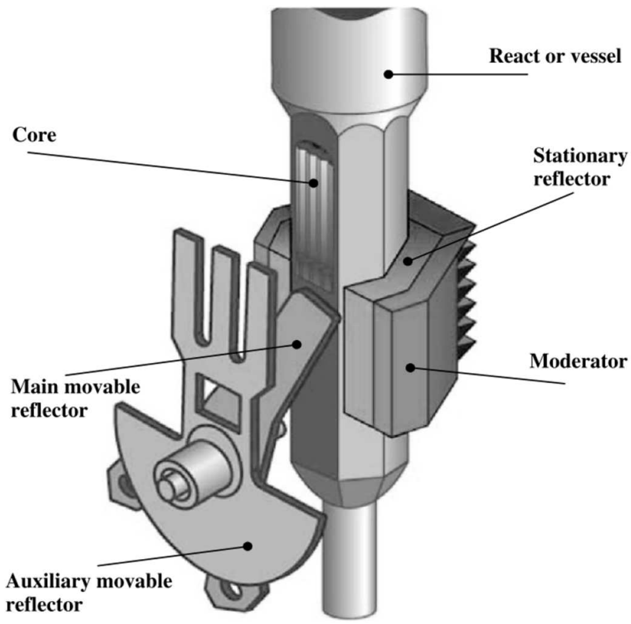


Fig. 9. Reactivity modulator of the IBR-2 reactor: two rotating reflectors [85]).

4.3 Miscellaneous modulators

Alternative modulator concepts to mechanical motions were also suggested and investigated in the literature. The designs were based on special features of the dedicated reactor type, thus they required less effort in core configuration modification than mechanical modulators. In pool-type reactors, reactivity modulation can be produced by the variation of in-core water level. [81] suggested a pneumatic system for water level oscillation in a heavy water moderated pool-type ZPR. A similar concept was tested in the CANDU reactors [82] where light water compartments were oscillated to measure kinetic parameters. In the work of [83] a boiling water loop was built to determine the transfer function between void fraction and flow rate, while the latter varied periodically. The experiment was however conducted out-of-pile. The measured transfer function was coupled to the ZPTF for the overall RTF estimate of boiling water reactors. A type of research reactor dedicated to neutron time of flight experiments is found in the literature [84]. This so-called periodic pulsed reactor has a moving reflector or fuel element, as shown in Figure 9.

References [86–88] discussed using variable magnetic fields or laser light as a reactivity control system, by successive polarization and depolarization of atoms. This relies on the large spin-dependence of neutron scattering and capture cross sections. Neutron spin filters following this principle are used for fundamental physics application [89]. However, no experimental device has been observed in the reactor physics field probably due to the difficulties in in-pile integration.

4.4 Calibration of the modulation

As discussed in Section 2.4, the analysis of RTF amplitude requires a normalization based on the modulation amplitude. Static methods, such as source multiplication [14] or null reactivity with a reference control rod [32,33], require the source or the control rod to be calibrated. Asymptotic period and inverse kinetic methods were performed by several authors [18,30,34] for various incremental positions of the modulator, in order to estimate time-dependent reactivity variation during modulator operation based on calculated or previously measured kinetic parameters. Another approach, adopted in [13] for oscillation experiments in the MINERVE reactor, relied on neutronic simulations to calculate the reactivity worth of reference samples (gold or light water).

It is observed that the reactivity calibration methodology was not always documented in the literature. Among the documented ones, it is observed that in most calibration approaches the reactivity estimation was based on a combination of experimental and calculated data. Indeed, the reactivity is not directly an experimental observable, but a calculated quantity that can either be estimated in simulations or be inferred from kinetic measurements through the knowledge of kinetic parameters. Therefore, uncertainties and biases related to the arbitrary choice of kinetic parameters is difficult to quantify. A possible experimental procedure to surmount this difficulty, suggested in [90], is to experimentally determine all the kinetic parameters experimentally and holistically (for instance through parameter fitting of kinetic experimental data).

5 Concluding remarks

Kinetic experiment based on reactivity or source modulation can be analyzed in the frequency domain with the reactor transfer function model. Reactivity and source modulation systems were designed, and modulation experiments were extensively conducted during 1950s and 1970s. The initial motivation was to study the system stability for reactor control. Efforts have then been made regarding the determination of reactor kinetic parameters. Several authors also investigated space-dependent effects in the measured transfer function, relative to detector's position. Since 1980, similar experimental studies became scarce. The lack of performance in electronics systems and computing power of the early studies limited the quality of experimental data analysis, and the associated uncertainty was not well documented.

The modulators were designed to adapt to the specific reactor of interest and the application. They showed various forms and different functional frequency ranges. Reactivity modulation system, driven by a mechanical motor was the most commonly adopted design option by virtue of its simplicity and performance.

The modulation technique regained some attention recently. The technological advances, as compared to the early studies, reveal new possibilities to experimental designs. Robust modulator design and data acquisition system would allow high precision transfer function measurement for accurate and reliable estimation of kinetic parameters and spatial kinetic modeling. The high quality experimental data could also contribute to the validation of innovative numerical tools currently under development, towards the improvement of safety analysis and online surveillance of nuclear reactors.

Author contribution statement

Y. Jiang conducted the literature review and wrote the manuscript. B. Geslot and P. Leconte conceived the original idea. B. Geslot, V. Lamirand and P. Leconte encouraged the study and were in charge of overall direction and planning. All authors provided critical feedback and analysis on the drafting of manuscript.

References

1. J. Dorning, in *Nuclear Computational Science: A Century in Review*, edited by Y. Azmy, E. Sartori (Springer Science & Business Media, 2010), Chap. 8, pp. 375–458
2. D.L. Hetrick, *Dynamics of nuclear reactors* (The University of Chicago Press, 1971)
3. M. Williams, *Random Processes in Nuclear Reactors* (Pergamon, 1974)
4. R. Uhrig, M. Ohanian, Pseudorandom pulsing of subcritical systems, in *Neutron Noise, Waves, and Pulse Propagation* (U.S. Atomic Energy Commission, 1967)
5. R. Uhrig, *Random noise techniques in nuclear reactor systems* (The Ronald Press Company, 1970)
6. J.M. Harrer, R.E. Boyar, D. Krucoff, Nucleonics (1952)
7. W. Foell, *Small-Sample Reactivity Measurements in Nuclear Reactors* (American Nuclear Society, 1972)
8. J.A. DeShong, Tech. rep., Argonne National Laboratory, 1960
9. C. Demazière, P. Vinai, M. Hursin, S. Kollias, J. Herb, Overview of the CORTEX project, in *Procedings of PHYSOR 2018: Reactor Physics Paving The Way Towards More Efficient Systems* (2018), 754316, pp. 2971–2980
10. S. Hübner, C. Lange, W. Lippmann, A. Hurtado, *Generation of high precise data for the verification of computational tools for reactor signal analysis The AKR-2 Training Reactor of the TU Dresden* (2018)
11. V. Lamirand, A. Rais, S. Hübner, C. Lange, J. Pohlus, U. Paquee, C. Pohl, O. Pakari, P. Frajtag, D. Godat et al., Neutron noise experiments in the AKR- 2 and CROCUS reactors for the European project CORTEX, in *Proceedings of ANIMMA2019* (Portoroz, 2019), p. 7
12. B. Geslot, A. Gruel, P. Walczak, P. Leconte, P. Blaise, Ann. Nucl. Energy **108**, 268–276 (2017)
13. E. Gilad, O. Rivin, H. Ettedgui, I. Yaar, B. Geslot, A. Pepino, J. Di Salvo, A. Gruel, P. Blaise, J. Nucl. Sci. Technol. **52**, 1026–1033 (2015)
14. S. Michálek, S. Tevo, G. Farkas, J. Haík, V. Slugeň, J. Rataj, A. Kolros, Progr. Nucl. Energy **52**, 735–742 (2010)
15. L. Li, M. Zeller, J. Chow, B. Sur, V. Anghel, B. van der Ende, J. Atfield, N. Lee, CNL Nucl. Rev. 1–10 (2016)
16. V.N. Anghel, L. Li, J.E. Atfield, L.R. Yaraskavitch, B. Sur, Ann. Nucl. Energy **147**, (2020)
17. K.O. Ott, R.J. Neuhold, *Introductory nuclear reactor dynamics* (American Nuclear Society, 1985)
18. B.A. Baker, Ph.D. thesis, Idaho State University (2013)
19. R. Barjon, *Physique des réacteurs nucléaires* (Institut des sciences nucléaires, 1993)
20. E. Gyftopoulos, in *The Technology of Nuclear Reactor Safety* (1964)
21. E. Gyftopoulos, Transfer function representation of nuclear power plants, in *Conference on Transfer Function Measurements and Reactor Stability Analysis* (1960)
22. E. Owen, Combined reactor and power system analysis for a boiling water reactor, in *Conference on transfer function measurements and reactor stability analysis* (1960)
23. G.R. Keepin, T.F. Wimett, R.K. Zeigler, Phys. Rev. **107**, 1044–1049 (1957)
24. I. Pázsit, Ann. Nucl Energy **23**, 407–412 (1996)
25. L.G. Kemeny, *Fundamental aspects of stochastic processes and fluctuation phenomena in fission reactors*, in *Neutron Noise, Waves, and Pulse Propagation* (1967)

26. R. Uhrig, *Neutron Noise, Waves, and Pulse Propagation* (United States Atomic Energy Commission, 1967)
27. W. Dutré, *Statistical Methods in Experimental Reactor Kinetics, and Related Techniques* (Petten, 1968)
28. C. Griffin, J.J. Lundholm, Tech. rep., North American Aviation (1959)
29. A. Baker, Oscillator tests in British fast reactors, in *Conference on transfer function measurements and reactor stability analysis* (1960)
30. R. Cordy, Measurement and Analysis of the KEWB transfer function by reactor modulation techniques, in *Conference on transfer function measurements and reactor stability analysis* (1960)
31. M. Petrovic, V. Markovic, D. Obradovic, A. Kocic, L. Velikovic, S. Jovanovic, Tech. rep., Boris Kidric Inst. Nucl. Sci. (1965)
32. C.L. Cowan, Tech. rep., University of California, Berkeley (1965)
33. E. Walker, *A Neutron Oscillator to Study Reactor Kinetics Phenomena in the O.S.U. Nuclear Reactor* (1967)
34. A. Jebb, Ph.D. thesis, Imperial College of Science and Technology (1973)
35. Y. Lee, Ph.D. thesis, Kansas state university (1964)
36. A. Klickman, R. Horne, H. Wilber, Tech. rep., Atomic power development associates, INC. (1967)
37. T.C. Chan, Ph.D. thesis, Iowa state university (1971)
38. K.J. Serdula, J.D. Kendall, P.M. Cloutier, C.B. Lawrence, Frequency Response Measurements of the GENTILLY Nuclear Reactor Dynamics, in *IAEA Symposium on Nuclear Power Plant Control and Instrumentation* (1973), January
39. W.C. Lipinski, EBWR stability analysis, in *Conference on transfer function measurements and reactor stability analysis* (1960)
40. M. Hara, H. Usui, Y. Fujii, N. Suda, J. Nucl. Sci. Technol. **5**, 79–85 (1968)
41. P.T. Hansson, L.R. Foulke, Nucl. Sci. Eng. **17**, 528–533 (1963)
42. R.J. Johnson, Ph.D. thesis, Georgia Institute of Technology, 1966
43. G. Saji, Nucl. Sci. Eng. **32**, 93–100 (1968)
44. D.N. Bridges, Ph.D. thesis, Georgia Instituts of Technology, 1970
45. H. Hinds, F. McDonnell, D. Walker, Tech. rep., Atomic Energy of Canada Limited, Chalk River, Ontario, 1972
46. O.V. Pakari, Ph.D. thesis, Ecole Polytechnique Fédérale de Lausanne, 2020, https://infoscience.epfl.ch/record/277921
47. P. Leconte, P. Archier, C. De Saint Jean, R. Diniz, A. Dos Santos, L. Fautrat, D. Foligno, B. Geslot, E. Gilad, P. Tamagno et al., *A consistent evaluation of delayed neutron group constants and covariances for 235 U and 238 U using a combination of microscopic and macroscopic data*, in *PHYSOR 2018* (Cancun, Mexico, 2018)
48. Y. Yamane, K. Tanaka, K. Nishina, H. Tamagawa, Nucl. Sci. Eng. **76**, 232–245 (1980)
49. T. Sanda, M. Makido, H. Otani, K. Sano, S. Tamura, T. Sandat, M. Makidot, H. Otanp, K. Sanot, J. Nucl. Sci. Technol. **20**, 199–212 (1983)
50. F. Zheng, W. Mansfield, Ann. Nucl. Energy **9**, (1982)
51. W.D. Rhodes, R.V. Furstenau, H.A. Larson, Nucl. Technol. **130**, 145–158 (1999)
52. A. Hainoun, I. Khamis, Nucl. Eng. Des. **195**, 299–305 (2000)
53. Y. Yedvab, I. Reiss, Determination of delayed neutrons source in the frequency domain based on in-pile oscillation measurements, in *Proceeding of PHYSOR-2006* (2006), pp. 1–9, http://mathematicsandcomputation.cowhosting.net/PHYSOR-2006/B073.pdf
54. P. Leconte, P. Archier, C. De Saint Jean, R. Diniz, A. Dos Santos, L. Fautrat, D. Foligno, B. Geslot, E. Gilad, P. Tamagno et al., Ann. Nucl. Energy **139**, 107250 (2020)
55. D. Foligno, Ph.D. thesis, Aix-Marseille University (2019)
56. D. Brown, M. Chadwick, R. Capote et al., Nucl. Data Sheets **148**, 1–142 (2018)
57. K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, K. Furutaka, N. Otuka, T. Ohsawa et al., J. Nucl. Sci. Technol. **48**, 1–30 (2011)
58. O. Cabellos, F. Alvarez-Velarde, M. Angelone, C.J. Diez, J. Dyrda, L. Fiorito, U. Fischer, M. Fleming, W. Haeck, I. Hill et al., EPJ Web Conf. **146**, 4–9 (2017)
59. A. Sakon, K. Hashimoto, W. Sugiyama, H. Taninaka, C.H. Pyeon, T. Sano, T. Misawa, H. Unesaki, T. Ohsawa, J. Nucl. Sci. Technol. **50**, 481–492 (2013)
60. M. Carta, A. D'Angelo, Nucl. Sci. Eng. **133**, 282–292 (1999)
61. V. Raievsk, J. Horowitz, Tech. rep., Commissarit à l'énergie atomique (1955)
62. C.W. Elenga, O. Reifenschweiler, The generation of neutron pulses and modulated neutron fluxes with sealed-off neutron tubes, in *Pulsed Neutron Research* (1965)
63. J.E. Garothers, in *Proceedings of the Second Symposium on the Application of Pulsed Neutron Source Techniques* (Berkeley, California, 1958)
64. Pulsed Neutron Research, in *Proceedings of the Symposium on Pulsed Neutron Research*, edited by D. Nastasia-Scotti, M. BROWN (IAEA, Karlsruhe, 1965), Vol. 1, ISSN 19450699
65. Pulsed Neutron Research, in *Proceedings of the Symposium on Pulsed Neutron Research*, edited by D. Nastasia-Scotti, M. BROWN (IAEA, Karlsruhe, 1965), Vol. 2, https://inis.iaea.org/search/search.aspx?orig{_}q=RN:44078830
66. J.K. Haywood, I. Robertson, K. Boddy, J. Radioanal. Chem. **48**, 117–124 (1979)
67. T.P. Lou, Ph.D. thesis, University of California, Berkeley, 2000
68. J.M. Elizondo-Decanini, D. Schmale, M. Cich, M. Martinez, K. Youngman, M. Senkow, S. Kiff, J. Steele, R. Goeke, B. Wroblewski et al., IEEE Trans. Plasma Sci. **40**, 2145–2150 (2012)
69. A. Billebaud, R. Brissot, C. Le Brun, E. Liatard, J. Vollaire, Progr. Nucl. Energy **49**, 142–160 (2007)
70. V. Bécares, D. Villamarín, M. Fernández-Ordóñez, E.M. González-Romero, C. Berglöf, V. Bournos, Y. Fokov, S. Mazanik, I. Serafimovich, Ann. Nucl. Energy **53**, 40–49 (2013)
71. W. Redman, M. Bretscher, Tech. rep., Argonne National Laboratory (1966)
72. E. Greenspan, K.B. Cady, J. Nucl. Energy **24**, 529–550 (1970)
73. E. Greenspan, J. Nucl. Energy **27**, 129–138 (1973)
74. L. Habegger, C. Hsu, Tech. rep., Argonne National Laboratory (1971)
75. T.E. Stern, A. Blaquiere, J. Valat, J. Nucl. Energy A/B **16**, 499–508 (1962)
76. R.E. Uhrig, J. Nucl. Energy. Parts A/B **18**, 27–28 (1964)
77. M. Buckner, Ph.D. thesis, University of Tennessee, 1970

78. J.M. Harrer, J.G. Beckerley, *Nuclear Power Reactor Instrumentation Systems Handbook* (Office of Information Services, 1973)
79. J.G. Lundholm, E.R. Meise, C.W. Griffin, Tech. rep., Atomics International (1960), https://catalog.hathitrust.org/Record/100902059
80. A.A. Wasserman, Ph.D. thesis, Massachusetts Institute of Technology (1962)
81. D. Babala, Measurement of $\delta\rho/\delta h$ in a water moderated reactor by an oscillating moderator-level technique, in *The Symposium on Exponential and Critical Experiments* (1964)
82. C. Demazière, O. Glöckler, On-line determination of the prompt fraction of in-core neutron detectors in CANDU reactors, in *Proceedings of PHYSOR 2004* (2004)
83. S. Zivi, R. Wright, Power-void transfer function measurements in a simulated SPERT IA moderator coolant channel, in *Conference on Transfer Function Measurements and Reactor Stability Analysis* (1960)
84. E. Shabalin, *Fast Pulsed and Burst Reactors* (Pergamon, 1979)
85. Y.N. Pepyolyshev, Ann. Nucl. Energy **35**, 1301–1305 (2008)
86. V.V. Orlov, Y. Kazachenkov, *The influence of a magnetic field on neutron diffusion, and the possibility of magnetic control of reactors* (1972), Vol. 33
87. V. Romanov, Atomnaya Energ. **68**, (1990)
88. W.L. Whittemore, A continuously pulsed TRIGA reactor: an intense source for neutron scattering experiment, in *IGORR-IV: Proceedings of the fourth meeting of the International Group On Research Reactors* (1996), pp. 140–156
89. H. Humblot, W. Heil, F. Tasset, D. Hoffmann, Physica B **241-243**, 56–63 (1998)
90. A. Dos Santos, R.Y.R. Kuramoto, R. Diniz, R. Jerez, G.S. De Andrade E Silva, M. Yamaguchi, International Conference on the Physics of Reactors 2008, PHYSOR 08 **4**, 2814–2821 (2008)

Cite this article as: Yifeng Jiang, Benoit Geslot, Vincent Lamirand, Pierre Leconte, Review of kinetic modulation experiments in low power nuclear reactors, EPJ Nuclear Sci. Technol. **6**, 55 (2020)