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Some Experimental Results from the Last Phases of the MUSE Program

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Since the beginning of a new phase of the MUSE (MUltiplication avec Source Externe) experiment in October 2000, a very extensive measurement campaign is nearly completed at the MASURCA facility (CEA Cadarache, France) [1]. In the last three years we have progressed from critical reference measurements to measurements at k_{eff}~0.995, 0.97, and finally 0.95. Most of the measures have been performed with DD and DT sources. In this paper, we present some results of measurements at k_{eff}~0.95 as well as a final comparison of all the results.

KEYWORDS: Accelerator Driven System (ADS), kinetics, subcritical, pulsed neutron source

1. Introduction

The fourth phase of the MUSE program, the MUSE-4 experiments, started on October 2000 within the frame of the 5th Framework Program. The major objectives of the MUSE-4 experiments are to investigate the physics of externally-driven subcritical multiplying media and to study the possibility to infer the reactivity levels of such systems without the need of a critical configuration. This was based on a parametric approach and the use of a well known external source, in terms of intensity and neutron energy, provided by the GENEPI (Générateur de Neutrons pulses Intense) neutron generator [1]. Several core configurations with different subcriticality levels - ranging from criticality to k_{eff}=0.95 -, two types of coolant - sodium and lead - , two different pulsed neutron sources - neutrons of 2.67 Mev and 14 Mev produced respectively by D(d,n)^{3}He reactions and D(t,n)^{4}He reactions - constitute the main parameters of these experiments.

In this paper, we give an overview of the experiment progress and a sample of the results that have been obtained up to now. As concerns kinetics measurement, the outcomes of on-going analysis is presented. A comparison between the various methods used for the reactivity determination is notably completed.

2. MASURCA and GENEPI devices

The MASURCA facility is dedicated to the neutronic studies of fast lattices. The materials of the cores are contained in cylindrical or square section rodlets. For the MUSE-4 cores, the basic cell consists of two MOX rodlets and two sodium rodlets. This pattern is then reproduced sixteen times in each fuel subassembly. These subassemblies are composed of a wrapper tube having a square section (1.27 x 1.27 cm) and about 3 meters long. The reactivity control is fulfilled by four "Safety Rods (SR)" which are made of fuel material in their lower part, so that the homogeneity of the core is kept when the rods are withdrawn. A "Pilot Rod (PR)", with a

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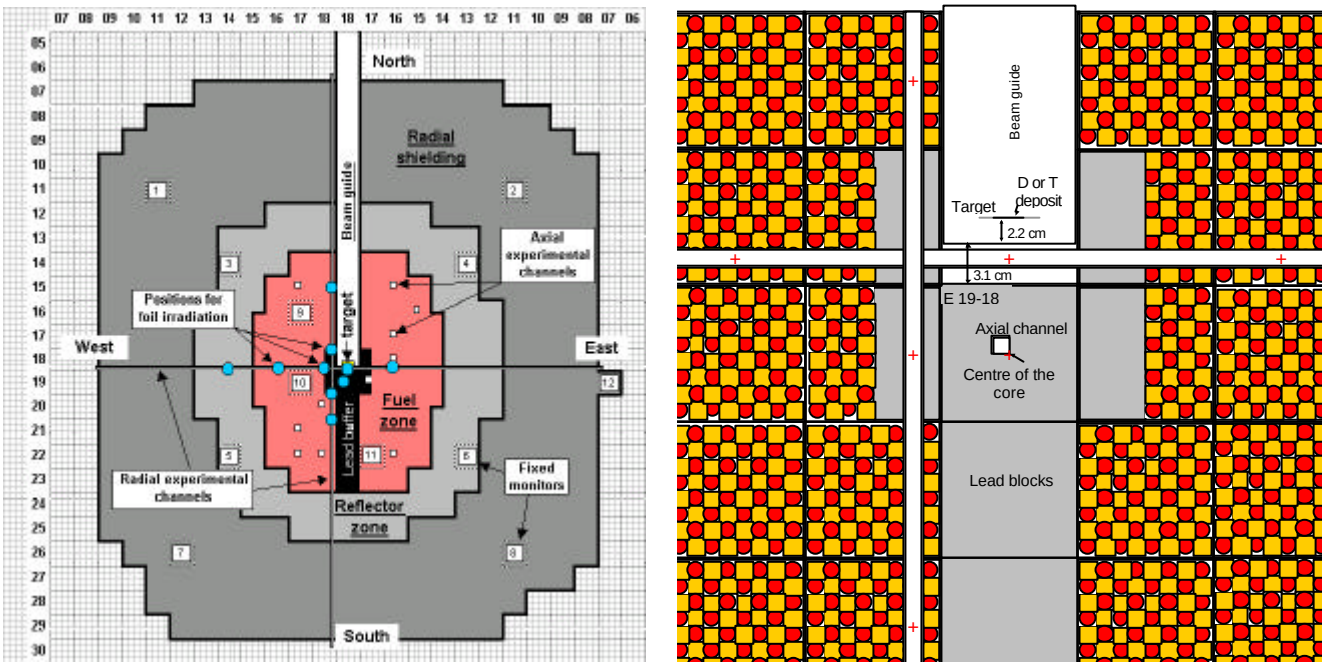
reactivity worth less than half a dollar, allows the fine-tuning of the reactivity. The core is cooled by air and the maximum operating power of the facility is limited to 5 kWth. The fuel zone is radially and axially reflected by a stainless steel/sodium shielding (75%/25%) (Figure 1, left).

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, whose ^{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 along the program to optimize their use (to decrease the dead time or to increase the counting rate).

The GENEPI (Générateur de Neutrons Pulsés Intense) pulsed neutron generator has been built specifically with a view to these experiments. Its main characteristic is to deliver very short pulses (<1µs) with a repetition rate going from 50-100 hertz to 4.5 kHz. The GENEPI beam guide is horizontally introduced at the core mid-plane and the target is located at the core center (Figure 1, right). Two different neutron sources, produced respectively by $D(d,n)^3He$ reactions and $D(t,n)^4He$ reactions, have been used. The neutron production rates were respectively found equal to $3.0\pm0.3\ 10^4$ neutrons per pulse and $3.3\pm0.3\ 10^6$ neutrons per pulse for a fresh tritium target [2].

Fig. 1 Radial cut at mid plane of a MUSE-4 core - Global view (left) and zoom of the central zone (right)



3. Experiment progress

After a preparation phase that lasted from November 2001 to March 2002, the full characterization of the reference critical configuration was completed from April to June 2002 . This long campaign was conducted in order to have a well-established reference measurement point. In particular, rod-drop experiments and measurements of kinetic parameters have been achieved with the objective of determining reference reactivity levels.

The study of subcritical states began again (a very brief campaign was conducted in January 2002) at the beginning of October 2002 with the investigation of the SC0 clean core configuration using neutron external sources provided by DD and DT. After this measurement phase ended on March 2003,

configurations with reactivity levels more representative of an industrial ADS have been studied : SC2 configuration (k_{eff} around 0.97) was from April to July 2003 and the SC3 configuration with a k_{eff} around 0.956 was studied from September to November 2003 (Table 1). A very last configuration with a central zone loaded with lead rodlets instead of the current sodium rodlets is planned from May to June 2004.

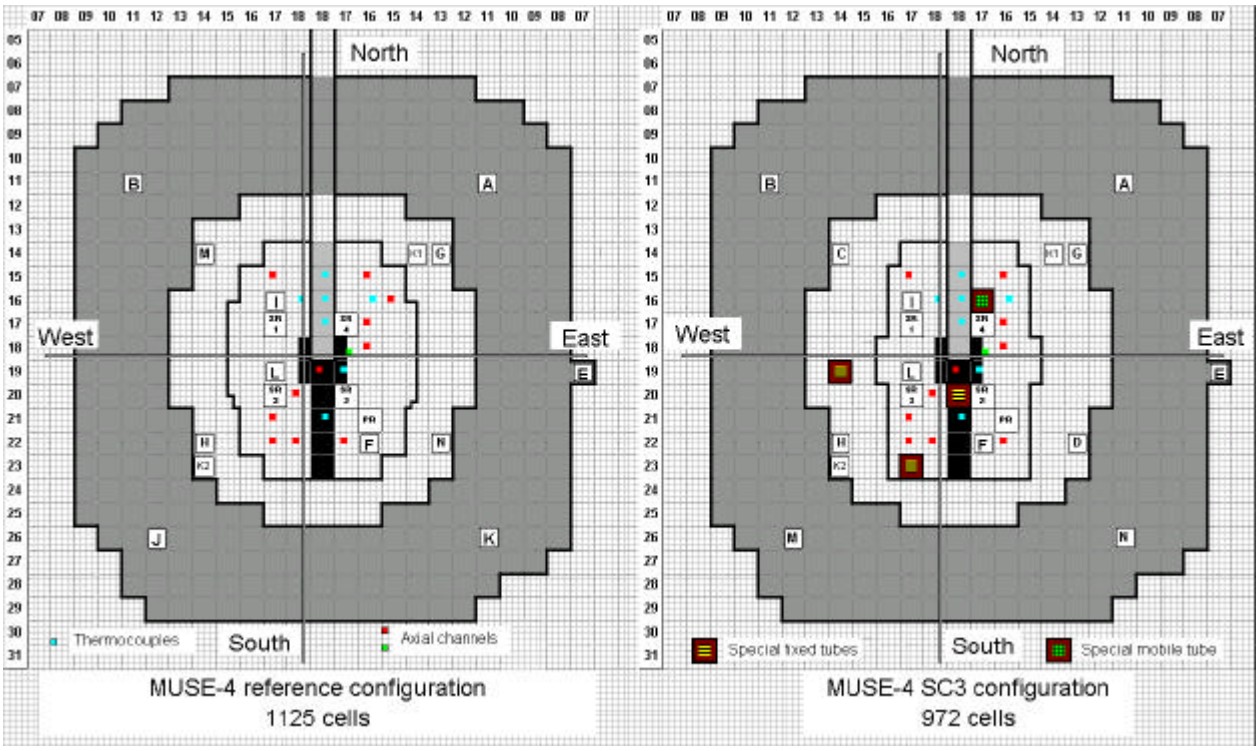
Table 1 Characteristics of the main configurations of the program

	Configuration					
	Reference	SC0		SC2		SC3
Total number of equivalent fuel cells	1125	1108		1006		972
Reactivity* : - in dollars - in pcm (date)	-0.26 ± 0.01 -86 (01/09/2001)	-1.9 ± 0.1 -635 (10/21/2002)		-9.0 ± 0.8 -3006 (03/26/2003)		-14.0 ± 1.8 -4676 (08/27/2003)
Target	-	D	T	T	D	T
Period	March-September 2002	November-December 2002	January-March 2003	April-June 2003	July 2003	September-November 2003
Maximum power with GENEPI ON	-	<10 W	<50 W	<10 W	<2W	<5 W

* : the reactivities were determined using the Amplified Source Method (ASM). They all correspond to configurations with the four safety rods up and the pilot rod down.

For these experiments, the subcriticality was adjusted by changing the number of fuel sub-assemblies. The difference is around 15% between the reference critical configuration and the most subcritical configuration (SC3) (Figure 2).

Fig. 2 Radial cut at mid plane of two MUSE-4 cores (reference critical and SC3)



4. Overview of the measurements performed

Table 2 provides an overview of the measures and analysis performed by the CEA experimental group. Other experiments and analysis have been conducted by partners involved in the MUSE project. Some of them are presented at this conference [3,4].

Table 2 Measurements and analysis conducted by CEA team

		Configuration								
		Critical reference	SC0			SC2			SC3	
		GENEPI OFF	Deuterium target	Tritium target	GENEPI OFF	Deuterium target	Tritium target	GENEPI OFF	Tritium target	GENEPI OFF
Cores characterization	Critical Mass	X								
	Rod-drop	X								
	Reaction rate traverses	X	X	X			X		X	X
	Spectral indices based on the use of fission chambers	X		X			X		X	
	Spectral indices based on foil activation	X	X	X			X			
	Importance Traverses	X			X					X
	Kinetic parameters	X								
Subcriticality level determination	Source Jerk				X					X
	PNS - Area method		(X)	(X)		(X)	(X)		(X)	
	PNS - α-fitting method		X	X		(X)	X		(X)	
	Noise - Rossi-α	X	X	X		X				
	Noise - Feynmann-α	X	X	X	X		X			
	Noise - CPSD	X	X	X						

(X) : on going analysis

4.1 Core characterization

Validation of the deviation (from the critical reference) of fission rate and spectrum index 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. These kind of measurements have been first performed on the reference critical configuration for a large sample of elements. Similar experiments were planned in subcritical configurations. However, owing to the increasing of the acquisition time duration due to the low counting rates when the core configurations become more subcritical, a reduced number of measurements could be completed. The list of fission rate traverses that we were able to perform on subcritical configurations is presented in Table 3.

Table 3 Characteristics of the main configurations studied along the program

	SC0				SC2	SC3		
Position of the PR	Down				Down	Down		Up
Target (D/T)	D	T	T		T	T	T	T
GENEPI frequency	4.5 kHz	OFF	2 kHz	4 kHz	4 kHz	OFF	2 kHz	2 kHz
Radial channels	N/S W/E	N/S	N/S W/E		N/S W/E	N/S	N/S	E/W
Axial channels	-	-	-		E19-18	-	-	-
Isotopes	^{235}U	^{235}U	^{235}U	^{238}U	^{235}U	^{235}U	^{235}U	^{235}U

Figure 3 well illustrates, for four reactivity levels, the changes due to the source dominated mode. Figure 4 shows the large effect of the 14.1 Mev neutrons provided by the external source.

Fig. 3 ^{235}U fission rate distributions in the north/south experimental channel

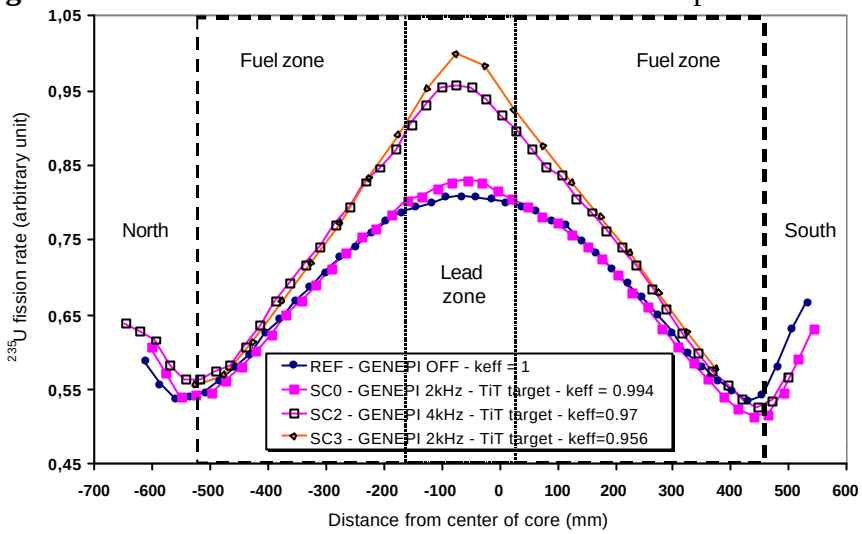
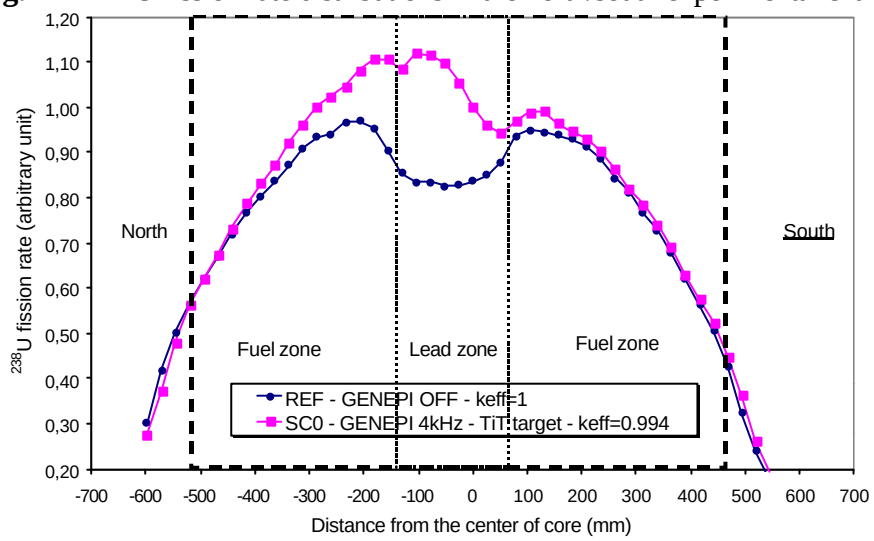


Fig. 4 ^{238}U fission rate distributions in the north/south experimental channel



The spectrum index evolution allows more precise quantification of the local energetic effects. Table 4 presents the data obtained close to the neutron source. We well see the spectral hardening as the reactivity levels drops. Other measurements have been achieved close to the beam guide and at the interface between the fuel zone and the lead buffer. These measure points are represented on the right part of the Figure 1

Table 4 : Evolution of some spectrum indices with the subcriticality level

	Center of the East-West experimental channel			
	Reference	SC0	SC2	SC3
^{237}Np	0.212	-	0.351	0.365
^{238}U	0.0220	0.0273	0.372	
^{239}Pu	0.894	-	-	0.900
	Center of the North-South experimental channel			
^{238}U	0.0204	0.0265	0.0431	0.0476
^{240}Pu	0.248	-	1.151	-
	Center of the E19-18 experimental channel			
^{237}Np	0.226	-	0.361	-

4.2 Kinetics results

We have utilized a number of techniques to determine kinetic parameters with two objectives :

- to obtain fundamental properties of the system (e.g., delayed neutron fraction β_{eff} or generation lifetime Λ)
- to infer the subcriticality level. For this purpose, we have used Rossi-α and Feynman-α, "Cross Power Spectral Density (CPSD)", "Source Jerk (SJ)", and "Pulsed Neutron Source (PNS)" as well as the classical source multiplication and rod-drop experiments.

Although a final analysis of all these techniques is underway at CEA/Cadarache, some indications for the future reactivity monitoring techniques can be already extracted. In general, we are finding that all the methods certainly do allow the discrimination among different reactivity levels.

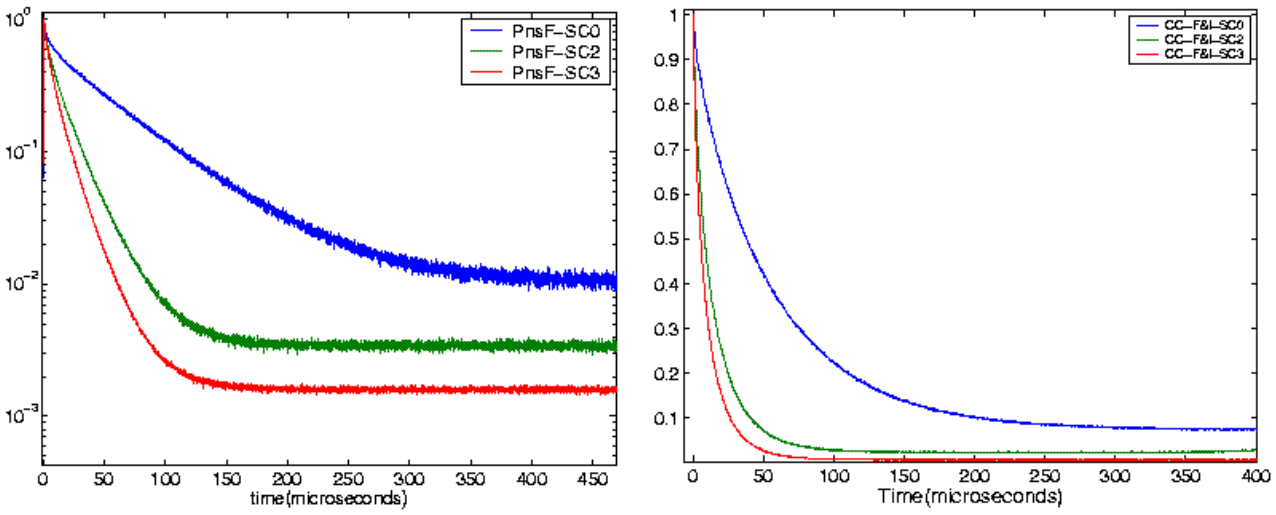
4.2.1 Measurement of the delayed neutron fraction

The delayed neutron fraction β_{eff} has been obtained using the transfer function technique after some parameters as the Diven factor were calculated by means of the ERANOS code system [5]. This analysis mode could be set-up only for the reference critical configuration. The value was found equal to 334 pcm (1 pcm = 10^{-5}) and consistent with other assessments [6]. From SC0 reactivity levels, the poor statistics did not allow us to extract a value.

4.2.2 Analysis of PNS experiments

Figure 5 below presents the data of PNS response for a ^{235}U fission chamber located in the core (left part of the figure). The different slopes agree with the increase in subcritical levels. However, the time response corresponds to the single exponential predicted by point kinetics only for the SC0 configuration. For deeper subcriticalities as SC2 and SC3 configurations, the neutron pulse decay cannot be described as a single exponential. The spatial and energetic effects as the pulse propagates into the core and the reflector become too important and simple point kinetics is no longer adequate.

Fig. 5 PNS (left) and cross correlation (right) functions in the F detector for three different reactivities



A similar situation is seen for the cross correlation technique (right part on Figure 5). The slopes can be differentiated by reactivity but a reasonable value can be extracted only at reactivities close to critical. However, the correlation technique with the pulsed source seems to

be a promising technique at zero power, especially because of its fast convergence [7].

4.2.3 Use of noise techniques

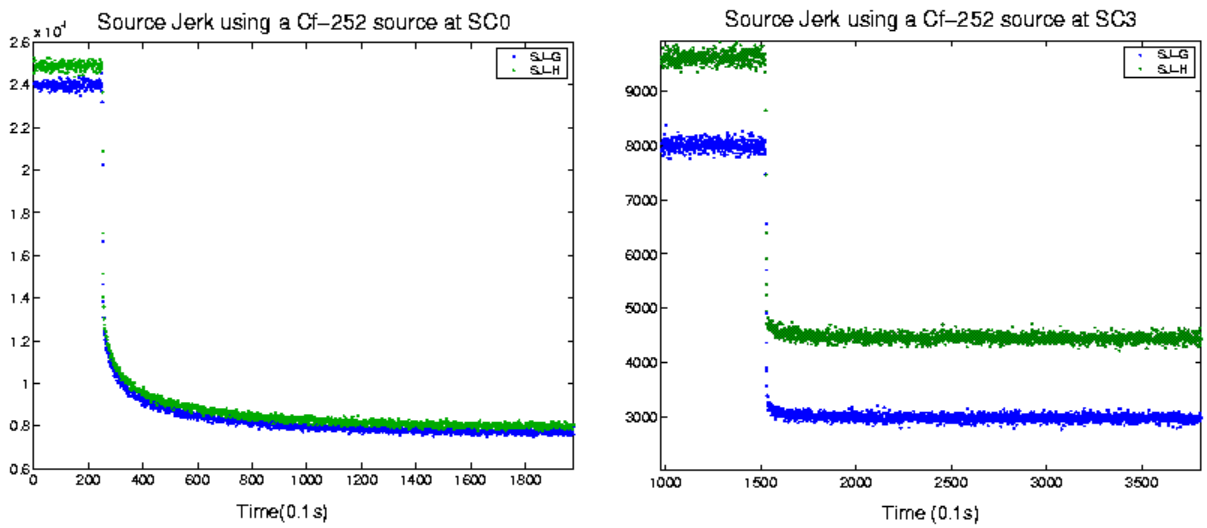
Other noise techniques as Feynman-α and transfer function have been applied to the pulsed driven system. The Feynman-α technique as proposed in [8] is not applicable to our system because of the low ratio of pulsed source to reactor frequency, although a qualitative agreement with the predicted shape is found. The CPSD method has been applied successfully close to critical [7] but limitations with electronics didn't allow us to test its capabilities at SC2 or SC3. Regardless, we can expect to see the same spatial and energetic effects in these methods as well.

4.2.4 Source jerk experiment

Measurements have been performed with a ^{252}Cf source instead of the pulsed source, in order to compare it with a time independent source. Although the intensity in number of neutrons per second is similar to the tritium source at 1 kHz (around 2.10^9), the measuring time needed to have a statistically adequate cross correlation function is more than 10 times the time needed for the tritium target. Approximately 30 minutes is needed for a detector located in the core. It makes the correlation technique hard to apply when using the spontaneous fission source. Because the random time contribution of the neutron sources causes the accidental correlation to be the same order as the real correlations, a long time is needed to get a well converged correlation function. When using the pulsed source their time distribution assists the neutron correlation.

Source-jerk measurements in the MASURCA reactor with the ^{252}Cf source at SC0 and SC3 configurations reveals this as a promising technique, to be tested further in TRADE [9]. The difficulties are the need for a high strength source and high efficiency detectors for fast reactors. An alternative technique modulating the pulsed source frequency is proposed in [10] to get the reactivity value in dollars unit. The advantages of this technique are shorter measuring times and a better control in the frequency modulation.

Fig. 6 Source jerk experiments with a ^{252}Cf continuous source for two subcritical levels



Some results of the prompt neutron decay constant, $\alpha=(\rho-\beta_{eff})/\Lambda$ (expressed in s^{-1}), using point kinetics with the techniques as described above, are presented in the Table 5 for the different configurations (SC0, SC2, SC3) and the PR inserted.

Table 5 Comparison of the prompt decay constant for different configurations and using different techniques

Configuration	Detector location	PNS (α-fitting)	Cross correlation	Source-jerk	CPSD
SC0	Core	16639±23	16674±11	16926±794	-
	Reflector	15911±30	15824±12	16643±659	16023±228
	Shielding	15642±45	15708±33	16303±799	
SC2	All	-	-	-	
SC3	Reflector	-	-	88878±4888	

All techniques applied at moderate subcritical levels show coherent results and a nearly point kinetic behavior. The tendency in the decreasing of the alpha value when measuring away from the reactor center has been confirmed with the PNS, correlation and SJ methods. However, we are noticing that even measurements taken at reactivities nearly critical (SC0, k~0.995) demonstrate an unexplained uncertainty of greater than 10%. From a conventional reactor physics point of view, this would be unacceptable.

The dashed line in the table above means that no results can be provide using the specified technique at the configuration where measurements were acquired. Because of the spatial and energetic influence at SC2 and SC3, further investigations are ongoing in order to estimate the reactivity value. The only technique remaining at deep subcritical is the source jerk because of the less important influence of the spatial effects for the delayed neutrons.

The source-jerk technique provides the reactivity in dollars. To give the value in s^{-1} we have considered that delayed neutron fraction is equal to 334 pcm (1 pcm=10^{-5}) and the generation time equal to 0.59 μs [6]. We did not utilize this technique in the SC2 configuration.

5. Conclusions

The MUSE-4 series of experiments that ranged from critical to k~0.95 have provided an extremely important set of data to the ADS community. The coupling of neutron sources of different energies (Cf, DD, and DT) have allowed us to investigate different regimes of source importance. This will provide the necessary steps to make the transition to the TRADE program, in which a real spallation source is coupled with a reactor [9].

Perhaps more important for the ADS community, the MUSE-4 program has provided a means of testing a variety of reactor physics experimental techniques for subcritical reactor monitoring. Some of these techniques as the Feynman-alpha were discarded for MUSE but perhaps could be tested in another conditions.

We have found that the quantification of the level of reactivity is difficult no matter what technique is used. At the present, we attribute this to a fairly complicated spatial and energy dependence as the pulse propagates through the reactor core and reflector. Further investigations are required, but at present we are not able to measure levels of sub-criticality with uncertainties better than around 10%. It is a point of discussion in the ADS community whether the uncertainty of 10% in the reactivity parameter is important to a system that is far subcritical.

Acknowledgments

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