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Study of reactor core loading monitoring within the SALMON program

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ABSTRACT

The use of the Area method to analyze Pulsed Neutron Source (PNS) experiments as a means of measuring the reactivity during the reactor loading in order to prevent loading error was studied in the phase 1 of the SALMON project. This paper presents the experiments carried out at the GUINEVERE facility, using the GENEPI-3C accelerator to generate neutron pulses in the VENUS-F fast neutron reactor at different steps of its unloading. The evolution of the neutron flux during these PNS experiments was measured by several ²³⁵U Fission chambers in various positions in the inner and outer reflector. The results show that, despite strong spatial effects observed in the least reactive configurations, a strong correlation between the reactivity value given by the Area Method and the true reactivity remains. Furthermore the responses to all detectors to PNS experiments could be reproduced and corrected using Monte Carlo simulations.

KEYWORDS: core loading safety, reactivity monitoring, subcriticality, Monte Carlo simulations

1. INTRODUCTION

During refueling operations of pressurized water reactors, the fuel assemblies must be (re)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 simple monitoring of the count rates of two detectors happened to be insufficient during the sub-critical approach to prevent error in fuel loading. Indeed, in 2001, a loading error occurred in a nuclear power reactor at Dampierre-en-Burly: assembly #25 was forgotten in the fuel storage building, creating a shift in the loading pattern. 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 radioactivity of neighboring fuel assemblies [1].

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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 site in Mol, Belgium) which couples the fast subcritical reactor VENUS-F with an external neutron source provided by the deuteron accelerator GENEPI-3C via $T(d,n)^4\text{He}$ fusion reactions occurring at the reactor core center. The experiments carried out at GUINEVERE since 2012 show 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. Obviously, the VENUS-F fast neutron reactor is nothing like a 900-MWe pressurized water thermal reactor. In addition, the collection of cores already studied contained cores of varying sizes, but all of them are quite symmetrical, while the loading steps of a power reactor create highly asymmetrical configurations, which favor, in dynamic experiments, large spatial effects that make it more difficult to measure reactivity.

This is the reason why a new research program has been undertaken at the GUINEVERE facility, specifically dedicated to the monitoring of core loading with reactivity measurement at each loading step. The SALMON (Subcritical Approach for core Loading MONitoring) 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 asymmetric cores created during the unloading of VENUS-F. The pulsed mode was chosen because it will be most likely the easier 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 a future power fast reactor. Phase 2 and 3 will be devoted to the study of the core loading monitoring of thermal configurations of VENUS-F and to the transposition of the results to power PWRs.

This paper presents the results obtained within Phase 1 of the SALMON project, more precisely the use of the Area-Ratio method for reactivity measurement during the unloading of the fast neutron reactor VENUS-F. It starts with an introduction to the GUINEVERE facility, presenting the VENUS-F configuration SC11/All-rods-in along with the GENEPI-3C deuteron accelerator. Then the experiments performed will be presented, as well as the results obtained. The experimental results will then be compared to Monte-Carlo simulations. Next the Monte-Carlo simulations method to reproduce the experiments will be presented along with the results of these simulations. Finally, first conclusions about the use of a pulsed neutron source with the Area-ratio method for core loading monitoring will be drawn.

2. EXPERIMENTAL SETUP

2.1. The VENUS-F reactor

The VENUS-F fast reactor is contained in a cylindrical vessel of 160 cm in diameter for a height of 140 cm. This vessel contains a square stainless steel casing surrounding a 12x12 matrix designed to receive 144 assemblies of $\approx 8 \times 8 \text{ cm}^2$ square section. In order to help localizing the various assemblies and detectors, an arbitrary coordinate system is used in the 12x12 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 steel casing are the 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. Cavities are present in some positions in the outer

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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 are based on the so-called SC11/All-rods-in sub-critical configuration (Fig. 1) of VENUS-F. The core is made of fuel assemblies (FA) (in purple), 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. Six safety rods (SR, in red), made of B₄C, with fuel followers as well as 2 control rods (CR, also in red) were inserted in all the configurations used for studying the reloading of the core. Specific assemblies were also inserted inside and around the core such as in-pile-sections (IPS, in blue) made of polyethylene surrounded by cadmium and stainless steel IPS (in orange). Finally, the 4 central slots 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 (see Fig. 1).

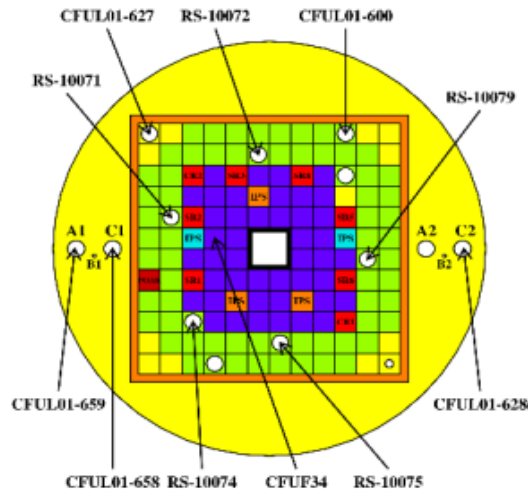


Figure 1. Schematic view of configuration SC11/All-rods-in

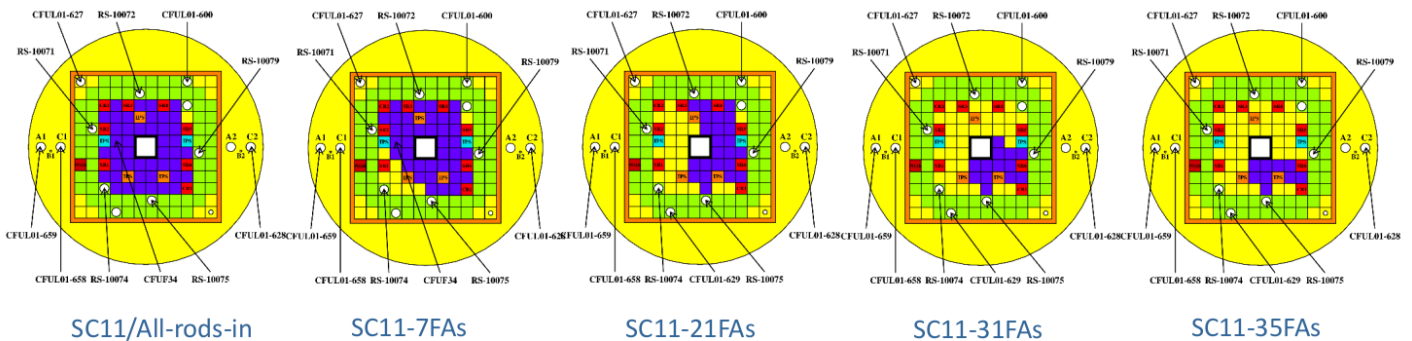


Figure 2. Schematic views of SALMON configurations

In addition to the SC11/All-rods-in configuration, 4 steps of the core unloading were studied, by removing 7, 21, 31 and 35 Fuel assemblies which were replaced by Lead assemblies (Fig. 2). The reactivity of each configuration was experimentally estimated using the Source Jerk Integral (SJI) method [6,7]. These configurations cover a large domain of anti-reactivity, from $\approx -22\%$ to $\approx -103\%$ (Table I).

Table I. Reactivity of SALMON core configurations determined using Source-Jerk method

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

2.3. Detector Configuration

The VENUS-F reactor core was equipped with various fission chambers (FC), working in pulse mode. These FCs were all located in the inner and outer reflectors, except for the CFUF34, as shown in Figs 1 and 2. Each fission chamber contains a highly enriched uranium deposit ($\geq 90\%$ ^{235}U) and is connected to a high voltage power supply and an amplifier-discriminator, as well as a data acquisition system that allows time-stamping of 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 with ≈ 1100 mg of ^{235}U deposit [8], 5 GE Reuter-Stokes (RS) FCs with ≈ 100 mg of ^{235}U deposit and one standard Photonis CFUF34 FC with ≈ 1 mg of ^{235}U deposit. Detector dead times were evaluated during continuous beam experiments with source power variations and were accounted for using a non-paralysable model [9].

Background measurements were regularly performed throughout the campaign to accurately evaluate the contribution of electronic noise, gamma rays, light particles and also the neutron coming from the reactor intrinsic source (mostly the spontaneous fission of the ^{238}U). This evaluation is quite critical as the counting rates during the Pulsed Neutron Source (PNS) experiments are very low for the least reactive configurations.

2.4. The GENEPI-3C accelerator

The GENEPI-3C [10] is a deuteron accelerator developed by a collaboration of CNRS/IN2P3 laboratories (LPSC, LPC, IPNO, IPHC). It accelerates deuterons up to 220 keV and guides them towards a TiT target inserted at the center of the VENUS-F core. The $\text{T}(d,n)^4\text{He}$ fusion reactions provide a quasi-isotropic source of 14-MeV neutrons. In addition, the alpha particles produced in the reaction are detected using Si detectors in order to monitor the source intensity. Different temporal modes are available for the source: continuous mode with or without beam interruptions and pulsed mode. In the work presented here, only the latter was used to inject $\sim 10^6$ neutrons per pulse in the reactor. The width of each pulse was less than 1 microsecond.

3. EXPERIMENT

3.1. Experimental method

For each studied configuration, neutron pulses were periodically injected in the reactor core at a frequency of 100 Hz in most configurations (and 200 Hz for SC11/All-rods-in and SC11-7FAs) for a few hours. Then the counts obtained from each period were piled up to obtain enough statistics, and the

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contribution from the background (mainly the FA intrinsic source mentioned in 1.4) was subtracted from the counting rates.

Figure 3 presents the final PNS histogram for detector RS-10075 in position (1,-5) in configuration SC11-31FAs. After a fast “prompt” decay of the neutron population during the first milliseconds after the pulse, a much slower decay takes over, creating a plateau driven by delayed neutrons.

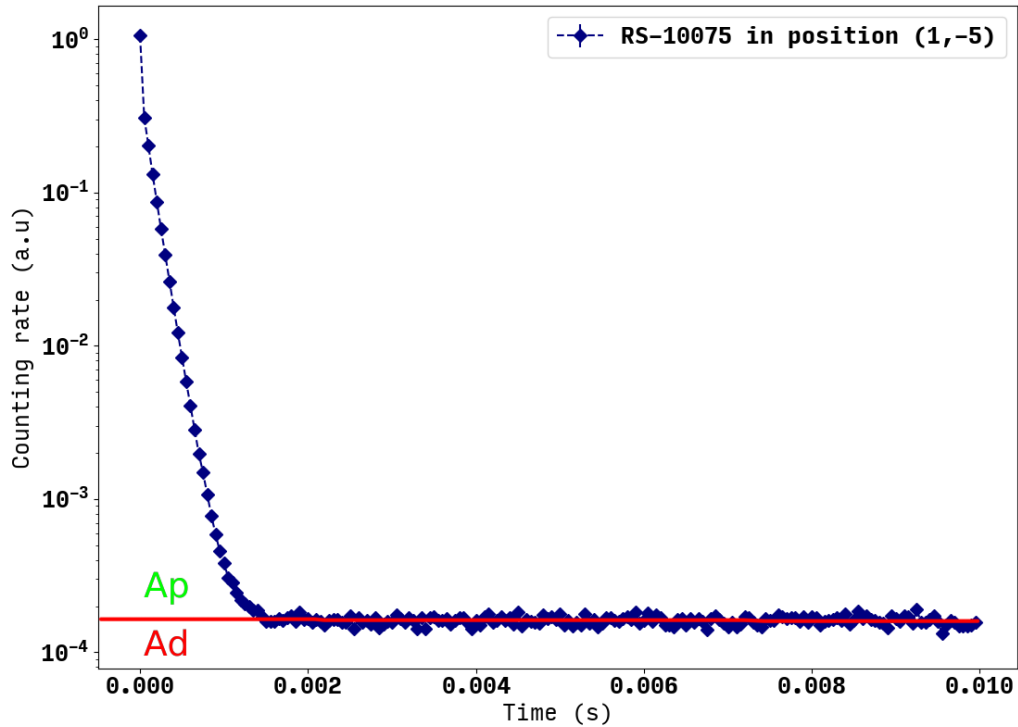


Figure 3. Detector counts as a function of time elapsed since the neutron pulse in position (1,-5) using SALMON core SC11-31FAs

The reactivity can be inferred from PNS histograms using the area-ratio method, or Sjöstrand method [11], based on Point Kinetics Theory. When a sub-critical reactor is excited with multiple periodic, Dirac neutron pulses, the temporal evolution of the neutron population $n(t)$ in the reactor after a sufficiently large number of pulses reads [12] :

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

where ρ denotes the reactivity of the reactor, β_{eff} the effective delayed neutron fraction, λ the decay constant of a single group of delayed neutrons, Λ_{eff} the mean generation time, t the time elapsed since the last neutron pulse.

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

$$\frac{\rho}{\beta_{eff}} = \frac{-A_p}{A_d} = 1 - \frac{A_{tot}}{A_d} \quad (2)$$

where A_d is the area under the delayed neutron plateau (red line on Fig. 3), A_p the prompt integral (the area enclosed between the blue curve and the red line on Fig. 3), and A_{tot} the total integration of the PNS histogram.

It is worth mentioning that unlike the simple recording of count rates or noise methods, the analysis of PNS experiments with the Area Method would be insensitive to a strong FA intrinsic radioactivity, because the latter can be evaluated before sending pulses in the core.

3.2. Reactivity values obtained

The Area-ratio method presented in section 3.1 was applied to the data obtained in each available position for all SALMON configurations. The uncertainties obtained for the Area-ratio reactivity include the statistical uncertainties on the count rates from the PNS experiments and from the background measurements and the uncertainty on the dead-time correction affecting A_p .

Figure 4 presents the reactivity values obtained from Formula (2) for each position and each SALMON configuration as a function of the reactivity of the configuration estimated by the Source Jerk Integral method [6,7] which is considered as the reference reactivity value.

As can be seen, the reactivity values given by the Area-ratio method depart more and more from SJI values as the reactor is getting smaller and huge spatial effects can be observed. Two groups of detectors can be distinguished: Detectors in positions (1,-5), (5,-1), (-4,4) and C2 give results close to the SJI value whereas detectors in other positions tend to diverge more and more with the SJI results as the core is being emptied. This can be explained by the fact that detectors in the first group remain close to the core throughout the unloading, whereas detectors belonging to the second group become more and more distant from the core. This generates strong spatial effects beyond PK, which prevents obtaining a reliable estimate of large subcriticalities. Spatial effects are visible in Fig 5, where PNS histograms are shown for detector RS-10079 in position (5,-1), hence in the inner reflector near the FAs, and detector CFUL01-658 in position C1, in the outer reflector and on the side where the FAs have been removed. The shape of the neutron population decay is conspicuously very different from one detector to another.

Nevertheless, 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, representative of detector locations in power reactors.

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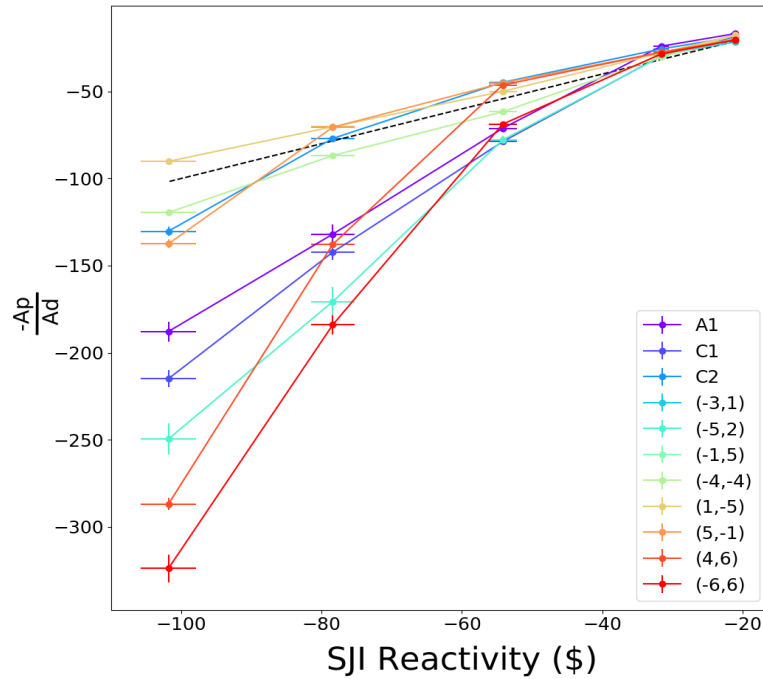


Figure 4. Reactivity given by the Area-ratio method as a function of SJI reactivity values (the dark dashed line represents the function $-A_p/A_d = \text{SJI reactivity}$)

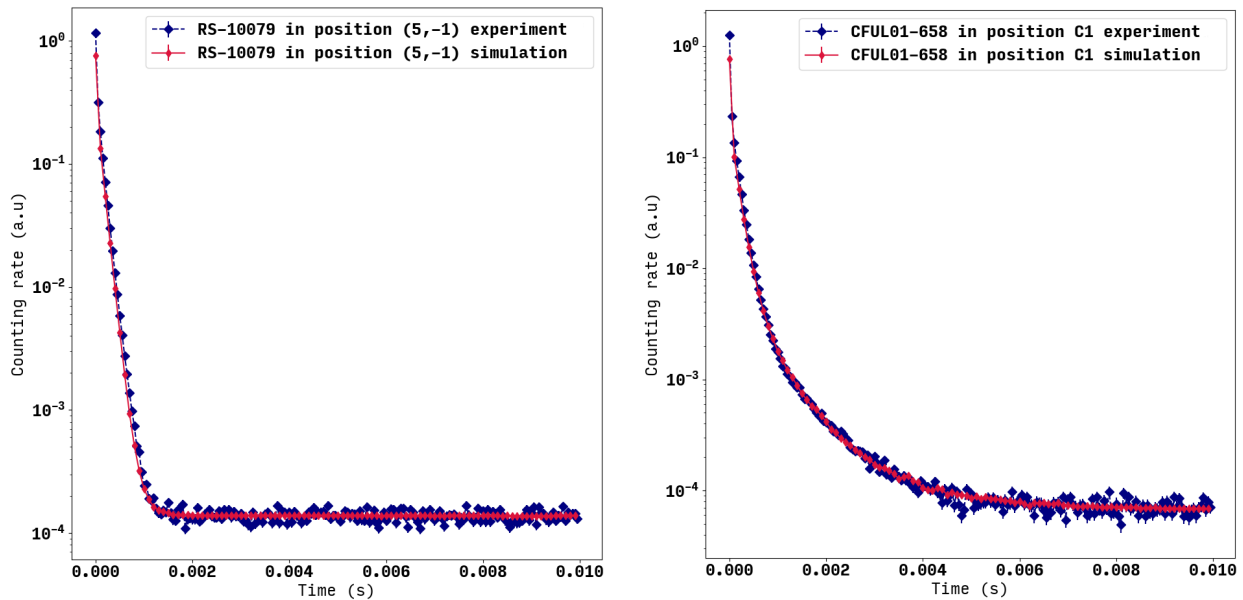


Figure 5. Experimental PNS histograms (blue) in the inner reflector (left panel) and the outer reflector (right panel) in the SALMON core SC11-31FAs compared to Monte Carlo Simulations (red)

3.3. Monte Carlo simulations of PNS experiments

The failure of the Area-ratio Method at estimating large subcriticality values obtained by partial unloading of the core is not surprising. Indeed, Point-kinetics 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 the effects outside the scope of the Point-kinetics, Monte Carlo simulations of the PNS Experiments were carried out to try to reproduce the experimental observations.

These simulations were done using the Serpent-2 [13] Monte-Carlo Transport code coupled to the JEFF3.1.1 [14] library. The input files used to describe SALMON configurations were simplified to save calculation time. Fuel assemblies were homogenized and some details of the bottom neutron reflector were not exactly reproduced. The detector were also simplified to volumes where Serpent-2 track-length estimator was applied to estimate reaction rates by convolution to ^{235}U and ^{238}U fission cross-sections. Furthermore, the neutron source was approximated to an isotropic point source at the center of the core, emitting 14-MeV neutrons. These simplifications were successfully employed in the analysis of past experiment at GUINEVERE [3,4,5].

One should note, that even with these simplifications, the simulations remain computer time consuming as reaction rates must be calculated with enough statistics in all fission chambers up to more than 1000 seconds after the initial neutron pulse, so that experiment-like PNS spectra could be reconstructed by folding the reaction rates with the periodic source pattern.

Simulation results are also presented in Fig. 5. The agreement between the simulated and experimental shapes, for both inner and outer reflector detectors is remarkable.

In order to fully test the capability of Serpent-2 at reproducing the spatial effects for each configuration and for each position, Serpent-2 can be used to calculate space-energy factors to correct experimental reactivity values from spatial effects. First, the reactivity (ρ_{serpent}) of each Serpent-2 reactor model was calculated thanks to the power iteration method. Then the simulated PNS histograms were analyzed using Formula (2) to obtain $(-A_p/A_d)_{\text{serpent}}$ for each detector position simulated. Then the Spatial factor (f_s) is simply :

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

and a corrected reactivity is calculated for each detector as

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

Figure 6 presents the corrected reactivity values as a function of SJI reactivity. The difference with Fig 4. is striking: even for the most sub-critical configurations, the corrected Area-ratio method reactivity values are in agreement with the SJI results for all detectors.

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

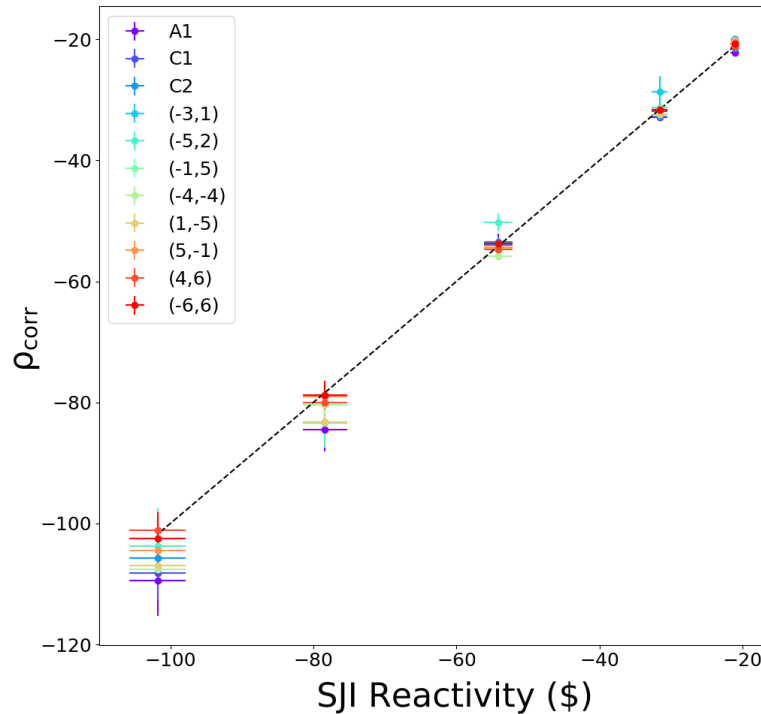


Figure 6. Area-ratio Reactivity corrected with Spatial factors as a function of SJI reactivity values (the dark dashed line represents the function $\rho_{\text{corr}} = \text{SJI reactivity}$)

4. CONCLUSIONS

Phase 1 of the SALMON project was devoted to the study of the analysis of PNS experiments using the Area-ratio method as a means of measuring the reactivity during the reactor core loading in order to prevent loading errors.

The experiments were carried out at the GUINEVERE facility using the VENUS-F fast neutron reactor at different steps of its unloading. The GENEPI-3C deuteron accelerator was coupled to a TiT target in the reactor to inject the neutron pulses in the cores and ^{235}U FCs were positioned at various positions in the inner and outer reflector to measure the neutron flux evolution during the PNS experiments.

The results of PNS experiments 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 method and the true reactivity, even for the detectors located in the outer reflector. Furthermore this correlation would remain even when strong FA intrinsic sources are present since its contribution could be measured before injecting pulses and then subtracted.

In addition, simulations were found to reproduce fairly well the spatial effects. Since the simulation model has been validated, it can be used to simulate the introduction of a wrong FA (for instance with a different k_{∞}) during loading and to investigate how much the area-ratio would be modified in a real experiment. This will allow us to determine the sensitivity of this method for detecting an error in VENUS-F loading.

Then in phase 2 of the SALMON project, 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.

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