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Study of reactor core loading monitoring
at the GUINEVERE facility

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Abstract

The potential use of a pulsed neutron source to measure reactivity during nuclear fuel loading as a means to prevent core loading errors has been studied at the GUINEVERE facility. This facility couples the deuteron accelerator GENEPI-3C to the fast neutron subcritical reactor VENUS-F at the Belgian Nuclear Research Center SCK·CEN. 14-MeV neutrons are produced in the reactor core center via $T(d, n)^4He$ fusion reactions. Pulsed Neutron Source (PNS) experiments were performed in five reactor configurations corresponding to different loading steps of VENUS-F. The evolution of the neutron flux during these PNS experiments was measured by several ^{235}U fission chambers in various positions in the inner and outer reflector and analyzed using the area-ratio method. The results show that, despite strong spatial effects, a strong correlation between the reactivity value given by the area-ratio method and the true reactivity remains throughout the reactor unloading. Monte Carlo simulations were first validated by comparison with the data and then used to investigate the sensitivity of the method. First results show that some loading errors could be experimentally detected using a pulsed neutron source.

Keywords — core loading safety, reactivity monitoring, subcriticality, Monte Carlo simulations, pulsed neutron source

I. INTRODUCTION

During refueling operations of pressurized water reactors, the fuel assemblies must be loaded according to a strict loading plan. In French 900-MWe PWRs, the monitoring of the refueling is ensured by two ex-core proportional counters. Unfortunately, this monitoring using the count rates of two detectors happened to be insufficient to prevent errors in fuel loading during at least one subcritical approach. Indeed, in 2001, at the Dampierre-en-Burly nuclear power plant, assembly #25 was forgotten in the fuel storage building, creating a shift in the loading pattern. Consequently, 138 additional assemblies were introduced at incorrect locations before the error was detected. The main reason for this monitoring failure was the lack of correlation between the detector count rates and the reactor reactivity, a significant part of the detector counts being due to the intrinsic neutron radioactivity of neighboring fuel assemblies [1].

This lack of correlation between count rates and reactivity is a well known problem in a related field, namely the reactivity monitoring of Accelerator Driven Subcritical reactors. This topic has been extensively investigated for twenty years, and most recently at the GUINEVERE facility [2] (SCK-CEN nuclear research center, Mol, Belgium) which couples the fast subcritical reactor VENUS-F with an external neutron source provided by the deuteron accelerator GENEPI-3C via $T(d, n)^4He$ fusion reactions occurring at the reactor core center. The experiments carried out at GUINEVERE since 2012 have shown that there can be a strong correlation between the evolution of the counting rates measured over time in a reactor and its reactivity, provided that a neutron source whose intensity varies over time is used [3, 4, 5]. In addition, the large range of VENUS-F cores already studied indicates that this strong correlation is present for cores of various sizes, suggesting that the excitation of a partially loaded core with a periodic external neutron source could provide counting rates strongly correlated to the reactor reactivity and thus help monitoring the reactor loading. On the other hand, the VENUS-F fast neutron reactor is obviously nothing like a 900-MWe pressurized water thermal reactor. Furthermore, the collection of reactor configurations already studied contained cores of varying sizes, but all of them were quite symmetrical, while the loading steps of a power reactor create highly asymmetrical configurations, which favors, in dynamical experiments, large spatial effects that make it more difficult to measure reactivity.

This is the reason why a new research program (named SALMON for Subcritical Approach for core Loading MONitoring) has been undertaken at the GUINEVERE facility, specifically dedi-

cated to the study of the monitoring of core loading with reactivity measurement at each loading step using a pulsed neutron source. This project has been divided into three phases. Phase 1 consisted in taking advantage of the end of the MYRACL program devoted to ADS studies, mid-2019, to carry out reactivity measurement experiments using the GENEPI-3C accelerator in pulsed mode, in very asymmetrical cores created during the unloading of VENUS-F. The pulsed mode was chosen because it will be most likely the easiest time-dependent mode to implement in a power reactor facility. The fast spectrum of VENUS-F, a disadvantage in terms of representativeness of pressurized water reactors, offered the opportunity to make use of the data collected with the previous reactor configurations and also to study the monitoring of the loading of future fast neutron power reactors. Phases 2 and 3 will be devoted to the study of the core loading monitoring of thermal configurations of VENUS and to the transposition of the results to power PWRs.

This paper presents the results obtained in Phase 1 of the SALMON project, more precisely the use of the area-ratio method [6] for reactivity measurement during the unloading of the fast neutron reactor VENUS-F. First the GENEPI-3C accelerator and the VENUS-F reactor are described. Then the experiments performed are presented, as well as the results obtained.

Next the results of comprehensive Monte Carlo simulations of the experiments will be discussed, which will help assessing the potential of the method for detecting an erroneous fuel assembly insertion. Finally, first conclusions about the merit of using a pulsed neutron source for core loading monitoring will be drawn.

II. EXPERIMENTAL SETUP

II.A. The GENEPI-3C accelerator

The deuteron accelerator GENEPI-3C [7] was developed at LPSC Grenoble by a collaboration of CNRS/IN2P3 laboratories (LPSC, LPC-Caen, IJCLab and IPHC). It can provide a beam of deuterons accelerated up to 220 keV and guided to a copper target with a tritiated titanium deposit located at the center of the VENUS-F reactor, which generates a 14 MeV neutron source by $T(d,n)^4He$ fusion reactions.

Several temporal modes are available to the GENEPI-3C: the continuous mode, the periodically interrupted continuous mode and the pulsed mode. Among these modes, only the pulsed and continuous modes were used in the experiments detailed below. Main beam characteristics for

TABLE I
GENEPI-3C characteristics in pulsed mode.

Peak current (mA)	20
Pulses frequency (Hz)	10 to 5000
Pulses duration (μ s) (FWHM)	$\simeq 0.7$
Neutrons per pulse (pulse^{-1})	$\simeq 10^6$

TABLE II
GENEPI-3C characteristics in continuous mode.

Mean current (μ A)	50 to 1000
Maximum intensity of the neutron source (s^{-1})	5×10^{10}

these modes are listed in Tables I and II.

II.B. The VENUS-F reactor

The VENUS-F reactor is a fast spectrum research reactor. It can be used as a stand-alone critical reactor, as well as a subcritical reactor when coupled to the GENEPI-3C accelerator.

The reactor is comprised in a cylindrical vessel of 160 cm in diameter and 140 cm in height. This vessel contains a square stainless steel casing surrounding a 12×12 matrix designed to receive 144 assemblies of $\simeq 8.07 \times 8.07 \text{ cm}^2$ square section. In order to help localizing the various assemblies and detectors, an arbitrary coordinate system is used in the 12×12 matrix: the upper left corner is labeled (-6,6) and the lower right one (6,-6) (there is no (0,0) element). Above and below the stainless steel casing are lead axial reflectors, and the radial spaces between the cylindrical vessel and the casing are filled by semi-circular lead plates constituting the outer reflector. Some cavities are present in the outer reflector to allow the insertion of detectors. In this paper, only the cavities labeled A1, C1 and C2 (see Figure 1) were used.

The core configurations studied in this work were based on the so-called SC11/All-rods-in subcritical configuration of VENUS-F (upper left corner of Figure 1). The core was made of 50 “type-13 Bi” fuel assemblies (FA), filled with rodlets of 30 wt.% enriched metallic uranium, 4 alumina rodlets and 8 bismuth bars surrounded by lead plates, hence forming a 5x5 pattern represented in Figure 2. Six safety rods (SR), made of boron carbide (B_4C) with fuel followers, as well as 2 control rods (CR) were fully inserted in all the configurations studied in this paper. Specific assemblies, mock-ups of in-pile sections (IPS), were also inserted inside and around the core. “Thermal” IPS were made of cadmium-wrapped polyethylene, and “fast” IPS of stainless

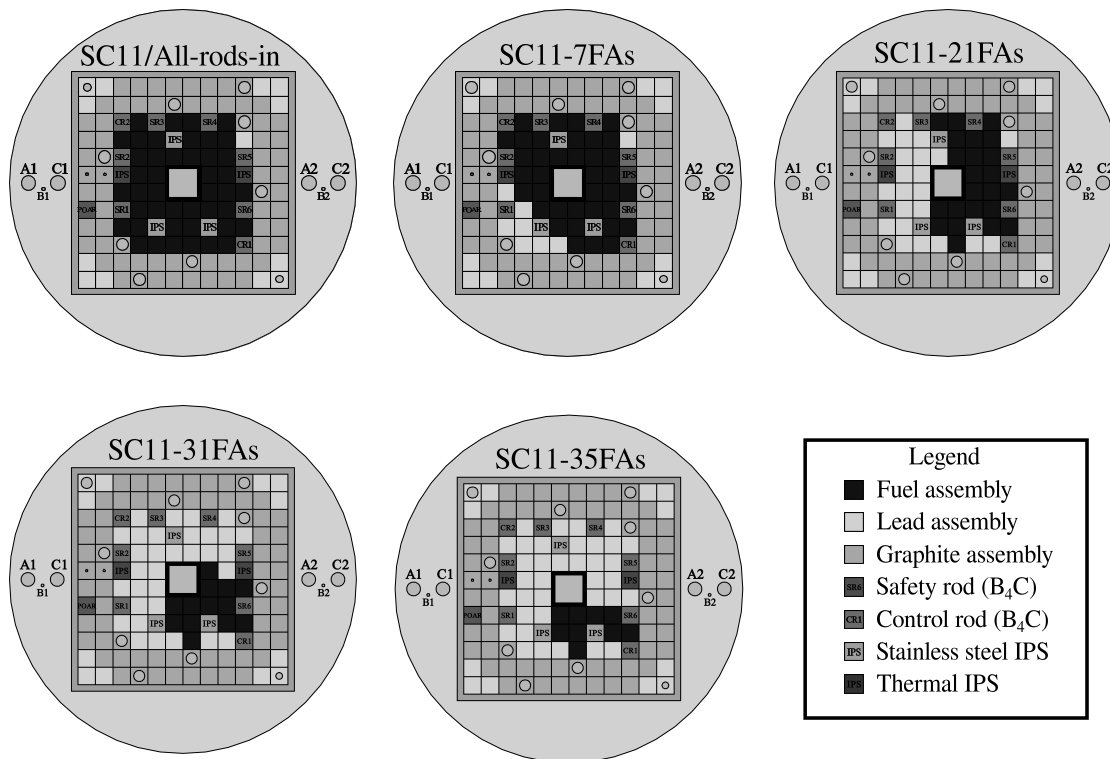


Fig. 1. Schematic views of VENUS-F configurations studied in SALMON program phase 1.

steel. Finally, the 4 central slots $((-1,-1),(-1,1),(1,-1),(1,1))$ were left empty to allow inserting the GENEPI-3C beam pipe.

Around the core, graphite and lead assemblies form the inner reflector. Some of these assemblies are hollow, providing space to host detectors.

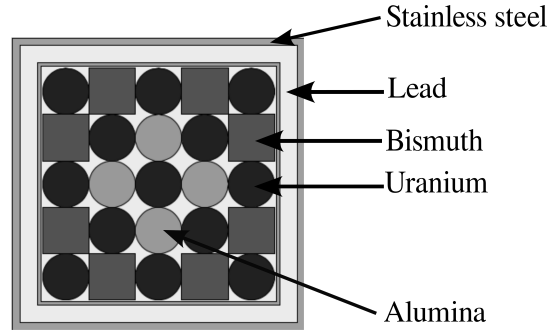


Fig. 2. Type-13 fuel assembly.

In addition to configuration SC11/All-rods-in, 4 steps of the core unloading, also shown in Figure 1, were studied, by removing 7, 21, 31 and 35 fuel assemblies, respectively, which were replaced by lead assemblies. The reactivity of each configuration was experimentally estimated by SCK-CEN using a Source Jerk Integral (SJI) method with Monte-Carlo calculated spatial corrections [8], a method which has been successfully used in the past for many VENUS-F configurations and compares well with the standard MSM method for estimating reactivity [9]. These reactivity values are considered as the reference ones, to which the results obtained using the pulsed neutron source will be compared. As shown in Table III, these configurations cover a large domain of anti-reactivity, from $\simeq -21\%$ to $\simeq -102\%$, which corresponds to k_{eff} varying from $\simeq 0.557$ to $\simeq 0.866$.

TABLE III
Reactivity of VENUS-F configurations determined using the SJI method.

	SC11/All-rods-in	SC11-7FAs	SC11-21FAs	SC11-31FAs	SC11-35FAs
$\rho_{\text{s}}(\text{SJI})$	-21.1 ± 0.6	-32.6 ± 1.1	-54.2 ± 2.0	-78.4 ± 3.1	-101.8 ± 3.9
$k_{\text{eff}}(\text{SJI})$	0.866 ± 0.003	0.806 ± 0.005	0.711 ± 0.008	0.624 ± 0.009	0.557 ± 0.010

II.C. Detector configuration

The VENUS-F reactor was equipped with fission chambers (FC) working in pulse mode. These FCs were mostly located in the inner and outer reflectors, in dedicated channels represented by white circles in Figure 1. Each fission chamber contained a highly enriched uranium deposit ($\geq 90\%$ ^{235}U in mass) and was connected to a high voltage power supply and an amplifier-discriminator, as well as a data acquisition system that allows time-stamping the fission events occurring in the FC with a time resolution of 20 ns. Three different types of FCs were used in SALMON: 5 standard Photonis CFUL01 FCs [10] with $\simeq 1100$ mg of ^{235}U deposit, 5 GE Reuter-Stokes (RS) FCs with $\simeq 100$ mg of ^{235}U deposit and one standard Photonis CFUF34 FC [10] with $\simeq 1$ mg of ^{235}U deposit. In order to deal with detector dead time, dedicated experiments were carried out: the detector count rates were measured for various intensities of a continuous beam of GENEPI-3C, in order to determine the parameter of a non-paralysable dead time model [11].

Background measurements were regularly performed throughout the campaign to accurately subtract the contribution of electronic noise, gamma rays, light particles and also the reactor neutron intrinsic source due to the spontaneous fission of ^{238}U . This evaluation is quite critical as the counting rates during the Pulsed Neutron Source (PNS) experiments were very low for the most subcritical configurations corresponding to largely emptied cores.

III. PULSED NEUTRON SOURCE EXPERIMENTS

III.A. Experimental method

When injecting multiple pulses in a subcritical reactor, the reactivity can be inferred from the temporal evolution of the neutron population using the area-ratio method, or Sjöstrand method [6]. Indeed, under the assumption of the Point Kinetics theory, the temporal evolution of the neutron population $n(t)$ in the reactor after a sufficiently large number of pulses, and provided that the pulse frequency is much larger than the precursor decay constants [12], reads:

$$n(t) = n_0 \left(\exp\left(\frac{\rho - \beta_{\text{eff}}}{\Lambda_{\text{eff}}} t\right) + \frac{\lambda \Lambda_{\text{eff}} \beta_{\text{eff}}}{(\rho - \beta_{\text{eff}})^2} \exp\left(\frac{\lambda \rho}{\beta_{\text{eff}} - \rho} t\right) \right) \quad (1)$$

where $\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}}$ denotes the reactivity of the reactor, β_{eff} the effective delayed neutron fraction, λ the precursor decay constant in a one group model, Λ_{eff} the mean generation time, t

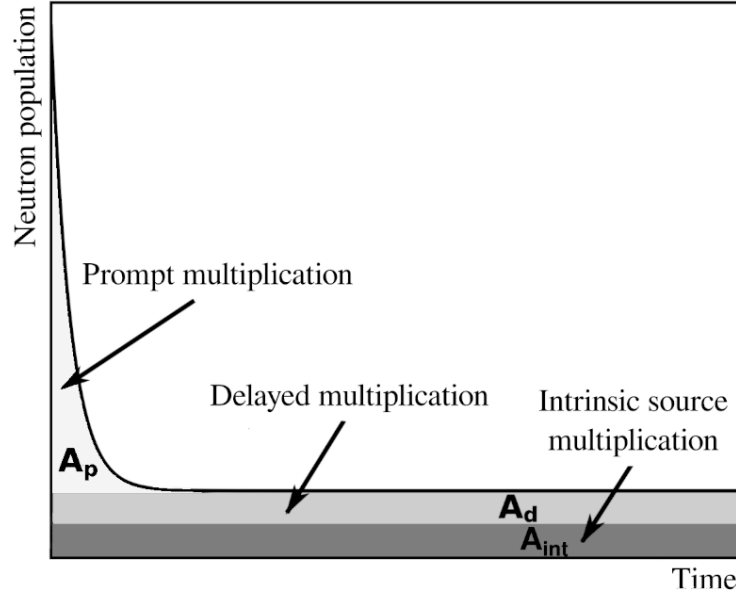


Fig. 3. Schematic PNS histogram after multiple periodic Dirac-like neutron pulses.

the time elapsed since the last neutron pulse. Schematically, PNS histograms look like Figure 3. Three components can be distinguished : The “prompt” decay of the neutron population directly following the pulse, the neutron “plateau” composed of the much slower “delayed” decay of the neutron population that takes over after the extinction of the prompt part and finally the constant contribution of the reactor intrinsic neutron source.

Then the reactivity can be estimated by integrating the delayed part and the prompt part of the PNS histogram:

$$\rho_{\text{§area}} = \frac{\rho}{\beta_{\text{eff}}} = -\frac{A_p}{A_d} = 1 - \frac{A_{\text{tot}} - A_{\text{int}}}{A_d} \quad (2)$$

where A_d is the area under the delayed neutron plateau (medium gray area in Figure 3), A_p the prompt integral (the light gray area in Figure 3), and A_{tot} the total integral of the PNS histogram.

Experimentally, neutron pulses were periodically injected in the reactor at a frequency of 100 or 200 Hz for a few hours. Then PNS histograms were constructed by accumulating the time differences between each detector fission event and the neutron pulse emission t_{pulse} .

Furthermore, the contribution of the intrinsic neutron source had to be subtracted from the counting rates to correctly measure A_d . To do so, count rates due to the intrinsic source

were measured when the deuteron accelerator was turned off, for all detectors and all reactor configurations. Although the intrinsic source is expected to be much stronger in a power reactor, this subtraction would still be possible.

Figure 4 illustrates the final PNS histograms for detectors in position (1,-5) and C1 in configuration SC11-31FAs after correction of dead time and removal of the background contribution, which includes the intrinsic source contribution. Then the A_d area was estimated using the level of the count rate at the very end of the period, and A_{tot} is simply the total number of counts in the histogram.

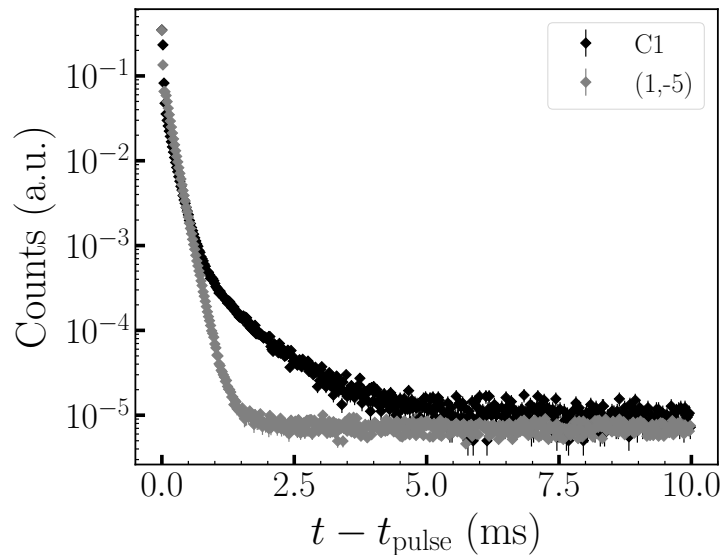


Fig. 4. Detector counts as a function of time in positions (1,-5) (in gray) and C1 (in black) during a PNS experiment in the configuration SC11-31FAs.

The shape of the neutron population decay is conspicuously very different from one detector to another. In this example, the large deformation of the prompt area in C1 is due to the return of thermalized neutrons from the concrete walls surrounding the outer reflector. This effect was already witnessed and studied in previous experimental programs [5]. With such differences between the PNS histograms, due to large spatial effects, one can expect large variations in the results given by the area-ratio method.

III.B. Reactivity values obtained

The area-ratio method presented in section III.A was applied to the data obtained for all detectors in all reactor configurations. The uncertainties on the area-ratio reactivity include the statistical uncertainties on the count rates, on the background measurements and on the dead-time correction.

Figure 5 presents the reactivity value $\rho_{\$area}$ obtained using Formula (2) for each position and each reactor configuration as a function of the reactivity estimated by the Source Jerk Integral method [8].

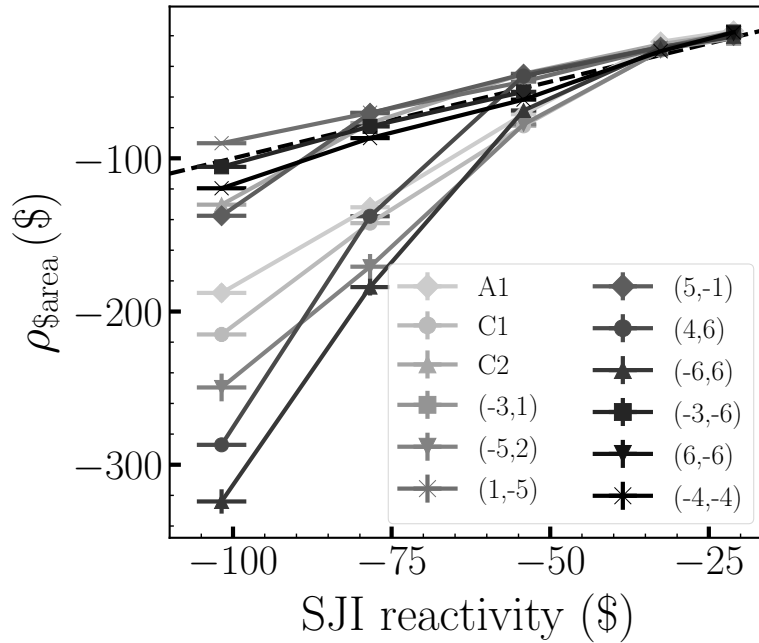


Fig. 5. Reactivity given by the area-ratio method, $\rho_{\$area}$, as a function of SJI reactivity (the dark dashed line represents the equality between $\rho_{\$area}$ and SJI reactivity).

As can be seen, some of the reactivity values given by the area-ratio method depart more and more from SJI values as the reactor is being emptied and huge spatial effects are observed. Two groups of detectors can be distinguished in regards to these effects: detectors in positions (1,-5), (5,-1), (-4,-4) and C2 give results close to the SJI values whereas detectors in other positions tend to diverge more and more from the SJI results as the core is being emptied. Interestingly, detectors in the first group remain close to the fuel throughout the unloading steps, whereas

detectors belonging to the second group become more and more distant from the remaining FAs. These strong spatial effects beyond Point Kinetics prevent one from obtaining a reliable reactivity estimate of large subcriticalities using formula (2) for more than half of the detectors.

Nevertheless, it is important to note that a strong correlation is kept between the area-ratio and SJI reactivities, even for the detectors of the second group and even for the detectors located in the outer reflector, more representative of detector locations in power reactors. This is in contrast with standard PWR loading monitoring in which correlation between signals and reactivity is lost in most part of k_{eff} range [1].

IV. MONTE CARLO SIMULATIONS

IV.A. Simulation of PNS experiments

The failure of the area-ratio method at estimating large subcriticality obtained by partial unloading of the core is not surprising. Indeed, Point kinetics theory becomes more and more inaccurate as the reactivity decreases, especially when large asymmetries are created by unloading the fuel on one side of the core. In order to further study these spatial effects beyond Point kinetics, Monte Carlo simulations of the PNS experiments were carried out.

These simulations were done using the Serpent-2 Monte-Carlo transport code [13] with the JEFF3.1.1 nuclear data library [14]. The input files used to describe VENUS-F configurations were simplified to save computer time. Fuel assemblies were homogenized and some details of the bottom neutron reflector were not reproduced. The detectors were also simplified to volumes where Serpent-2 track-length estimators were used to estimate reaction rates by convolution with the ^{235}U fission cross-section. Furthermore, the neutron source was approximated to an isotropic point source at the center of the core, emitting 14-MeV neutrons. These simplifications have already been successfully employed in the analysis of past experiments at GUINEVERE [3, 4, 5].

However one should note that, even with these simplifications, the simulations remained computer time consuming as reaction rates had to be calculated with enough statistics in all fission chambers up to more than 15 minutes after the initial neutron pulse, so that experiment-like PNS histograms could be reconstructed by folding the reaction rates with the periodic source pattern.

Typical simulated PNS histograms are presented in Figure 6. The agreement between the simulated and experimental shapes, for both inner and outer reflector detectors is remarkable.

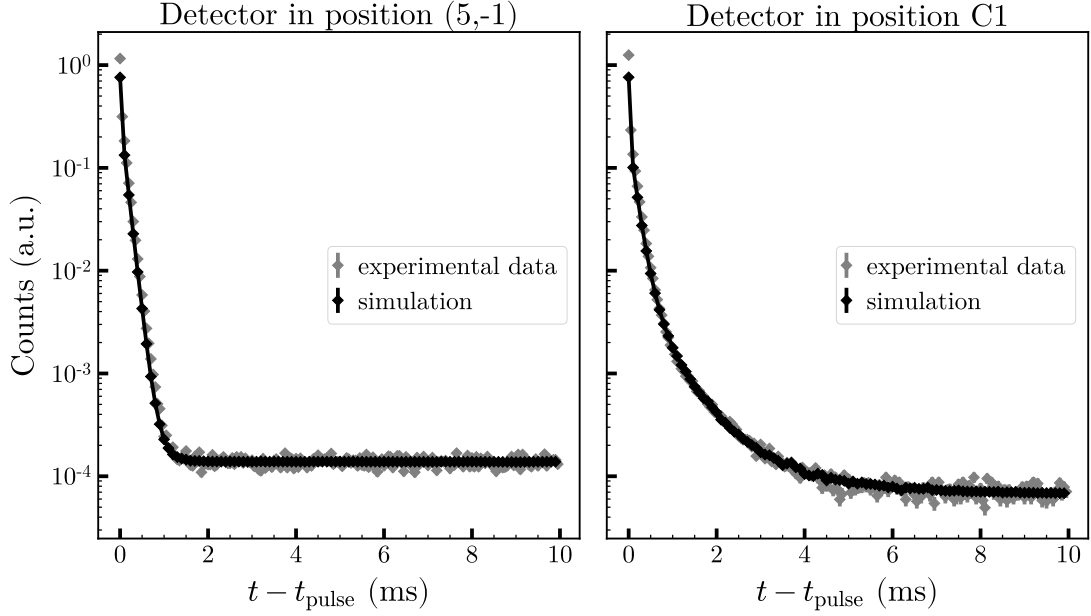


Fig. 6. Experimental and simulated PNS histograms in the inner reflector (left panel) and in the outer reflector (right panel) in configuration SC11-31FAs.

In order to obtain a quantitative estimator of the capacity of the simulations to reproduce the spatial effects for each configuration and for each position, Serpent-2 was used to calculate spatial factors to correct all experimental reactivity values from spatial effects. To do so, the reactivity (ρ_{serpent}) of each Serpent-2 reactor model was first calculated thanks to the power iteration method. Then the simulated PNS histograms were analyzed using Formula (2) to obtain the simulated area-ratio $(-A_p/A_d)_{\text{serpent}}$ for each detector position. Finally a spatial factor was calculated as:

$$f_s = \frac{\rho_{\text{serpent}}}{(-A_p/A_d)_{\text{serpent}}} \quad (3)$$

and a corrected reactivity was calculated for each detector as:

$$\rho_{\text{corr}} = f_s \times \rho_{\text{area}} \quad (4)$$

Figure 7 presents the corrected reactivity values as a function of SJI reactivity (the scale of Fig. 5 has been retained to aid comparison). The difference with Fig. 5 is striking: even for the

most subcritical configurations, the reactivity values given by the corrected area-ratio method are in agreement (2σ) with the SJI results for all detectors.

This shows that the spatial effects can be accurately accounted for using Monte Carlo simulations with simplified semi-homogeneous models of the VENUS-F configurations, even in the most extreme cases (corrections up to hundreds of dollars in reactivity for the SC11-35FAs configuration).

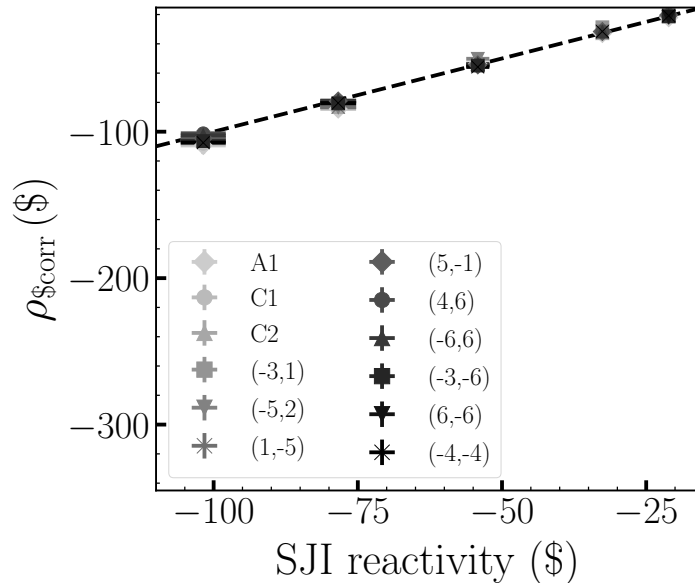


Fig. 7. Area-ratio reactivity corrected with spatial factors, ρ_{corr} , as a function of SJI reactivity (the dark dashed line represents the equality between ρ_{corr} and SJI reactivity).

IV.B. Source effects

As observed in Figure 5 reactivity is particularly underestimated when using detectors located closer to the external neutron source than to the remaining FAs. This points out to a source effect: a significant part of the neutrons causing fission in these detectors could come from the source, directly or after scattering, whereas, for detectors on the other side, neutrons from multiplication in the fuel represent a larger fraction of the detection events.

To study this effect, two PNS experiments were simulated per reactor configuration. In both cases, a point 14-MeV source was simulated, but in the second simulation, the fission reactions were disabled and treated as capture. The ratio between reaction rates R_{all} and $R_{\text{nofission}}$, estimated

with and without fission reactions, respectively, gives P_{source} :

$$P_{\text{source}} = R_{\text{nofission}}/R_{\text{all}} \quad (5)$$

which is the proportion of detected neutrons coming from the source over the total number of detected neutrons.

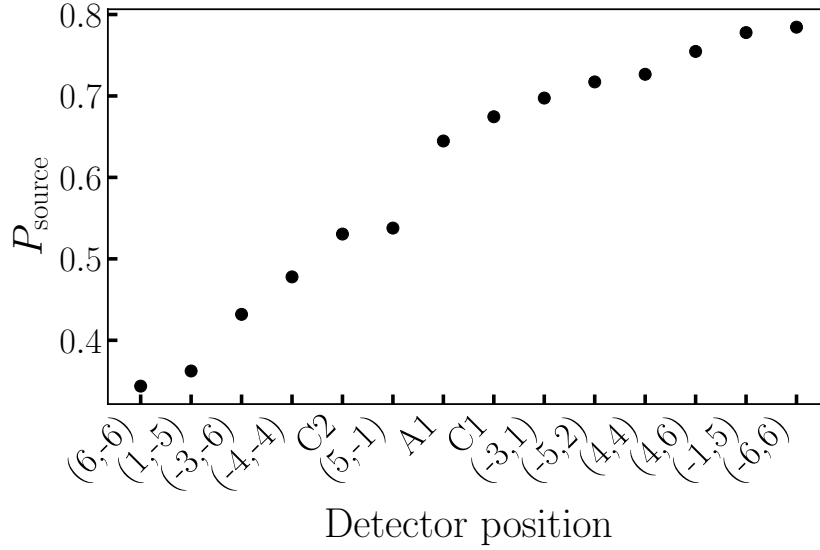


Fig. 8. P_{source} as a function of detector position in configuration SC11-35FAs.

An example of P_{source} obtained for configuration SC11-35FAs is represented in Figure 8. In this case a huge proportion of the detector counts are actually coming from the source. As suspected, the detectors with which the reactivity is the most underestimated in the experiments (see Figure 5) seem to be the detectors with the highest P_{source} . To further investigate such correlation between the proportion of the counts originating from the neutron source and the spatial distortion of the reactivity measurement, the spatial factors calculated for each position and configuration in section IV.A are represented in Fig. 9 as a function of P_{source} .

No clear link between P_{source} and spatial factors can be established for the two less subcritical configurations. However that is not the case for the three most subcritical configurations, for which FAs are completely removed from one side of the core. Indeed there appears to be a clear anticorrelation between P_{source} and f_s (weighted linear correlation coefficients were found to

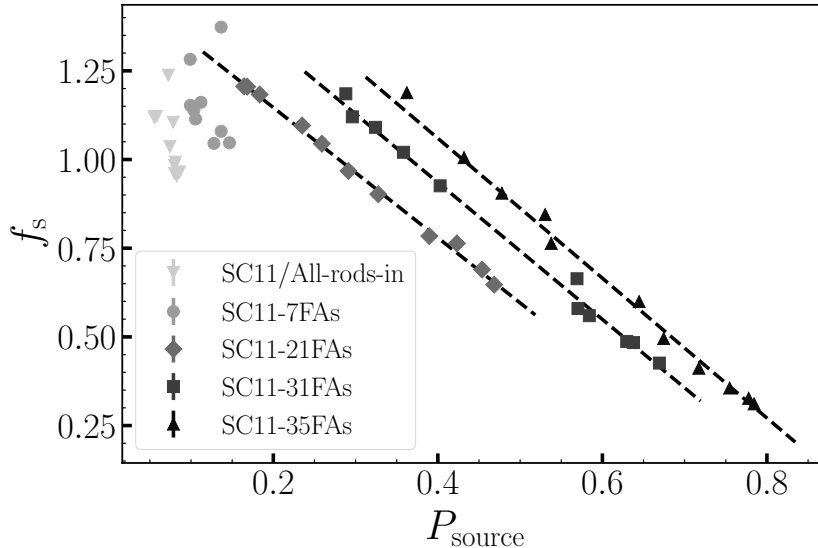


Fig. 9. Spatial factors f_s as a function of P_{source} for all VENUS-F configurations. Linear fits for the three most subcritical configurations are represented by black dashed lines.

be less than -0.996).

Therefore two regimes can be distinguished:

- for the least subcritical and least emptied configurations SC11/All-rods-in and SC11-7FAs, the source effect does not drive the values of spatial factors, as it does not seem to be dominant over the other spatial effects like the deformation of the shape of the neutron flux when the external neutron source is on, or the return of thermalized neutrons from the concrete walls to the outer reflector.
- however, for configurations SC11-21FAs, SC11-31FAs and SC11-35FAs the neutron source effect appears to be the main driver of the spatial effects, hence the vast reactivity underestimations observed for the detectors far from the remaining FAs.

The underestimation of reactivity increases when the proportion of source neutrons in the neutron flux seen by a detector approaches 1. Indeed these neutrons, uncorrelated to the reactivity, are counted in the prompt area A_p , which decreases the area-ratio estimation of the reactivity. This points to the importance of the relative positions of the neutron source, detectors and FAs for the area-ratio measurement, especially in the first steps of the core loading.

IV.C. Sensitivity of the method to assembly insertion errors

The modeling of the experiments being validated, the simulations can be used to investigate the sensitivity of the area-ratio method to errors in fuel loading. To do so, errors in fuel loading were simulated by replacing one of the FAs in some of the Serpent2 models by a modified one. This modified assembly is similar to the regular one except for the enrichment of the metallic uranium, which was decreased from 30% to 28.1% in order to lower its k_∞ value by $\simeq -1500$ pcm compared to the initial one. The positions of the modified FA were chosen to be as representative as possible of a power reactor loading pattern. The location of the modified FA in the new configurations as well as its impact on the k_{eff} values are given in Table IV.

TABLE IV
Change in reactivity for the Serpent 2 models due to the insertion of the modified FA.

Configuration name	position of the modified FA	original k_{eff}	modified k_{eff}	$\Delta\rho_{\text{serpent}}$ (pcm)
SC11-7FAs	(1,-4)	0.80560(2)	0.80483(3)	-126.0(1.1)
SC11-21FAs	(-1,4)	0.70361(3)	0.70322(2)	-79.2(2.2)
SC11-31FAs	(2,1)	0.61863(2)	0.61764(2)	-256.7(3.3)
SC11-35FAs	(3,-2)	0.55167(2)	0.55016(2)	-499.8(4.3)

New simulations of PNS with the modified versions of the Serpent2 models were performed and new area-ratios $(-A_p/A_d)_{\text{serpent,modified}}$ were calculated. The differences $\Delta\rho_{\text{\$area,serpent}}$ between these new area-ratios and the ones calculated with the original input models are shown in Fig. 10.

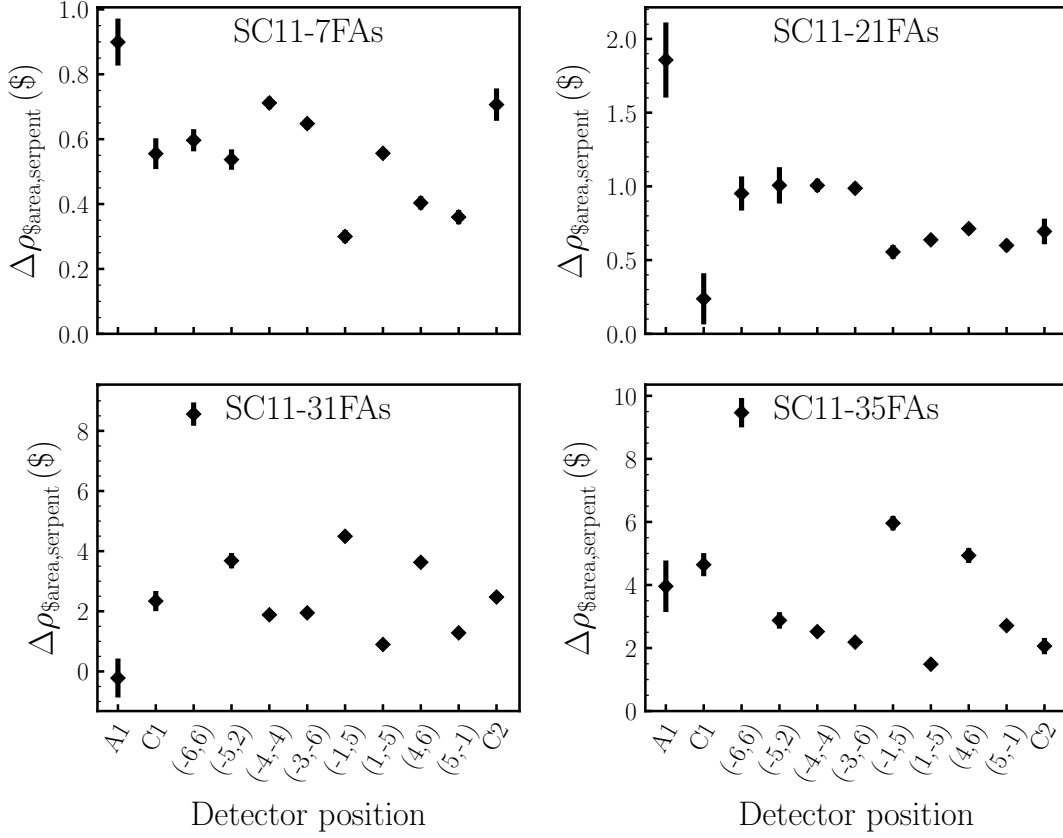


Fig. 10. Differences of the computed area-ratios between the original and modified simulation input models as a function of position for configuration SC11-7FAs (top left), SC11-21FAs (top right), SC11-31FAs (bottom left) and SC11-35FAs (bottom right).

As expected the reactivity differences depend on detector position. Nevertheless, it is remarkable that the vast majority of the detectors (and at least one detector in the outer reflector) give a significant change in reactivity between the regular configurations and the configurations featuring a modified FA.

V. CONCLUSION

Phase 1 of the SALMON project was devoted to the study of the core loading monitoring of a fast neutron reactor using a pulsed neutron source, in order to measure the reactivity and prevent loading errors.

The use of a pulsed neutron source allows the measurement of the intrinsic source contri-

bution prior to the injection of neutron pulses. This method is therefore not sensitive to intrinsic neutron radioactivity unlike the simpler monitoring of the detector count rates, which is the standard procedure for French PWR core loading monitoring.

The PNS experiments were carried out at the GUINEVERE facility, using the GENEPI-3C deuteron accelerator in pulsed mode coupled to the VENUS-F fast neutron reactor at several steps of its unloading. ^{235}U FCs were positioned in the inner and outer reflectors of VENUS-F to measure the temporal evolution of the neutron flux at various locations during these experiments.

The results of the analysis of these PNS experiments using the area-ratio method show that, despite spatial effects getting stronger and stronger as the reactor is being emptied, there still exists a strong correlation between the reactivity value given by the area-ratio method and the true reactivity, even for the detectors located in the outer reflector.

In addition, Monte Carlo simulations were found to reproduce very well the spatial effects seen in the experiment. Also, it was shown that “source” neutrons causing a large amount of fissions in the detectors is the main reason for the large underestimation of reactivity in the most subcritical configurations studied in the SALMON program.

The validated Monte Carlo models were also used to study the sensitivity of the method to the introduction of a modified FA (with a modified k_∞) in four steps of the VENUS-F loading. PNS experiments were simulated in these modified models for comparison with the simulations of the original PNS experiments. In all investigated cases, the majority of detectors and at least one detector in the outer reflector give a significant change in reactivity between the original and modified configurations, which allows detecting the loading error.

These results are promising for an application to fast spectrum reactor core loading monitoring. For thermal reactors, it is a strong motivation to proceed to phase 2 of the SALMON project. In this phase, it is planned to study this method on the loading of a thermal spectrum version of VENUS, in order to increase the representativeness of the experiments for PWR loading monitoring.

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