Innovative neutronic experiments

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Content

1. ADS experiments at IN2P3

1.1 Until 2013

1.1.1 Original motivations: research on ADS

1.1.1.1 The transmutation of Minor Actinides in ADS

In terms of radioactive waste management, the partitioning and transmutation (P&T) of long-lived radioactive elements is a complementary line of research to deep geological disposal. If the idea of transmuting Long-Lived Fission Products (LLFP) has been abandoned, the transmutation of Minor Actinides (neptunium, americium, curium) is still under investigation. Indeed, in the case of multi-recycled plutonium, after a few hundred years, the Minor Actinides (MA) are responsible for most of the radiotoxicity of the spent fuel, and the residual thermal power of the High Activity packages is essentially due to americium alone. Recycling and transmutation of high-level radioactive materials would make it possible to reduce the quantity of high-level radioactive materials in the waste, thus reducing their radiotoxicity, and would also lead to a clear reduction in the size of the storage area for high-level waste (around a factor of 10). The transmutation of high-level waste would thus allow the optimization of radioactive waste management [CEA12]. The transmutation of spent fuel should be considered in a fast spectrum nuclear reactor, because fission is favored over capture. It can be carried out in critical fast reactors (FR) or in a second stratum of accelerator-driven subcritical fast reactors (ADS) dedicated solely to transmutation.

In the case of critical FRs, the chain reaction is self-sustaining, the new neutrons that appear in the reactor (mainly by fission) compensating for the disappearance of neutrons by absorption or leakage from previous generations. More precisely, if we define the neutron multiplication coefficient as:

$$k_{\mathrm{eff}} = \frac{\text{Number of neutrons of generation i+1}}{\text{Number of neutrons of generation i}} \qquad (1)$$

or, equivalently, the reactivity as:

$$\rho = \frac{k_{\mathrm{eff}}-1}{k_{\mathrm{eff}}} \qquad (2)$$

or, alternatively, by introducing the effective delayed neutron fraction β_{eff}, the reactivity “in dollar” as:

$$\rho_{\$} = \frac{\rho}{\beta_{\mathrm{eff}}} \qquad (3)$$

One can see that a critical reactor will be characterized by $k_{\mathrm{eff}} = 1$ or $\rho = \rho_{\$} = 0$. Unfortunately the introduction of AM in the fuel degrades significantly the reactivity coefficients and the kinetics of the FR, more precisely the coolant void coefficient, the Doppler feedback and the effective delayed neutron fraction which constitutes the margin to prompt criticality[1]. These phenomena limit the amount of AM that can be inserted in a critical FR.

Conversely, in the case of ADS, the reactor is voluntarily subcritical ($k_{\mathrm{eff}} < 1$ or $\rho < 0$ and $\rho_{\$} < 0$), i.e., in the absence of a constantly renewed injection of neutrons by an external source in order to

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[1] Thermal feedbacks left apart, the reactor reactivity should never exceed $\rho = +\beta_{\mathrm{eff}}$ (that is 1 \$) or it will become uncontrollable, this is prompt criticality.

permanently initiate new fission chains, their power cannot be maintained (it is either zero or decreases with time until it becomes zero). Practically, the external source of neutrons is made by coupling the subcritical reactor to a proton accelerator via a spallation target. Then the fuel can be highly loaded with AM, since subcriticality gives an additional margin to prompt criticality that can largely cover the lack of Doppler feedback and the increase of the coolant void effect. As for the effective delayed neutron fraction, it no longer plays any role in driving the subcritical reactor and its decrease caused by the introduction of AM is no longer important. Consequently, ADS have a transmutation capability of AM far superior to that of critical FRs.

In 1996-1997, a research framework called GEDEON (Gestion des Déchets par des Options Nouvelles) was set up in France by CEA, CNRS, EDF, and Framatome, with the objective of coordinating the research effort on the transmutation of long-lived isotopes, the axis I of the law on the management of radioactive waste of 30 December 1991. This effort focused initially on the potential of accelerator-driven subcritical reactors with a fast neutron spectrum, and on their feasibility. Thus, several research programs have been supported on various challenges related to ADS: the improvement of nuclear data and models related to spallation, the improvement of the understanding of the physico-chemical phenomena of corrosion in the spallation target and the behavior of the associated materials, the study of the coupling between a reactor and an external neutron source, and the improvement of the performance of the linear accelerators providing the beams driving the neutron source. At the international level, these subjects have also found support in the European framework programs of EURATOM (5^{th}, 6^{th}, 7^{th} FP and H2020). At IN2P3, the teams dedicated to experimental reactor physics have been involved in experimental programs carried out with ADS mock-ups in order to study the particular behavior of ADS.

1.1.1.2 The problem of reactivity measurement

In addition to the reliability of the proton accelerator and to the ADS fuel cycle (manufacture, transport, recycling), the reactivity of the subcritical reactor must be measured on-line, otherwise the ADS cannot be operated. Indeed, the advantages of ADS originating from its subcriticality, this subcriticality must be ensured under all conditions (normal, incidental or accidental). Consequently, it is necessary to ensure that the reactivity never exceeds, during the life cycle of the ADS, a value chosen so that the maximum insertion of reactivity which could be added during an accident would remain insufficient to make the reactor critical [Sar17]. An important part of the experiments on reactivity monitoring is carried out on ADS mock-ups operated in Europe. The study of methods for measuring the reactivity on such facilities at almost zero power, whose external source is produced by well-known reactions such as d+T fusion, makes it possible to free oneself from the thermal effects and the evolution of the fuel and to decouple the physics of the subcritical core from that of the spallation source (envisaged for power ADS).

1.1.2 The MUSE program

The MUSE-4 experiment within the "MUSE" program (MUltiplication d'une Source Externe), financed by the 5th FP of EURATOM (2000-2004), associated the CEA, EDF, Framatome, the CNRS and other European partners around an ADS mock-up (with a power of less than 100 W) consisting of the MASURCA reactor (CEA/DEN Cadarache), and an external source of neutrons. The core was loaded with MOx fuel and solid sodium. Several subcritical configurations were designed by varying the size of the core. The external source was produced by the GENEPI (Générateur de Neutrons Pulsé Intense) accelerator, designed and built by the LPSC, which delivered pulsed beams of 250 keV deuterons (from a duoplasmatron source) onto a tritiated (or deuterated) target located in the center of the reactor.

The MUSE-4 experiment allowed testing the coupling of the accelerator with the reactor and the piloting of the latter by the accelerator, to reinforce the qualification of the calculation tools, and to propose a methodology of reactivity monitoring for the future power ADS based on the combination of two techniques [MUS05]:

- on the one hand, the permanent measurement of the ratio of the intensity of the proton beam (to which the intensity of the spallation neutron source is proportional) to the neutron flux in the reactor (to which the thermal power of the subcritical reactor is proportional) ;
- on the other hand, the regular measurement of the neutron population decrease in the reactor during short programmed and periodic interruptions of the continuous proton beam.

These two measurements are essential. Indeed, the first one allows one to detect a variation of reactivity but not to measure the reactivity itself, the proportionality coefficient between the measured ratio and the reactivity being difficult to determine and likely to evolve with time. On the contrary, the second measurement, more difficult experimentally, can give access to an estimate of the reactivity by making assumptions on the behavior of the neutron flux during the transients. Unfortunately, these assumptions and the robustness of the measurement protocol could not be tested at MASURCA during MUSE, as the GENEPI accelerator only delivered pulsed beams.

1.1.3 The EUROTRANS integrated project of the 6th Euratom FP

The GUINEVERE (Generator of Uninterrupted Intense NEutrons at the lead Venus REactor) project [Bil09] was born within the new sixth Euratom Framework Program (FP) Integrated Project in support of ADS, EUROTRANS (2005-2010). It consisted in building a new fast neutron ADS mock-up at SCK CEN (Belgian Nuclear Research Center, Mol, Belgium). The main partners of the GUINEVERE project were SCK CEN, CNRS and CEA/DEN. The latter supplied the fuel in the form of uranium metal rods enriched to 30%. On the CNRS side, a new deuteron accelerator, GENEPI-3C, was built by the LPSC, the LPC Caen, the IPHC and the IJCLab under the project management of the former. This new accelerator has the advantage of being able to deliver pulsed, continuous and continuous beams with programmed periodic interruptions, the latter two modes of operation corresponding better to what will be used in a power ADS. On the reactor side, the SCK modified the VENUS thermal reactor to transform it into VENUS-F, a fast neutron reactor whose fuel assemblies contain mainly the fuel rods already mentioned and lead rodlets, in order to be representative of power ADSs envisaged in Europe, with lead coolant such as EFIT[2] [Art08] or in the shorter term with lead-bismuth such as MYRRHA [Ait19]. Figure 1 shows a schematic view of the SC1 configuration of VENUS-F, the first subcritical configuration created. The fuel assemblies (U+Pb+steel) are in blue, the lead is in yellow, the steel in orange, the absorbing elements in red, the measurement channels in white (between 6 and 11 fission chambers have been used during the successive programs carried out at GUINEVERE). The size of the core can be easily modified by changing the number of fuel assemblies present among the 144 slots in the 12x12 matrix visible on the left of the figure.

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[2] European Facility for Industrial Transmutation

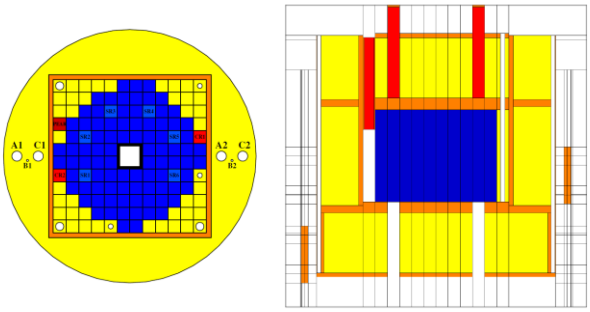


Figure 1. The SC1 subcritical configuration of VENUS-F.

VENUS-F can be operated alone in its critical configuration, or coupled to the GENEPI-3C accelerator when subcritical. As was the case for GENEPI-1, a tritiated titanium target ensures the conversion of deuterons into 14-MeV neutrons via the T(d,n)^{4}He fusion reaction. The commissioning of the facility allowed testing the performance of the external neutron source (pulse width ≈ 0.7 µs (1σ), maximum 10^6 neutrons/pulse in pulsed mode for a peak current of 20 mA, and 5×10^{10} neutrons/s in continuous mode for 1 mA).

If other ADS mock-ups exist in the world (YALINA in Belarus, KUCA in Japan, VENUS-II in China), none has a subcritical reactor as representative of a future power ADS as the GUINEVERE installation. It therefore remains the ideal place for new experiments dedicated to the study of the physics of ADS.

1.2 Experiments carried out at GUINEVERE

1.2.1 An effort of representativeness: from FREYA (2011-2016) to MYRTE (2016-2019)

1.2.1.1 Scope and objectives of the European FREYA project

The FREYA project (Fast Reactor Experiments for hYbrid Applications) was led by SCK CEN, co-financed by Euratom FP7 for 2.8 M€. CNRS/IN2P3 was the second partner in terms of human and financial investments (this project gathered 16 partners in total). The objectives of the FREYA project were:

- To continue the experimental program dedicated to the validation of the reactivity monitoring methodology initiated during the GUINEVERE project;
- To carry out experiments in support of the design and certification of the critical and sub-critical configurations of MYRRHA;
- To carry out experiments in support of the design and certification of lead-cooled fast nuclear reactors (LFR).

The FREYA project was divided into five work packages (WP1: ADS on-line reactivity monitoring methodologies, WP2: Subcritical configurations for design and licensing of MYRRHA/FASTEF, WP3: Critical configurations for design and licensing of MYRRHA/FASTEF, WP4: Critical configurations for Lead Fast Reactor, WP5: Training and Education). CNRS/IN2P3 was in charge of the coordination of WP1 but was also strongly involved in WP2, and to a lesser extent in WP3 and WP5. Practically, the IN2P3 teams participated in the definition of the measurement programs and the configurations of VENUS-F to be studied (with a massive recourse to Monte Carlo simulations to prepare the experiments), in the data taking, their analysis and their interpretation.

If the main objective of the reactivity measurement experiments was to validate the monitoring protocol proposed at the end of the MUSE4 experiment - that is to say the combination of the monitoring of the current-to-flux ratio and the analysis of the neutron population decrease during short interruptions of the continuous beam of the accelerator - many other experiments in which our teams were strongly involved had to be carried out:

- Pulsed Neutron Source (PNS) experiments. These experiments allowed to bridge the gap with the MUSE experiments performed at MASURCA and to continue the study, initiated in MUSE, of different methods to estimate the reactivity from the response of the detectors to neutron pulses, which could eventually be used when loading an ADS.
- MSM (Modified Source Multiplication) experiments. The MSM method is a proven method (unfortunately unusable in a future power ADS) to measure the reactivity of a subcritical configuration from another already known one by comparing the count rates generated by a radioactive source in these two configurations. All VENUS-F configurations were measured by MSM, either "conventionally" with an Am-Be source [Lec15a,Lec15b] or by modifying the method to use GENEPI in continuous mode [Bil21].

The fourteen subcritical configurations studied in FREYA WP1 were all derived from SC1 (Fig. 1), either by modifying the number of fuel assemblies, or by modifying the insertion of control rods, or by adding "perturbations" to the reactor. The objective was both to probe a large range in reactivity (from ≈ -18 \$ to ≈ -4 \$, i.e., from $k_{eff} \approx 0.885$ to $k_{eff} \approx 0.971$) but also to study the effect of local changes in the reactor on the response of detectors located nearby.

The reason why the validation of reactivity measurement methods must be the subject of such ambitious measurement programs is that these methods are generally based on Point Kinetics Theory, which postulates that the neutron flux within the reactor can be factorized into two components: a shape function that depends on the position, direction and energy considered, but not on time, and an amplitude function that depends only on time. In other words, it is assumed that the flux does not change shape over time. While this assumption is rather well verified near criticality ($\rho \approx 0$) when the flux is in its fundamental mode, it is expected to be challenged in ADS. This is because the external source placed in the center of the reactor excites harmonics of the flux that each vanish with a different time constant when the source ceases to operate, causing the shape of the total flux to change over time. The more subcritical the reactor will be, the more pronounced these effects will be, since the shape of the flux with external source will be more different from the shape of the fundamental flux without source.

An overview of the numerous results obtained by the IN2P3 teams is presented in the three following sections.

1.2.1.2 Pulsed source experiments in FREYA

Pulsed source experiments have been performed in all the subcritical configurations of VENUS-F investigated in FREYA. In order to accumulate enough statistics, neutron pulses were injected for several hours, generally at a frequency of 200 Hz. Figure 2 shows the evolution of normalized count rates of ^{235}U fission chambers in some of the detectors placed at different positions in the reactor in SC1 configuration. As expected, the temporal evolution is more or less different from one detector to another, indicating the presence of "spatial effects", i.e. a modification of the shape of the flux over time in the reactor.

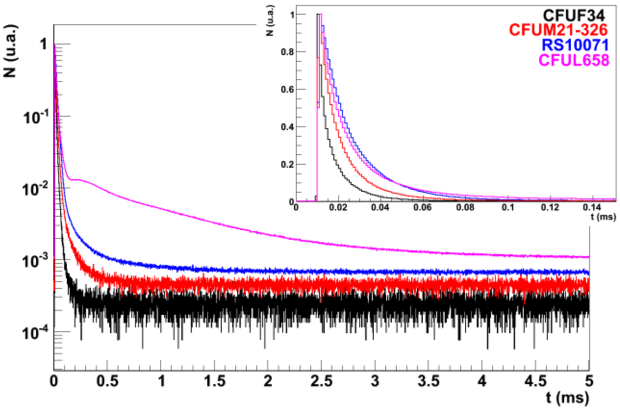


Figure 2: Evolution of the count rates of some fission chambers during pulsed source experiments in SC1

In Fig. 2, one can easily distinguish two regimes in the evolution of the count rates: a very fast decay, called "prompt" decay, before the establishment of a plateau (which corresponds in fact to an extremely slow decay invisible in these time scales) called the "delayed neutron level". Using Point Kinetics, one can show that the reactivity, the effective delayed neutron fraction and the areas under the prompt peak Ap and under the delayed neutron plateau Ad are related by the relation:

$$\rho_{\$} = \frac{\rho}{\beta_{\mathrm{eff}}} = -\frac{A_p}{A_d} \qquad (4)$$

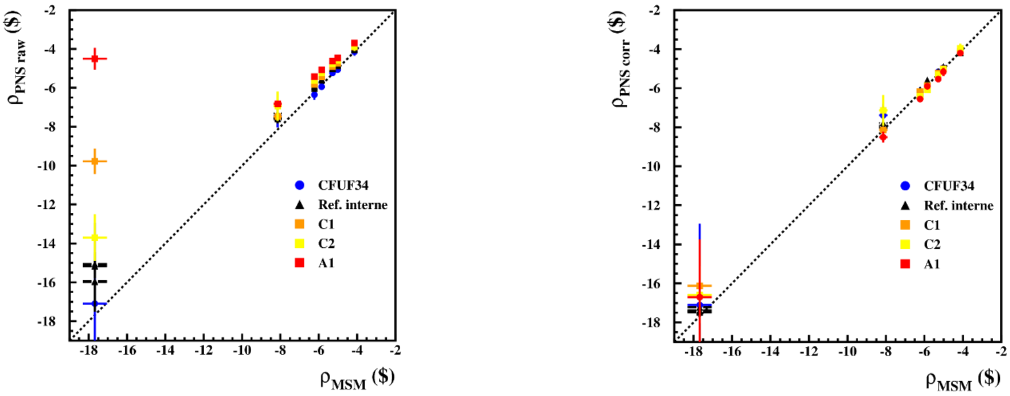


Figure 3. Results of reactivity measurement experiments using the Area method. Left: raw results. Right: results corrected for spatial effects.

The left part of Fig. 3 presents the results obtained with relationship (4) for all detectors in all configurations of VENUS-F of WP1 as a function of the reference reactivity values obtained with the MSM method. Rather (or even very) important deviations are observed, unfortunately for the detectors placed outside the core, where detectors would be localized in a power ADS.

These results have motivated the massive use of Monte Carlo simulations of neutron transport in simplified models of VENUS-F in order to calculate correction factors, called "space-energy factors" or SEF. As can be seen on the right side of Fig. 3, the use of these space-energy factors allows one to obtain a good estimate of the reactivity whatever the detector used or the configuration of VENUS-F chosen. The robustness of these factors has obviously been investigated, but this work is not completely finished, the priority having been given to the analysis of the experiments of periodic interruptions of the continuous beam.

In addition, in the case of unperturbed core configurations, solving the time-dependent diffusion equation in one dimension with a few energy groups using a modal approach has also led to quite satisfactory SEFs for the Area method [Leh17].

The kp method, initially developed at LPSC during the MUSE4 experiments, is based on the observation that the distribution of inter-generation times in a reactor such as VENUS-F is not exponential as predicted by Point Kinetics (as illustrated in the left part of Fig. 4). The kp method consists of using the realistic distribution of these inter-generation times P(τ), obtained by Monte Carlo simulation, to construct an estimator related to the prompt decay of the neutron population observed in the PNS experiments and depending on the prompt neutron multiplication coefficient kp. The comparison between this set of curves from the simulation and the curve obtained from the experimentally observed decays allows then to determine the value of kp. In order to adapt to the experimental conditions provided by the GUINEVERE facility, a new integral estimator was developed during the FREYA project. The right part of Fig. 4 shows a very good agreement for all detectors between the reactivity values obtained by the kp method and the reference values for the SC1 configuration [Cha14].

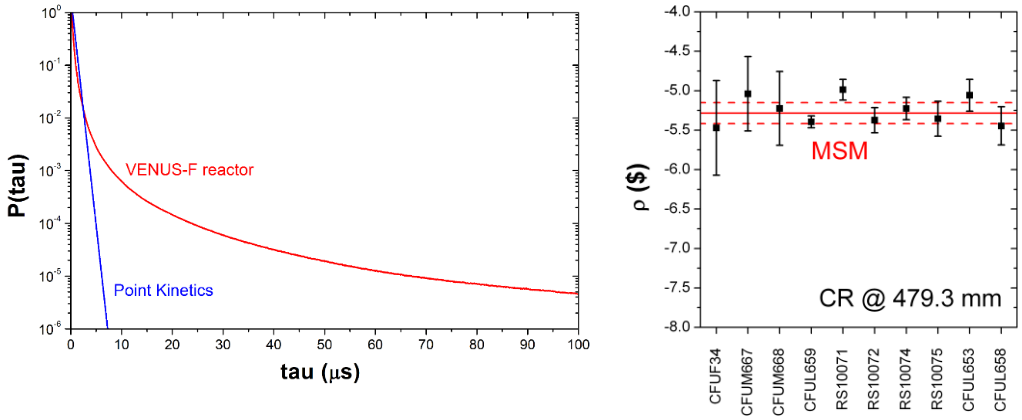


Figure 4: kp method. Left: distribution of inter-generation times in VENUS-F (simulation). Right: results for SC1.

1.2.1.3 Periodically interrupted continuous source experiments in FREYA

Periodic beam interruption experiments have received a lot of attention, since it is envisaged to regularly measure the reactivity of a power ADS by analyzing the decay of the neutron population during these interruptions. Indeed, starting from Point Kinetics, it can be shown that the comparison of the count rates before interruption, n_0, and once the delayed neutron level n_1 is established, allows estimating directly the reactivity:

$$\rho_{\$} = \frac{\rho}{\beta_{\text{eff}}} = c\left(1 - \frac{n_0}{n_1}\right) \qquad (5)$$

Where c is the duty cycle of the external neutron source. All experiments were performed with a high duty cycle of 92% and very short interruptions (beam interrupted for 2 ms every 25 ms), representative of the duty cycle that could be used in a power ADS. The challenge was to test if the relation (5) could be used to estimate the reactivity under these conditions, over a wide range of reactivity and with ex-core detectors.

The analysis of these experiments was the subject of Th. Chevret's PhD thesis [Che16]. The left part of Fig. 5 presents the evolution of the normalized count rates of ^{235}U fission chambers in some of the detectors placed at different positions in the reactor in SC1 configuration. As for the pulsed source experiments, the temporal evolution is more or less different from one detector to another, indicating the presence of "spatial effects". Nevertheless, we observe, for almost all detectors, after an abrupt drop of the count rates corresponding to the interruption of the beam, the more or less rapid establishment, in a few ms, of a "delayed neutron level". Reaching this plateau in a few ms is crucial since it is essential for the use of relation (5). As for the Area method in a NPS experiment, the use of Point Kinetics alone gives rise to a dispersion of the reactivity values obtained, all the more important as the reactivity is low. Again, the massive use of Monte Carlo simulations allows to drastically reduce this dispersion, as can be seen in the right side of Fig. 5 [Che14,Che16]. Obviously, if this approach confirms the ability of Monte Carlo transport codes to account for the physical phenomena at work in the subcritical reactor, it is only of interest in terms of reactivity estimation if the space-energy factors are not very sensitive to the reactor modeling errors. This seems to be confirmed by the sensitivity studies carried out to date.

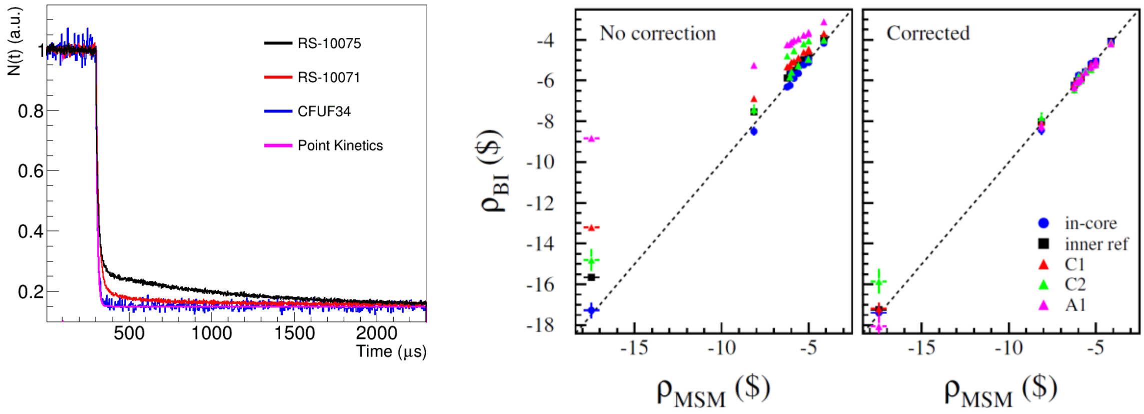


Figure 5. Periodic beam interruption experiments. On the left, examples of decrease observed in some fission chambers in the SC1 configuration. Right: results of the use of relation (5) without correction of spatial effects and with correction.

1.2.1.4 The current-to-flux relationship in FREYA

In addition to the absolute measurement of the reactivity using relationship (5), it is planned to continuously evaluate the ratio of the accelerator current to the neutron flux in the reactor. Indeed, since the reactor thermal power Pth (and consequently the flux) is proportional to the external neutron source intensity (hence to the accelerator current I in the case of a spallation target) and inversely proportional to the reactivity ρ, the latter is directly proportional to the current-to-flux ratio.

In the case of the experiments carried out at GUINEVERE, the intensity of the deuteron beam was more or less constant during the whole experiment and it is the intensity of the neutron source that was directly measured and compared to the count rates R of fission chambers placed in the reactor:

$$\rho = C\left(\frac{S}{R}\right) \qquad (6)$$

Figure 6 shows the reactivity variations estimated using relationship (6) for each of the 7 fission chambers placed in VENUS-F in SC7 configuration when the height of the control rods is changed. As can be seen on the left side of Fig. 6, not all detectors give the same variation in reactivity, depending on their position relative to the control rod that is operated. However, again, it is possible to find functionals relating the apparent variation to the actual variation in reactivity for each detector using Monte Carlo simulations [Mar19].

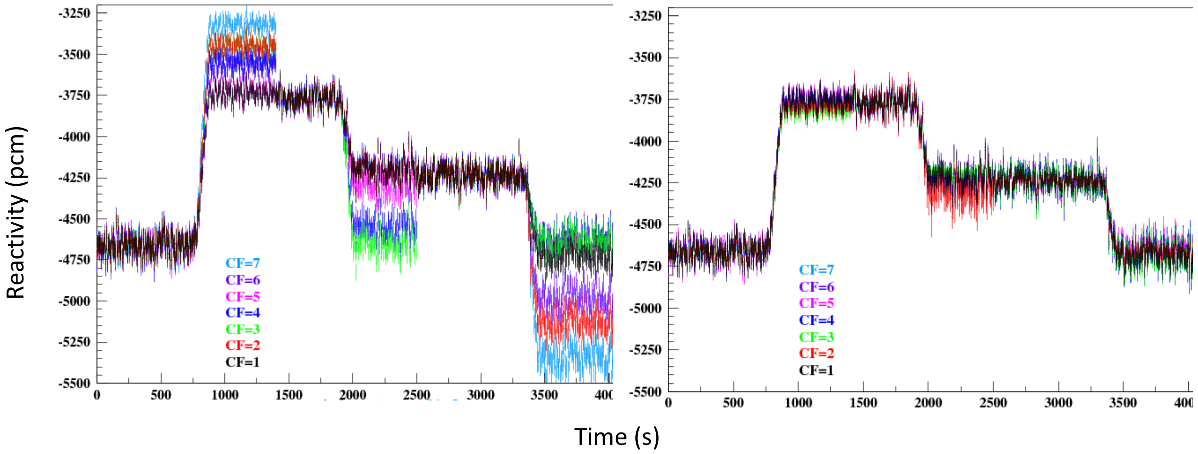


Figure 6. Measurement of reactivity during control rod motions in the SC7 configuration of VENUS-F using the current-to-flux ratio. On the left, apparent reactivity variations for seven different detectors. On the right, with Monte Carlo corrections.

1.2.1.5 The MYRTE project

The European project MYRTE (Horizon 2020) ran from 2015 to 2019. Supported by the H2020 program with 9 M€, it involved 27 European organizations for more than 900 FTE person-months and was coordinated by SCK CEN. Work Package 5 was dedicated to the realization of new experiments at the GUINEVERE facility in a configuration more representative of the most recent design of the subcritical reactor planned for MYRRHA and its instrumentation.

The IN2P3 teams were responsible for task n°4 on the study of a new instrumentation for the VENUS-F reactor. The high flux level expected in MYRRHA and the desire to continue to use fission chambers in pulse mode led to the consideration of the use of fission chambers equipped with a threshold deposit [Lec17]. We have therefore proposed to use three fission chambers in VENUS-F with ^{238}U deposits of various purity and to complete the instrumentation with ^{235}U fission chambers coated with boron nitride (BN).

To test these instrumental choices, a new measurement campaign with VENUS-F was organized in 2017. The MSM and beam interruption experiments took place in the SC11 configuration (and a variant) of VENUS-F much closer to those envisaged for MYRRHA: addition of alumina and bismuth in the fuel assemblies, graphite reflector placed at the periphery. This campaign has been particularly successful: for the configurations studied (around -6 $), we have shown that the reactivity measurement with high-purity threshold fission chambers suffers much less from spatial effects than with ^{235}U chambers, whatever the detector location. On the other hand, while the use of boron nitride significantly improves the reactivity measurement at very short beam interruptions (< 1ms), it has little effect on the results obtained with longer interruptions. Finally, we have also shown that Monte Carlo simulations could be used to correct the results obtained with ^{235}U fission chambers [Lec18].

1.2.2 An effort of completeness: MYRACL, a joint SCK/CNRS program (2017-2020)

As soon as the MYRTE WP5 experiments were completed, it became clear to us that a new experimental program was needed to qualify this new instrumentation further. Indeed, the MYRTE experiments had only allowed to probe a very reduced reactivity range (from -6 to -5 $), with a temporal structure of the beam representative of an operation at nominal power, whereas the reactivity measurement will be necessary during all the (re)start-up phases of a facility such as MYRRHA. With the help of the “Pôle Accélérateurs et Sources d'Ions” team at LPSC Grenoble, we then started discussions with SCK-CEN to establish a new collaboration at GUINEVERE, the MYRACL (MYRrha ACceLerator) program, as part of a larger bilateral collaboration between the two organizations on ADS and in particular its accelerator (MYRRHA-100MeV). The ambition of the MYRACL program was fourfold:

- to study very subcritical configurations, obtained by inserting two to six safety rods in SC11, configurations representative of the (re)start-up of a facility such as MYRRHA ;
- to study new configurations with a smaller core representative of a "fresh" core;
- to use a very low source duty cycle (0.02 instead of 0.92) representative of the time structure of the MYRRHA proton accelerator envisaged for the (re)start-up phases;
- to study the impact of random beam micro-cuts on the reactivity measurement.

A total of seven new VENUS-F configurations (with reactivity ranging from ≈ -6 to ≈ -31 $) were subject to measurement campaigns in 2018 and 2019. The analysis of MYRACL experiments is part of Alexandre Bailly's PhD thesis (2019-2022).

While the use of a low duty cycle did not fundamentally alter the results already observed in MYRTE, unexpected results were observed when safety rods were inserted into VENUS-F. Detailed results are shown in Figure 6 for the SC12 configuration with all safety rods inserted. While for the ^{235}U fission chambers, a similar pattern is observed as in previous experiments (without SEF, the reactivity is either well estimated or overestimated), the reactivity values extracted from the ^{238}U FCs show a completely new behavior: without SEF, the reactivity can be strongly underestimated, which means that reactivity measurements using only relationship (5) without neutron transport simulations are no longer satisfactory in terms of reactor safety.

A closer look at the results for all configurations shows that the absorber rods play an important role in the observed space-energy distortions. All the results were the subject of a comprehensive report provided to SCK CEN [Bai20]. A new version of this report is currently being written, which includes minor modifications of the reference reactivity values as well as the application of a new method for calculating the SEF uncertainties to all the VENUS-F configurations studied in MYRACL. The results of MYRACL will of course be published later.

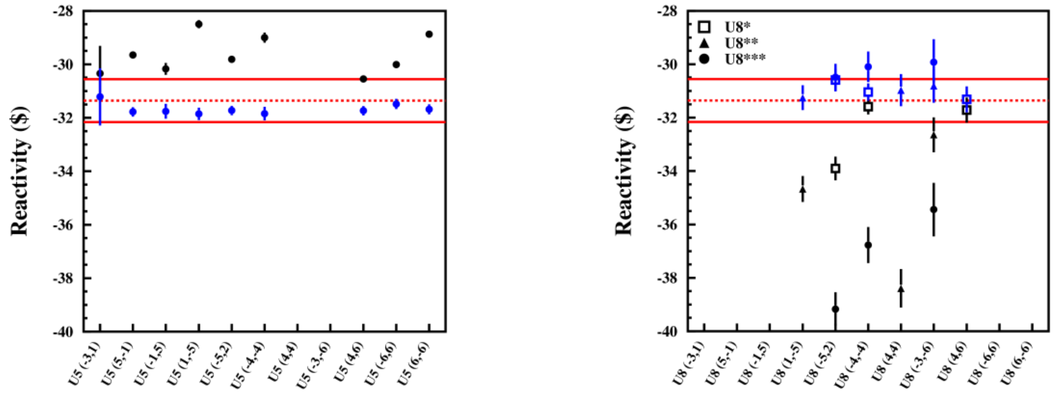


Figure 7. Estimation of the reactivity of the SC12 configuration during beam interruptions, using relationship (5). The results on the left correspond to ^{235}U detectors, the results on the right to ^{238}U detectors. Values obtained with relationship (5) alone are in black, those obtained with the use of space-energy factors are in blue. The reference reactivity (MSM) and its uncertainty range is in red.

2. From ADS research to other reactor physics issues

2.1 Monitoring the fuel loading of power reactors

2.1.1 The problem

Pressurized water nuclear reactors (PWR) are shut down for refueling every 12 to 18 months. During these operations, the core is unloaded of all its fuel and 1/3 (or 1/4) of the assemblies, completely used, are discarded. The reactor is then reloaded with the remaining assemblies (in different locations) and 1/3 (or 1/4) of new assemblies. The assemblies must be replaced in the core in a precise order according to a loading plan fixed in advance, which makes it possible to optimize the fuel burnup of the assemblies and to respect certain constraints (shape of the neutron flux, vessel fluence, etc.)

The refueling of a nuclear reactor is a complex operation. On April 2, 2001, a loading error occurred in unit 4 of the Dampierre-en-Burly power plant (France): assembly n°25 was forgotten in the fuel building, creating a shift in the loading. 138 additional assemblies were inserted in the wrong places before the error was detected. During loading, two detectors placed in the reactor vessel allow monitoring of the evolution of the neutron flux. Unfortunately, while the evolution of the reactivity of the core could be an indicator of the correct progress of the loading, it turns out that the count rates of the detectors are poorly correlated with the reactivity of the core, the neutrons detected coming largely from the intrinsic radioactivity of the assemblies loaded near the detectors [Ver05].

Conversely, the experiments we have conducted since 2012 at the GUINEVERE facility show that there can be a very strong correlation between count rates measured in a reactor and its reactivity, provided that a neutron source is used whose intensity varies with time. Moreover, the wide range of VENUS-F cores already studied indicates that this strong correlation is present for cores of various sizes, which suggests that the excitation of a reactor being loaded with a periodic external neutron source could make it possible to obtain count rates strongly correlated with the reactivity of the reactor and thus to monitor its loading stages.

2.1.2 The SALMON project

Obviously, the VENUS-F fast neutron reactor is nothing like a 900 MWe thermal pressurized water reactor. Moreover, the collection of cores already studied contains cores of various sizes, but all are fairly symmetrical, whereas the loading stages of a power reactor create highly asymmetrical configurations, which are more subject, during dynamical experiments, to large spatial effects that make reactivity measurements more difficult.

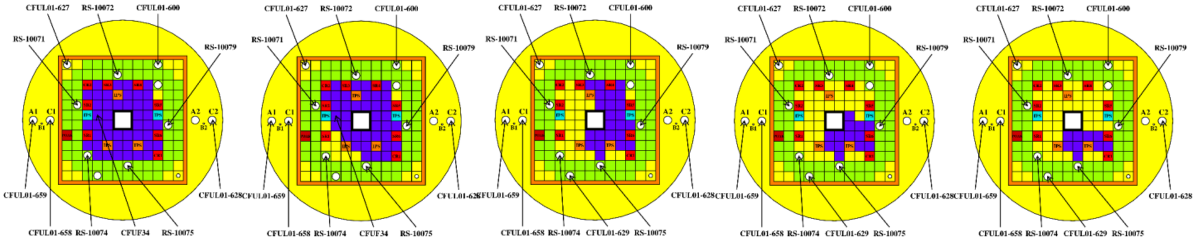
This is why we proposed a new project of experiments at the GUINEVERE facility, the SALMON (Subcritical Approach for core Loading MONitoring) project. Ideally, this project was to be articulated in three phases:

- Phase 1 consisted of taking advantage of the end of the MYRACL program experiments in mid-2019, to perform reactivity measurement experiments using the GENEPI-3C accelerator used in pulsed mode, in highly asymmetric cores created during the unloading of VENUS-F. The pulsed mode was chosen because it is the standard operating mode of commercial neutron generators. The fast spectrum of VENUS-F, a disadvantage in terms of the representativeness of power reactors, made it possible to take advantage of the data collected with the previous configurations of the reactor but also to work on the monitoring of the loading of a future power fast reactor.
- Phase 2 should have been completed by the end of 2020, early 2021. Indeed, after the end of the MYRACL program and the unloading of the last fast core, the VENUS-F reactor was to recover its original thermal spectrum with its return to water coolant and the use of fuel

slightly enriched in fissile material. The idea was to repeat the experiments described previously in this thermal version of the reactor, obviously much more representative of pressurized water reactors, by taking advantage of the loading stages of the new core. These experiments had been integrated into the structuring project SUCRE of NEEDS but could not be carried out to date, since the return of VENUS-F to thermal is no longer envisaged in the short term.

- The results of the first two phases concerning the impact of the reactivity measurement on the control of the loading, but also concerning the transposition to a power reactor, will make it possible to envisage a third phase of greater importance, dealing with both the research or the development of a miniature neutron generator fulfilling the specifications (performances, size) outlined during the previous phases, and the realization of experiments even more representative of a reloading, for example, using several types of fuels at the same time (LEU, MOX).

The unloading of the SC11 configuration of VENUS-F was performed in 2019. For each of the selected steps (shown in Figure 8), measurements with GENEPI-3C in pulsed mode (100 or 200 Hz) were performed. The reactor was equipped with about ten ^{235}U fission chambers. The analysis of the data constitutes the second part of Alexandre Bailly's PhD thesis (2019-2022).



SC11/All-rods-in SC11-7FAs SC11-21FAs SC11-31FAs SC11-35FAs

Figure 8. Steps in the unloading of the SC11 configuration of VENUS-F

Figure 9 shows the reactivity values obtained from each detector using the Area method as a function of the reference reactivity[3]. As can be seen, the range in reactivity probed is impressive (from ≈ -21 $ to ≈ -100 $). Nevertheless, despite strong differences between detectors, a strong correlation between the Area result and the reference reactivity is clearly visible for all detectors, including those positioned in the outer reflector, as in power reactors. It should be noted that this correlation would not be impacted by the presence of the intrinsic sources of the different fuels since their contribution could be measured (then subtracted) before injecting the neutron pulses. These results have been submitted to the international conference PHYSOR 2022. Monte Carlo simulations are in progress to determine the sensitivity of the Area method to the insertion of an erroneous fuel assembly.

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[3] For the SALMON experiments, it is not the MSM method that was used as a reference, due to lack of sufficient statistics, but the full "Source Jerk" method, which we do not have the space to discuss here.

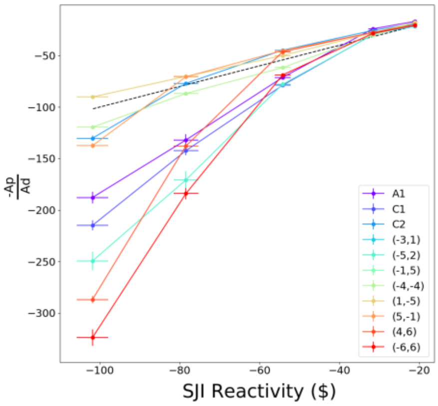

Figure 9. Comparison of the reactivity obtained using the Area method with the reference value for the five unloading steps of VENUS-F.

In view of the promising results of this first phase of SALMON, it seems important that at least phase 2 be performed. Without waiting for the return of VENUS-F to thermal, alternatives are being studied:

- to replace Pb and Bi present in the fuel assemblies of VENUS-F with polyethylene in order to make its spectrum thermal;
- to take advantage of the (un)loading of another thermal research reactor to carry out preliminary tests with a commercial neutron generator.

2.2 The in-depth study of space-energy effects in the reactor

2.2.1 A look back at space effects during source transients

If we examine all the measurement campaigns devoted to the absolute measurement of reactivity during external neutron source variations, carried out between 2012 and 2019 in the GUINEVERE facility, we can roughly draw the following conclusion.

First, relationship (5) cannot be used as it is to measure the reactivity of an ADS because the hypothesis that the spatial and/or energy distributions of the neutron flux do not change during the power transients caused by the periodic shutdown of the external neutron source has been shown to be poorly verified in an ADS, even for a reactivity corresponding to its nominal power. These space-energy effects are more important as the reactivity decreases and lead to a dispersion of the reactivity values obtained depending on the position and the type of deposit used (^{235}U or ^{238}U) in the fission chamber (FC). In general, the use of relationship (5) with a ^{235}U FC leads to an overestimation of the reactivity. This overestimation can rise to several tens of % at the periphery of the reactor where, contrary to the predictions of the point kinetics, the plateau of delayed neutrons is not quite reached during the beam interruption (2 ms). The results are even more problematic for ^{238}U FCs: depending on the level of subcriticality and the proximity of neutron absorbers (control or safety rods), the relation (5) can lead to an over- or underestimation of the reactivity. In other words, the use of a ^{235}U CF may lead for some positions to a very important additional safety margin (and thus constraints on the accelerator intensity or the thermal power of the ADS) and may even be problematic in terms of safety with a ^{238}U FC, in particular in the presence of control and/or safety rods, which are envisioned in some ADS to regulate the reactivity during the irradiation cycle, for example in the MYRRHA reactor. However, considering the expected neutron fluxes in power ADS, FCs using fission threshold deposits are likely to be more suitable than FCs with fissile deposits such as ^{235}U.

Second, the complete simulation of the experiments carried out at GUINEVERE using stochastic transport codes such as MCNP5 or Serpent 2 has allowed the development of a methodology for the calculation of space-energy factors in order to get rid of space-energy effects which disturb the reactivity measurement. Once corrected, the reactivity values obtained from neutron decay measurements during beam interruptions do not deviate from the reference values by more than ≈ 4%. If these results show that the transport codes are able to reproduce the space-energy effects at work in GUINEVERE during a source transient, they do not guarantee that the reactivity can be measured with the same bias and uncertainties in a future power ADS. Indeed, it is clear that the space-energy effects that bias the reactivity measurement remain in some cases poorly understood, or even unexpected and therefore difficult to anticipate. For example, the underestimation of the reactivity observed at certain points of the reactor, in certain configurations, with ^{238}U FC, was discovered only belatedly during the realization of the final MYRACL measurement program. A critical re-examination of the previous campaigns provides the first explanations:

- if the range of configurations of the VENUS-F reactor studied during the measurement campaigns represents an unprecedented effort, it appears that most of the distortions observed in the reactivity measurements were rather due to spatial effects in which the variations of the energy distribution of the flux during the transients do not play a large role, in particular because the large majority of the configurations were not very heterogeneous and few fission threshold FCs were available;
- the measurements were mainly carried out in the reflector, certainly because it is unthinkable to place permanent detectors in the core of a power ADS, but to the detriment of the measurement of the flux shape evolution in the core and of valuable information on the impact of the interaction of source neutrons with the detectors.

In summary, the measurement of reactivity during periodic interruptions of the continuous beam has given very good results during multiple measurement campaigns at the GUINEVERE installation. It is certainly the most promising and advanced technique. Unfortunately, in the current state of our knowledge, its robustness has not been demonstrated yet, in particular because the space-energy effects responsible for the biases on the reactivity measurement are not completely understood, especially in their energy component. It is therefore premature to transpose the results obtained to a power ADS.

2.2.2 Towards a neutron source of higher intensity and greater stability at the GUINEVERE facility

2.2.2.1 The SPATIAL project

The SPATIAL project aims at the most comprehensive understanding of the space-energy effects at work in ADSs during beam interruptions, in particular in their energy aspects, the study of which has barely been sketched at GUINEVERE, by carrying out a systematic mapping in space and energy of these effects and their temporal dependence, and to transpose the results obtained for a power ADS, in order to quantify the biases and uncertainties on the measurement of its reactivity. This ambitious project was the subject of a funding request in November 2021 for 2 M€ from the Banque Publique d'Investissement as part of a call for projects on "innovative solutions for the management of radioactive materials and waste, and the search for alternatives to deep geological disposal."

2.2.2.2 Neutron flux shape mapping

In a nuclear reactor, direct measurement of the energy spectrum at any point is impossible. The observable of choice to study the energy distribution of the neutron flux is rather the spectral index (SI). It is the ratio between fission rates of different nuclides:

$$SI^{za}_{\zeta\alpha}(\vec{r},t) = \frac{F\boldsymbol{za}}{F\zeta\alpha}(\vec{r},t) = \frac{\int dE\,\sigma_{\mathrm{f}}\left({}^{AA\boldsymbol{a}}_{Zz}X\right)\phi(\vec{r},E,t)}{\int dE\,\sigma_{\mathrm{f}}\left({}^{AA\alpha}_{Z\zeta}Y\right)\phi(\vec{r},E,t)} \tag{7}$$

where $\phi(\vec{r},E,t)$ is the neutron flux of energy E at point $\vec{r}$ and time t, and σ_f the microscopic fission cross sections of nuclides X and Y. The SI does not depend on the amount of flux present but only on its energy distribution via the fission cross sections.

The spectral index, very sensitive to the energy distribution of neutrons, is traditionally measured in steady state. What we propose here is to measure, for the first time, the spectral indices along a reactor traverse using pairs of FCs with different deposits, during periodic beam interruptions so that the variations of the energy spectrum as a function of time and space can be observed directly, and everywhere in the reactor (by taking advantage of the symmetries of the reactor configurations). Obviously, the SI measurement requires measuring the evolution of the fission rates separately, which allows one to study at the same time the influence of the nuclide used for the reactivity measurement on the measurement biases.

Figure 10 shows the fission cross sections of some nuclides that could be used as deposits in FCs. As expected, the fission cross sections of the threshold nuclei (^{237}Np, ^{238}U, ^{241}Am, ^{242}Pu) are very different from those of the fissile nuclei (^{235}U, ^{239}Pu). Moreover, the fission cross sections of ^{235}U and ^{239}Pu have significantly different shapes and the fission thresholds of the ^{237}Np, ^{242}Pu, ^{241}Am and ^{238}U nuclei are in an increasing order.

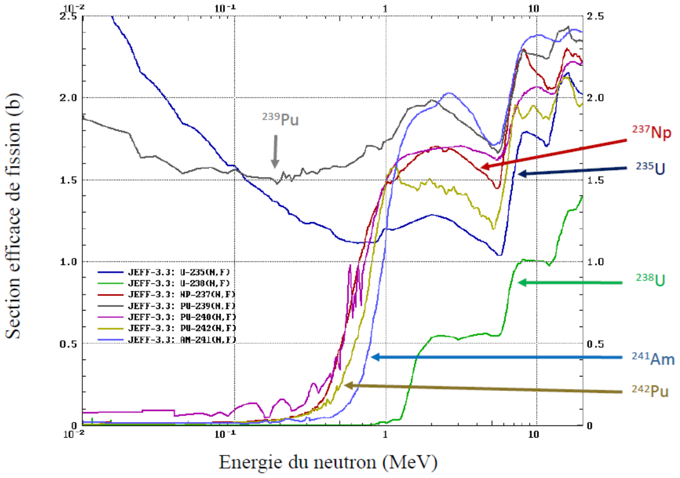

Figure 10. Fission cross sections as a function of incident neutron energy, for some nuclides of interest for the SPATIAL experiments (source JEFF3.1).

Consequently, by combining these isotopes two by two to form SIs, it is possible to probe different energy ranges of the neutron flux and the variation of each SI in space and time will sign a spatial and temporal variation of the energy spectrum more or less sensitive to this or that range. For example, an increase of SI^{28}_{25}, corresponding to the ratio of the fission rate of ^{238}U to that of ^{235}U, would sign a hardening of the neutron spectrum. Among the above mentioned nuclei, the couple (^{238}U, ^{237}Np) is of particular interest:

- $^{23\mathbf{8}}$U (Z=9**2**) and ^{237}Np (Z=9**3**) have very different fission thresholds. Measuring the evolution of IS^{28}_{25} and IS^{37}_{25} during beam interruption as a function of position will allow comparison of the evolution of the energy spectrum over two very different fast ranges.
- If compared to ^{235}U, too few data have been collected with ^{238}U FCs, the situation is even more dramatic for ^{237}Np: no periodic beam interruption experiment has ever been performed with

^{237}Np. However, the results of preliminary simulations tend to show that ^{237}Np FCs are less sensitive to space-energy effects than their ^{238}U counterparts.

Obviously, the choice of reactor configurations will be of paramount importance to disentangle the space-energy effects at work during beam interruptions. For example, the comparison of the dynamical traverses of SI between two reactor configurations with the same reactivity but with differently distributed absorbing rods will make it possible to measure directly the effects of the proximity of absorbing rods on the evolution over time of the energy spectrum in the whole reactor during beam interruptions and to finally understand the biases observed in the previous experimental programs.

Beyond the direct comparisons allowed by the proposed systematic mapping, the collected data will allow very accurate comparisons with analyses based on new modal expansion methods of the neutron flux at several energy groups, using transition rate matrices computed by stochastic codes [Che17], in order to understand the origin of the space-energy effects. In addition, the unprecedented accuracy and completeness of the collected data will at the same time provide a very demanding test of the transport codes used to simulate the experiments. Finally, the understanding of the space-energy effects and the limitations of the transport codes revealed will allow to determine the biases and uncertainties to be expected on the reactivity measurement of a power ADS using these same transport codes for the transposition work as well as to evaluate the confidence level on the simulations performed.

The reason that the experiments briefly described in the previous section have never been performed yet, although they are of paramount importance in determining the reliability of the reactivity measurement, is because they are extremely difficult to implement. No current facility in the world is able to provide both the external neutron source, the subcritical reactor and the instrumentation required. Indeed, for the measurement of space-energy effects to be reliable, the detectors used must be as small as possible in order not to disturb the neutron flux shape. This condition imposes in return to carry out a large number of beam interruptions, reproducible over several days, thus with a very stable external source of neutrons, and moreover very intense, in order to obtain enough events in the detectors so that the statistical fluctuations remain under control.

This is why, in the framework of the SPATIAL project, we propose very ambitious modifications of the GENEPI-3C source already mentioned to make these experiments possible. The GUINEVERE facility has been chosen for the following reasons:

- It is one of only two facilities in the world that already couples an external neutron source to a subcritical fast reactor (the other is in China, but its specifications are not well known);
- The facility is very well known to the CNRS teams since the latter built the GENEPI-3C accelerator there.

In order to make measurements of dynamical SI traverses possible, the GENEPI-3C accelerator must undergo profound modifications and the instrumentation used in the VENUS-F subcritical reactor must be adapted.

If the duoplasmatron deuteron source which currently equips the accelerator is very versatile, it will not be able to reach the stability required for the SPATIAL experiments and its intensity can hardly be increased. For this reason, we propose to replace it by an ECR source, delivering a more intense and much more stable continuous beam, coupled to a fast beam chopper. The increase of the beam intensity (at least a factor 3) requires a rethinking of the tritiated titanium target allowing the production of neutrons.

Concerning the reactor instrumentation, most of the existing detectors are too big to be introduced inside the VENUS-F core without distorting the measurements. We will therefore call on the know-how of the Dosimetry, Sensors and Instrumentation Laboratory (LDCI) of CEA Cadarache, whose expertise in the manufacture of miniature FCs using various deposits is internationally recognized, to create the appropriate chambers. The challenge here is to have FCs with a diameter of less than 1.27 cm, with a few effective milligrams of deposit, at least for ^{237}Np and ^{238}U.

2.2.2.3 Transposition to a power ADS

The last part of this project consists in transposing the results obtained on the reactivity measurement to a power ADS. Indeed, if many concepts of power ADS, proto-industrial like MYRRHA, or able to transmute AM like EFIT, have been the subject of very detailed numerical simulations (fuel cycle, transmutation rate, etc.), nothing exists concerning the transposition of the results obtained on the reactivity measurement in near-zero power models such as GUINEVERE to power ADS. This transposition work is necessary because :

- the energy spectrum of the spallation neutrons extends over a large energy range (several orders of magnitude) whereas the spectrum of the neutron source used in GUINEVERE is almost mono-energetic. Threshold detectors are likely to be sensitive to these spectrum differences;
- In zero power installations, the fuel does not evolve, so the energy and the flux shape is always identical when the external source injects neutrons into the reactor. This will not be the case in a power ADS which will see the distribution of the flux in space and energy change during the irradiation cycle.

As can be seen, the questions raised by the transition from the mock-up to the power ADS are caused in particular by the differences in energy spectrum for the source and the core between the two types of ADS. Thus the work consisting in characterizing as precisely as possible the space-energy effects also takes all its meaning in the framework of the transposition.

This part of the work will therefore consist, by relying :

1. on the biases and uncertainties observed on the reactivity measured in the VENUS-F configurations studied in the framework of the SPATIAL project;
2. on the deconvolution of the space-energy effects, made possible by modal analyses, which will make it possible to understand these effects and thus to anticipate their presence or not in the power reactors;
3. on the comparison between the data collected on the whole reactor with the set of FC deposits used, during the beam interruption experiments carried out in SPATIAL, which will make it possible to evaluate the performances of the neutron transport codes;

to simulate in detail, with the help of neutron transport codes, the reactivity measurement during proton beam interruptions in the complete system (proton beam + spallation target + power ADS such as MYRRHA and EFIT) and this, at different points of the irradiation cycle. The uncertainties and biases to be expected on this measurement according to the position and the type of detector used and the progress of the irradiation cycle, will then be quantified.

2.3. Towards a more thorough integration of the experimental results

Even if, so far, experimental research in reactor physics at IN2P3 has been devoted mainly to ADS and thus to the subcritical reactor, the projects in progress or proposed now go far beyond this framework. In the case of the SALMON project, the work of IN2P3 concerns the improvement of the safety of the fuel loading of (critical) power reactors. In the case of the SPATIAL project, if the work is still motivated by the development of ADS, the expected results will contribute to a better description of the neutron flux behavior of critical reactors. For example, the study of spatial effects is also a subject of research for critical reactors, especially in large cores.

Whether in the framework of SALMON or SPATIAL, the data obtained will constitute advanced tests of modal transient analysis methods that can also be used to analyze power excursions in power reactors. All these data collected from GUINEVERE will have their place in the numerical platform proposed by IN2P3 (see the document "Modelling for reactor physics - Interest of a numerical platform" and the presentation of X. Doligez) and which has already been presented during the recent prospectives of the institute (GT11: Nuclear energy and environment).

3. Human and financial resources

3.1 Human resources at IN2P3 and their evolution

To give an idea of the forces invested, the FREYA project has mobilized at IN2P3 about 160 person-months (including technical support), including about 4.5 full-time physicists during the peak times of the project.

Currently there are six permanent physicists involved in the experimental reactor physics (1 DR, 2 CR, 3 MCF) distributed between the LPC, the LPSC and the IJCLab. One PhD student (A. Bailly) has started the third year of his PhD thesis. It should also be noted that many students from ENSICAEN in the Nuclear Engineering and Energy major have been able to carry out 3rd year mini-projects in connection with the experiments at GUINEVERE.

Finally, it should be noted that the past projects could not have been carried out without a close and fruitful collaboration with the physicists of SCK CEN (reactor instrumentation, certification of the critical cores indispensable for the passage to subcriticality, participation in the simulation, preparation and realization of the experiments, piloting and control of the VENUS-F reactor, maintenance of the installation, and analysis of data not presented in this document) and CEA Cadarache (supply of the fuel and of part of the instrumentation).

3.2 Financial resources

Not only have the successive Euratom FPs strongly stimulated research related to the problem of Partitioning and Transmutation in Europe and constituted the initial framework of our close collaboration with SCK CEN, but the impact of the funding granted by Euratom has been decisive for our research activities. Also, within the framework of the MYRRHA-100MeV contract between the CNRS and the SCK, we received funding to carry out the MYRACL experiments. In parallel, funding was obtained each year from IN2P3 in the form of “AP” (before they disappeared for our research field...), mainly to finance missions, but also in the form of a half thesis grant. We have also obtained additional funding from the NEEDS program of the CNRS. Let us add that NEEDS has recently played a structuring role for our activity via the creation of the structuring project SUCRE (2019-2022) which gathers CNRS, CEA and IRSN on the theme of experiments in reactor and instrumental developments for the measurement in reactor.

4. Conclusion

IN2P3 has been involved in accelerator-driven subcritical reactor (ADS) physics experiments for about 20 years. Since the construction of the GUINEVERE facility, which couples the GENEPI-3C accelerator, designed and built by CNRS/IN2P3, to the VENUS-F subcritical reactor at SCK CEN, IN2P3 teams have succeeded in developing a fruitful collaboration with SCK CEN and CEA. They have participated in (and often led) important experimental campaigns at GUINEVERE, dedicated to the study of ADS reactivity measurements, within the framework of the European projects FREYA (2011-2016) and MYRTE (2015-2019), then of the MYRACL (2017-2020) programs and of the SALMON project (2019). The magnitude and range of data collected remain unique in the field. The IN2P3 teams have acquired a recognized know-how in the field of subcritical reactor physics, which has allowed them to be a force of proposal in all the programs in which they have participated. The analysis methods developed have shown their efficiency and precision over a wide range of reactivity and in reactor configurations as representative as possible (for a near-zero power mock-up) of a future power ADS.

However, there are still some physics points to be clarified, before we can close the subject of reactivity monitoring in power ADS. The return to the forefront of ADS in transmutation scenarios following the interruption of the ASTRID project and the postponement sine die of the deployment of Fast Neutron Reactors in France, gives us the opportunity to propose, within the framework of the SPATIAL project, new improvements of the GUINEVERE installation in order to carry out new, very ambitious and innovative experiments dedicated to the most comprehensive study of the variations in space and energy of the flux shape during source transients. The impact of this project goes far beyond the sole questions of monitoring the reactivity of ADS, since the problem of spatial effects is common to both critical and subcritical reactors. Similarly, phases 2 and 3 of the SALMON project will be devoted to the development of a methodology to improve the safety of power reactor loading.

Annexes

A.1 References used in the text

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A.2.3. PhD thesis

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2013-2016 : T. Chevret, Mesure de la réactivité de réacteurs sous-critiques pilotés par accélérateur par l’analyse d’expériences d’interruptions de faisceau programmées, Université de Caen-Normandie