PROGRESS OF THE MUSE-4 EXPERIMENTS AND FIRST RESULTS FROM THE MEASUREMENTS AT SUBCRITICALITY LEVELS REPRESENTATIVE OF AN ADS

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Started in October 2000 within the frame of the 5FP, the fourth phase of the MUSE experiments is now in a key phase with the investigation of core configurations with subcriticality levels representative of those envisaged for future industrial Accelerator Driven Systems (ADS's) [1]. An extensive characterization of the MUSE-4 cores have been performed with and without the external neutron source in order to extend the validation area of neutronic code systems. The use of many experimental techniques and analysis methods, aiming to determine subcriticality levels and kinetic parameters, provided also a large amount of results whom analysis is being pursued. This paper summarizes briefly the progress of the project and the first lessons which can drawn from the experiment analysis.

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* Partner of the MUSE Contract

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1. Introduction

After a very long preparation phase, the first coupling between MASURCA core and the GENEPI neutron generator happened the 27th of November 2001. A series of preliminary measurements in slight subcritical configurations (k_{eff}=0.995) was performed at the beginning of the year 2002 to get not only first results but, to have also a feedback on experimental conditions necessary to improve and optimize measurements in the following phases.

Then, the full characterization of the reference critical configuration was achieved from April to June 2002 so that we have at our disposal a well-established reference measurement point. This program included importance traverses using a ^{252}Cf source, foil irradiations, spectral indices and numerous axial and radial traverses of fission rates. Rod-drop experiments and measurements of kinetic parameters have been also achieved in view to determine the reference reactivity levels.

The study of the subcritical states began again at the beginning of October 2002 with the investigation of the SC0 clean core configuration using neutron external sources provided by D(d,n)^{3}He and T(d,n)^{4}He reactions on both TiD and TiT targets. Since this measurement phase ended on March 2003, configurations with reactivity levels more representative of an ADS are being studied : SC2 configuration (k_{eff} around 0.97) was from April to July 2003, SC3 configuration with a k_{eff} around 0.956 representative of the subcriticality level at the end of life is currently being studied. Static measurements have been performed again with and without external neutron sources to study the physics of such cores and notably to characterize the neutron spectrum variations and the fission rate relative distribution changes in zones of interest. Pulsed neutron source (PNS) technique, source jerk techniques and noise measurements have been greatly applied in order to determinate the prompt decay constant (α_p), the prompt multiplication factor (k_p), the kinetic parameters and finally the reactivity of the configurations.

2. Description of the experimental devices

2.1. *The MASURCA mock-up*

The MASURCA facility is dedicated to the neutronic studies of fast lattices. The materials of the core are contained in cylinder rodlets, along with in square platelets. These rodlets or platelets are put into wrapper tubes having a square section (4 x 4 inches) and about 3 meters in height. The reactivity control is fulfilled by absorber rods in varying number depending of core types and sizes.

These safety rods (SR) are composed of fuel material in their lower part, so that the homogeneity of the core is kept when the rods are withdrawn. The core is cooled by air. The limited maximum operating power of the facility is limited to 5kWth. The maximum flux level is around 10^9 n/cm^2.s.

2.2. *The MUSE-4 core configurations*

The MUSE-4 configurations are based on the ZONA2 fuel cell (Figure 1), representative of a fast Pu burner with sodium coolant.

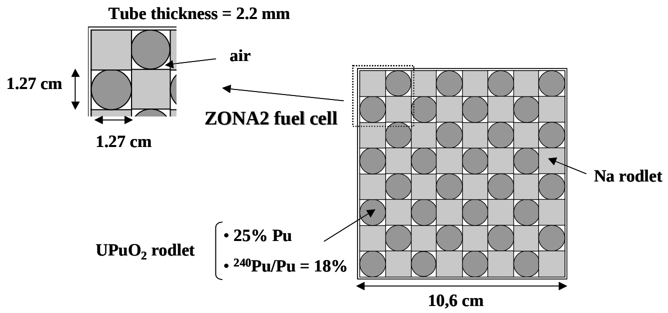

Figure 1. Radial cut of a tube loaded with 16 ZONA2 fuel cells

The fuel zone is radially and axially reflected by a stainless steel/sodium shielding. The GENEPI guide is horizontally introduced at the core mid-plane and the deuterium or tritium target is located at the core centre (Figure 2).

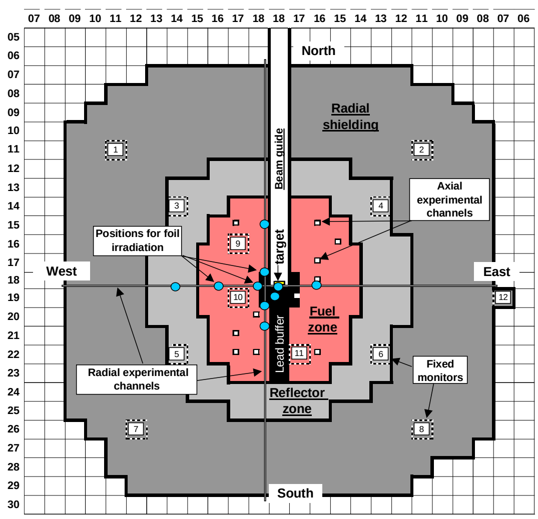

Figure 2. Radial cut at mid-plane of the MUSE-4 reference critical configuration

To perform the measurements, special channels have been opened throughout the MASURCA tubes to introduce different measurement devices (fission chambers, foils) : two horizontal channels at 90° around the mid-plane (radial channels) and thirteen axial channels.

Twelve monitors, whom ^{235}U and ^{10}B deposits have not been calibrated, are also used in a relative way. Their location inside the core changed several times all along the program to optimize their use (to decrease the dead time or to increase the counting rate).

2.3. *The GENEPI neutron generator*

2.3.1 *Characteristics*

Mainspring of the MUSE-4 experiments, the GENEPI (Générateur de Neutrons Pulsés Intenses) neutron generator is born from a close collaboration between CEA and CNRS. Built specifically with a view to these experiments, its main characteristic is to deliver very short pulses (<1µs) with a repetition rate going from some hertz to 4.5kHz. Two different pulsed neutron sources - neutrons of 2.67 MeV and 14 MeV produced respectively by $D(d,n)^3He$ reactions and $T(d,n)^4He$ reactions - have been used.

2.3.2 *Calibration and monitoring of the source*

The absolute values of the two external sources have been measured using nickel foils (8.4 mm in diameter, 0.5 mm thick) inserted in the axial experimental channel located in the tube at the E19-18 position. These irradiations were performed with all the safety rods inserted in order to minimize the activation due to the inherent source. From the activity of the different isotopes produced during the irradiation (more than 5 hours with GENEPI at a frequency of about 4kHz), one can deduce the numbers of neutrons per pulse. The neutron production rate of the deuterium target was found equal to $3.0 \pm 0.3 \times 10^4$ neutrons per pulse (for a 60 mA peak current, oscilloscope measurement). The one with the tritium target was found equal to $3.3 \pm 0.3 \times 10^6$ neutrons per pulse (40 mA peak current).

By recording simultaneously the monitoring detectors, which consist in silicon detectors counting the recoiled charged particles associated to the neutron production, it was also possible to associate the number of these particles detected to the absolute neutron production, and then to have an online monitoring of the source. The detection rate was found equal to $1.92 \pm 0.20 \times 10^{-7}$ proton per source neutron ((d,D) source monitoring) and to $2.44 \pm 0.24 \times 10^{-7}$ alpha-particle per source neutron ((d,T) source monitoring). More details about the experimental set-up and the results obtained can be found in [2].

3. Characterization of the MUSE-4 core configurations

One of the objective of the MUSE-4 experiments is notably to extend the experimental database and the validation area of neutronic code systems. A full characterization of the critical configuration have been first performed to have at our disposal a reference measurement point allowing the determination of the initial calculation biases. Then, for each subcritical level, the same measurements have been reproduced with the external source. These measurement programs included mainly spectral index and fission rate distribution measurements in the various experimental channels, as well as some importance traverses (not presented in this paper) and online neutron spectrum measurements [3]. Irradiations of several types of activation foils (indium, iron, cobalt, nickel, …) in the regions of interest, principally near the lead/fuel, accelerator/fuel and fuel/reflector interfaces, where the spectral fluctuations are the more important, completed this characterization.

3.1. *Fission rate relative distributions*

Validation of the deviation (from the critical reference) of fission rate distributions constitute an objective of prime importance regarding the definition of recommended calculation tools for the prediction of the neutronic features of future ADS's. Thus, fission rate relative distributions close to the beam guide, inside the lead buffer and in front of the target, have been first measured on the reference critical configuration with all SR up for a large sample of elements (Table 1). The objective of such a measurement campaign was not only to quantify initial biases not depending of the external source, but also to allow the assessment of minor actinides nuclear data.

Table 1. Fission rate relative distribution measurements performed on the reference configuration with 1115 fuel cells.

Position of the pilot rod	Critical position	Down
Reactivity (in dollars)	~0	~-0.37
Radial channels	N/S, W/E	N/S, W/E
Axial channels	E19-18, E16-15, W21-17, W20-18	E19-18, E16-15, W21-17, W20-18
Isotopes used	^{232}Th,^{233}U, ^{235}U, ^{237}Np ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{244}Cm, ^{10}B	^{233}U, ^{235}U ^{237}Np, ^{239}Pu, ^{10}B

Similar measurements were planned in subcritical configuration. Nevertheless, owing to the difficulties with the carrying out of the experiments and above all because of the increasing of the acquisition time duration due to the low counting rates when the core configurations become deeply subcritical, only ^{235}U fission rate traverses have been achieved for all subcritical configurations (one day per traverse). For the same reason, only the tritium target was used, for such measurements, for the SC2 and the SC3 configurations. All the measurements have been carried out with the four SR up and the pilot rod down (Table 2)..

Table 2. Fission rate relative distribution measurements performed on subcritical configurations

Configuration	SC0				SC2	SC3**
Reactivity* (in dollars)	~ -1.9				~ -9.1	~ -14.1
Target (D/T)	D	T	T		T	T
GENEPI frequency	4.5 kHz	OFF	2 kHz	4 kHz	4 kHz	2 kHz
Radial channels	N/S W/E	N/S	N/S W/E		N/S W/E	N/S
Axial channels	-	-	-		E19-18	-
Isotopes used	^{235}U	^{235}U	^{235}U	^{238}U	^{235}U	^{235}U

* : obtained with the amplified source multiplication method

** : measurements underway . More traverses are planned

On the figures 3 and 4, we can directly note the external source influence. Generally speaking, the distribution shape keeps similar far from the perturbation, in the external part of the fuel zone and the reflector. For this reason, the curves have been normalised to a measurement point located in the external part of the fuel zone in order to make more visual the changes due to the external neutron source.

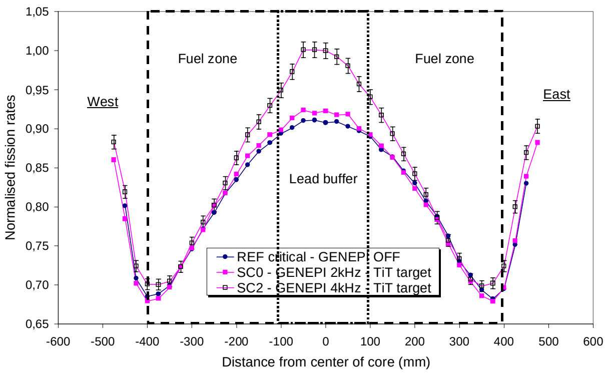

Figure 3. ^{235}U fission rate distributions in the West/East experimental channel

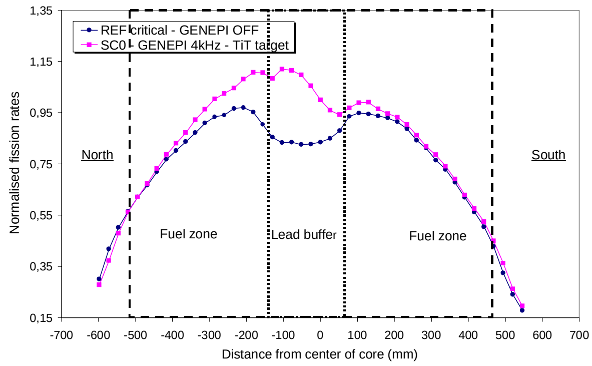

Figure 4. ^{238}U fission rate distributions in the North/South experimental channel

3.2. *Spectral index and foil activation measurements*

The impact on the local neutron spectrum of new types of heterogeneities (e.g. a central lead region and a voided channel), and of the external source itself, must be adequately assessed for the accurate prediction of operational characteristics. In this context, investigations of spectral characteristics of different critical and driven subcritical configurations were done with both spectral index measurements and the accomplishment of specific foil activation.

3.2.1 *Spectral indices*

Since a spectral index measurement is more time consuming than a fission rate distribution measurement, few spectral indices have been performed in subcritical configurations. They were all obtained with all SR up and using the tritium target. The Tble 3 below summarizes the results that have been obtained.

Table 3. Relative evolution of the spectral indices $\sigma_f^{238U} / \sigma_f^{235U}$ - Reference value is located at the center of the channels (x=0 mm).

Configuration		Reference critical	SC0	SC2
Position of the pilot rod		Critical position	Down	Down
GENEPI frequency		-	4 kHz (^{238}U fission rates) 2 kHz (^{235}U fission rates)	4 kHz
W/E channel	x=200 mm	1.36	1.50	-
	x=0 mm	1	1.24	1.69
	x=+200 mm	1.36	1.49	1.48
N/S channel	x=-200 mm	1.26	1.39	-
	x=0 mm	1	1.30	2.11
	x=+200 mm	1.25	1.48	1.78

3.2.2 *Foil irradiation*

The technique of foil irradiation constitutes an interesting alternative to the spectral index measurements. First, a lot of foils can be irradiated simultaneously (most of the foils are disc-shaped with a thickness of 0.25mm and a diameter of 9mm). Then, a judicious selection of the foils, with a range of threshold energy values as wide as possible, allow a deeper study of the spectral variations.

During the MUSE-4 experiments, more than 300 foils have been irradiated in the critical, SC0 and SC2 configurations. The full list of activation reactions that have been employed is given in another paper presented at this workshop [4]. The studied locations are given in Figure 2 (circles).

The interpretation, realized through MCNP-4C and ERANOS-2.0 calculations, has permitted to quantify important aspects, such as the asymmetry of the core along the north/south axis, the moderation/multiplication effects of the central diffusing lead region and the spectral perturbations due to the external source. Generally, the non threshold and low threshold (<3 MeV) ratios are reproduced as well as it is for the critical configuration. More details about the organization and the interpretation of these measurements can be also found in [4].

4. Measurement of the subcriticality

The fine determination of reactivity level of ADS's and the proof of its control will be decisive for the acceptability of such machines. This objective summon up largely energy of all experimental teams involved in the MUSE-4 program. Many experimental techniques like the PNS technique, the source jerk techniques, the noise techniques, as well as several analysis methods have been used in this goal. From these measurements and depending on the method used, one can deduce an experimental value of respectively, the prompt multiplication factor $k_p=(1- \beta_{eff})k_{eff}$, the prompt neutron decay constant $\alpha_p=(\beta_{eff}- \rho)/ \Lambda$, the reactivity expressed in dollars $\rho_{\$}= \rho/ \beta_{eff}$. Depending or not on complementary measurements or calculated values, the neutron generation time Λ , the effective delayed neutron fraction β_{eff} and the ratio Λ/β_{eff} can be also deduced from these methods.

4.1. *The reference method*

The classical technique used in several critical systems for the reactivity calibration is based on rod drop experiments and the use of the source multiplication methods : Amplified Source Multiplication (ASM) method or Modified Source Multiplication method (MSM). This protocol will not probably be used in the subcritical systems if we keep in mind that the criticality could never be achieved and secondly the presence of control rods is still not determined. Moreover, the MSM method is a "a posteriori" method which needs to calculate corrective factors that are enough complex and time consuming to determine.

4.2. *Methods investigated during the Muse experiments*

Several methods, that do not need to pass by a critical configuration, have been applied during the MUSE-4 experiments (Table 4). In a practical way, two families of analysis methods are used. The first one is interested in the time evolution of the neutron level following a modification of the external source (PNS technique, source jerk techniques). The second family analyses the fluctuation of the neutron level in a steady state (Rossi-α, Feynman-α, Cross Power Spectral Density -CPSD-) with or without the external source.

Within the frame of the MUSE project, a new analysis method, the k_p method, have been developed [5], and new formulas of the Feynman-α and the transfer function have been derived to take into account the dynamic aspects introduced by the time dependency of the source [6,7].

Table 4. Type of source and analysis method list used for the subcriticality measurement

<table>
<tr><th>Type of source</th><th colspan="2">Analysis method</th><th>"Experimental" parameter</th><th>Calculated parameters used</th></tr>
<tr><td rowspan="4">Intrinsic source</td><td colspan="2">Reference method</td><td>$\rho_\$$</td><td>Kinetic parameters, MSM factors</td></tr>
<tr><td colspan="2">Rossi-α</td><td>α_p</td><td>None</td></tr>
<tr><td colspan="2">Feynman-α</td><td>α_p</td><td>None</td></tr>
<tr><td colspan="2">CPSD</td><td>α_p</td><td>None</td></tr>
<tr><td rowspan="2">^{252}Cf source</td><td colspan="2">Rossi-α</td><td>α_p</td><td rowspan="2">Kinetic parameters</td></tr>
<tr><td colspan="2">Source jerk</td><td>$\rho_\$$</td></tr>
<tr><td rowspan="7">Pulsed neutron source</td><td rowspan="3">PNS method</td><td>Area method</td><td>$\rho_\$$</td><td>None</td></tr>
<tr><td>Slope fit method</td><td>α_p</td><td>None</td></tr>
<tr><td>k_p method</td><td>k_p</td><td>Calculated P(τ) distribution [5]</td></tr>
<tr><td colspan="2">Rossi-α method</td><td>α_p</td><td>None</td></tr>
<tr><td rowspan="2">Feynman-α method</td><td>Deterministic method</td><td rowspan="2">α_p</td><td rowspan="2">None</td></tr>
<tr><td>Stochastic method</td></tr>
<tr><td colspan="2">CPSD</td><td>α_p</td><td>None</td></tr>
</table>

A large amount of data have been already collected and analysed. Several of these data (PNS, noise measurements, GENEPI frequency variation experiments) are presented in separated contributions to this workshop [8,9,10]. The main findings which can be drawn are as follows :

- qualitative agreement with theoretical models have been found for all the analysis methods.
- for the subcriticality level up to –1.5$, a good agreement was found above all the methods. The use of the one point kinetic model lead to biases of about 10%.
- the analysis of results at deeper subcriticality seems however to be more complex and advanced models are necessary to fit adequately the signals and to extract the correct value for the different parameters.
- whatever the subcriticality level is, it was shown that small reactivity changes can be discriminate.

As concerns the various analysis methods, the measurement results show first, that the use of noise methods driven by the intrinsic source was difficult at subcriticality levels representative of an ADS (very low noise/signal ratios => measurement duration >5h).

Then, with the pulsed neutron source, the results indicate that :

- the Rossi-α method can be used if pulsed source frequency is not higher than around 2 kHz. On the contrary, an analysis with the stochastic and deterministic Feynman-α methods should need frequencies higher than the GENEPI maximum frequency.
- the analysis in current mode using the CPSD are more delicate compared to the analysis based on pulse mode. It is also limited by both the acquisition chain used at MASURCA and the performances of GENEPI (higher intensity necessary),
- Rossi-α and PNS methods seems promising because of their easy set-up. Good statistics have been also obtained. However, advanced kinetic models have to be defined to strengthen the use of these methods at deep subcriticality levels.

All the remarks above have to be analysed considering the GENEPI performances, the experimental conditions during the MUSE-4 experiments (characteristics and locations of the detectors) and also the new constraints that will be appear in a real industrial ADS.

4.3. *Assessment of kinetic parameters*

Today, three analysis methods have been used for the determination of kinetic parameters (Table 5). The two first are based on noise measurements (CPSD and Rossi-α) with the intrinsic source and at a slight subcriticality [11]. The last one is resting on an experimental technique based on the modulation of the source between two frequencies (typically from 300 Hz to 4 kHz) [10]. It has been used on SC0 and SC2 configurations. In any case, the determination of the kinetic parameters needs calculated parameters. As concerns the determination of $\beta_{eff,}$ final results are presented below (Table 5).

Table 5. Experimental assessment of the effective delayed neutron fraction (β_{eff}).

Analysis method	Parameters used	β_{eff} (pcm)
CPSD	$\rho_{\$}$, DIVEN factor (calculated), total fission rate in the core (calculated)	334 ± 6
Rossi-α	$\rho_{\$}$, DIVEN factor (calculated), total fission rate in the core (calculated)	317 ± 13
Source frequency variation	$\rho_{\$}$, mean neutron generation time	330 ± 30 (SC0) 300 ± 30 (SC2)

5. Calculation tools for the prediction of ADS characteristics

As concerns the definition of a recommended route for the prediction of ADS features, a calculation benchmark under the auspices of the OECD/NEA have been defined at the beginning of the project in view to analyse code system and cross section library performances when they are used to predict neutronic features of a source-driven system. Fourteen organizations from twelve countries are taking part in this exercise. Results from the two first of the three steps which compose this benchmark are currently under analysis and are being compared to experimental values. Publishing of synthesis report is planned before the end of this year.

The detailed interpretation of the MUSE-4 experiments is also being performed by several organizations and could not be synthesised for this workshop . These contributions will be presented in a next future.

6. Conclusions

Since October 2002, subcritical configurations with reactivity varying from near criticality to –14$ have been investigated in the MASURCA facility. A large amount of results have been collected in view to extend the experimental database used for the validation of code systems. As concerns the measurement of the subcriticality levels, extensive measurement campaigns have been conducted with three type of neutron source (intrinsic, 252Cf and pulsed source) using several experimental techniques and analysis methods. Some trends and conclusions have been already obtained. The full interpretation of these data will however need more investigations and simulations, to develop advanced models, to define biases, corrective factors, uncertainties. Then, some relevant propositions for the control and the monitoring of the subcriticality could be proposed taking into account the new constraints introduced by the characteristics of a more industrial system.

Acknowledgments

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References

1. R. Soule & al, "Neutronic studies in support of ADS : The MUSE experiments in the MASURCA facility", Submitted to NSE
2. J. Vollaire & al, "Calibration and Monitoring of the GENEPI Neutron Source for the MUSE IV Experiment", LPSC, IN2P3-CNRS/UJF/INPG, Report LPSC 03-26.
3. A. Billebaud & al, "The Muse-4 experiment : Prompt reactivity and neutron spectrum measurements", PHYSOR 2002.
4. M. Plaschy & al, "Interpretation of foil activation and reaction rate measurements in critical and subcritical MUSE4 configurations", this workshop.
5. F. Perdu & al, "Prompt reactivity determination in a subcritical assembly through the response to a Dirac pulse", Progress in Nuclear Energy, Vol. 42 (2003) 107-120.
6. I. Pazsit, M.Ceder, "Theory and Analysis of the Feynman-α Method for Deterministically and Randomly Pulsed Neutron Sources", Submitted to NSE.
7. Y.Rugama & al, "Application of the Stochastic Theory to Reactivity Measurements in a Subcritical Assembly Driven by a Pulsed Source", M&C 2003, Gatlinburg, USA, 6-10 April.
8. E. Gonzalez-Romero & al , "Pulsed neutron source measurements of kinetic parameters in the source-driven fast subcritical core MASURCA", this workshop.
9. P. Baeten & al, "Measurement of kinetic parameters in the source-driven fast subcritical core MASURCA with noise methods", this workshop.
10. A. Billebaud & al, "Online measurement of parameters relevant for ADS monitoring : Experimental technique validation in MASURCA", this workshop.
11. F. Mellier & al, "MUSE-4 Experiment Progress at Subcriticality Levels Representative of ADS Operating", Submitted to GLOBAL 2003.