PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

The MUSE4 Pulsed Neutron Source experiments

E. González-Romero[*1], D. Villamarín[1], M. Embid[1], M. C. Vicente[1], C. Destouches[2], P. Chaussonnet[2], J. M. Laurens[2], F. Mellier[2]
[1]*CIEMAT, Avda. Complutense, 22, Madrid, Spain*
[2] *CEA, St Paul lez Durance, France*

The latest results of the Pulsed Neutron Source experiments of the MUSE4 project [1], performed in the framework of the European 5FP, are described. Two analysis methods, one based on the counting rate time decay shape and the other on the ratio between the prompt and delayed neutrons integrals, are presented and compared. Both methods provide excellent results for configurations from near criticality to $K_{eff} = 0.95$.

KEYWORDS: Reactivity measurements, MUSE, subcritical reactor, ADS

1. Introduction

The most direct method to study the kinetic response of a system is to inject an instantaneous neutron pulse. In MUSE, the GENEPI accelerator has been used to produce very short pulses (<1μs long) by the deuterium-deuterium, DD, or deuterium-tritium, DT, reactions in the center of the MASURCA core. For these experiments, MASURCA has been setup in 4 different configurations corresponding to Critical, slightly subcritical (SC0: K_{eff} close to 0.995), subcritical(SC2: K_{eff} close to 0.97), and deep subcritical (SC3:K_{eff} close to 0.95). In addition the insertion of one or several B_4C safety rods, have allowed to reach even deeper subcritical states (K_{eff} close to 0.86) and asymmetrical configurations with reactivity close to the subcritical configuration (K_{eff} close to 0.97). Finally, the insertion of the pilot rod, PR, was used to generate small reactivity changes (about 135 pcm), allowing the verification of the sensitivity of these measurements.

High statistics experiments performed in each configuration and the combination of ^{235}U detectors and ^{237}Np detectors placed in different positions of the fuel core, reflector and shielding of MASURCA, allow to characterize the detailed kinetic response of the MUSE core [2]. The latest experimental results are presented in this paper.

The measurements are being analyzed by different methods, but only the area method [3], which provides ρ/β, and the determination of the point kinetic $\alpha = (\rho - \beta)/\Lambda$ decay constant, using an extension of point kinetics to multiple regions and energy groups, are presented here.

2. Experimental setup

MASURCA (figure 1) is a zero-power fast spectrum experimental facility that for the MUSE-4 experiments has been loaded with a MOX fuel of ~25% plutonium enrichment (~18% ^{240}Pu/Pu) and sodium. Thus, it is representative of a fast plutonium burner with sodium coolant. A lead central buffer surrounds a tritium target at the end of the GENEPI accelerator tube, and makes the role of a spallation target. A stainless steel/sodium reflector surrounds the core, and the shielding is made axially with stainless steel and radially with iron. The neutron pulse generated by GENEPI via the (D,T) source had a FWHM duration

---

[*] Corresponding author, Tel. +34913466120, FAX +34913466576, E-mail: enrique.gonzalez@ciemat.es

of ~1µs, and the frequency of the pulse had been varied from 1 kHz to 4 kHz depending on the experiment.

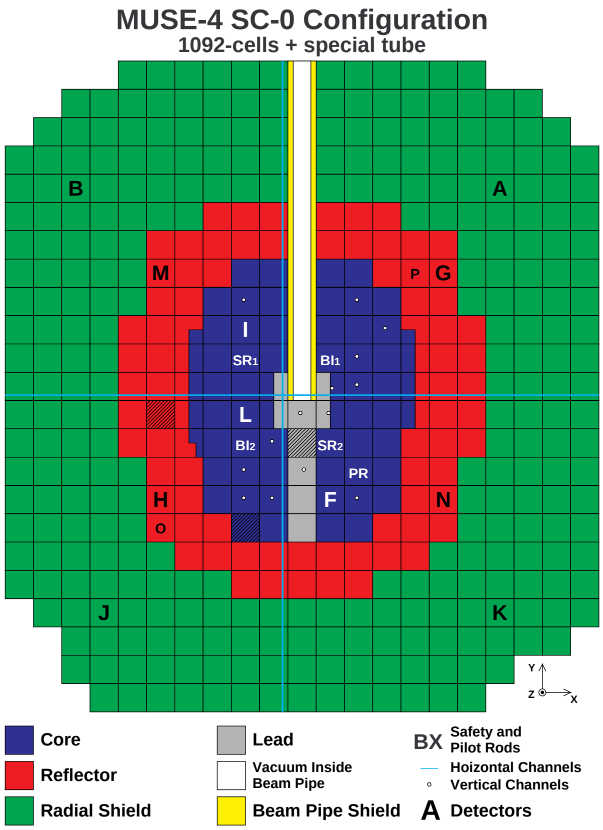

Fig.1 MASURCA reactor in the MUSE-4 SC0 configuration.

3. Experimental results

To measure the time evolution after the neutron burst, up to 9 ^{235}U detectors (3 in the core, 4 in the reflector and 2 in the shield) have been used, but for simplicity in the exposition, only the detectors F (core), G (reflector) and A (shield) will be shown in the figures of this section.

Figures 2 to 7 show the flux evolution obtained after the insertion of a neutron pulse produced by the DT source of GENEPI accelerator for ^{235}U detectors placed in the three regions of MASURCA. Six configurations are shown, corresponding to the approximate levels of reactivity $k_{\mathrm{eff,\ SC0\ 4SR\ up\ PR\ down}} = 0.993$, $k_{\mathrm{eff,\ SC2\ 4SR\ up\ PR\ down}} \approx 0.97$, $k_{\mathrm{eff,\ SC0\ 3SR\ up\ SR\text{-}1\ down}} \approx 0.96$, $k_{\mathrm{eff,\ SC0\ 3SR\ up\ SR\text{-}2\ down}} \approx 0.96$, $k_{\mathrm{eff,\ SC3\ 4SR\ up\ PR\ down}} \approx 0.95$ and $k_{\mathrm{eff,\ SC2\ 4SR\ down\ PR\ down}} \approx 0.87$. In this figures the intrinsic source (spontaneous fission and (α,n)), determined in calibration measurements, and the pseudo-constant level resulting from the delayed neutrons have been subtracted.

Figure 2 shows that for configurations close to criticality, after a short time where spatial and spectral effects are observed, the flux reaches an asymptotic exponential evolution which is similar in the three regions.

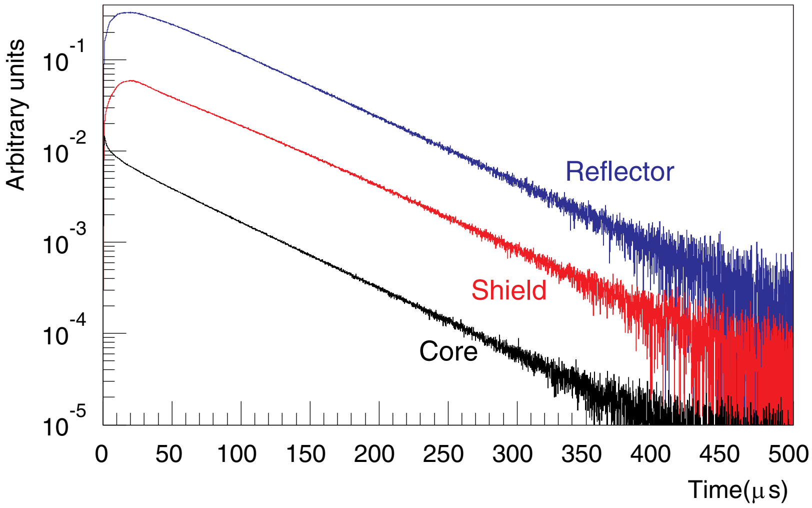

Fig.2 Reduced times histograms after the insertion of a 14 MeV neutron pulse in the SC0 configuration, 4 SR up (not inserted) PR down, of the MUSE-4 experiment.

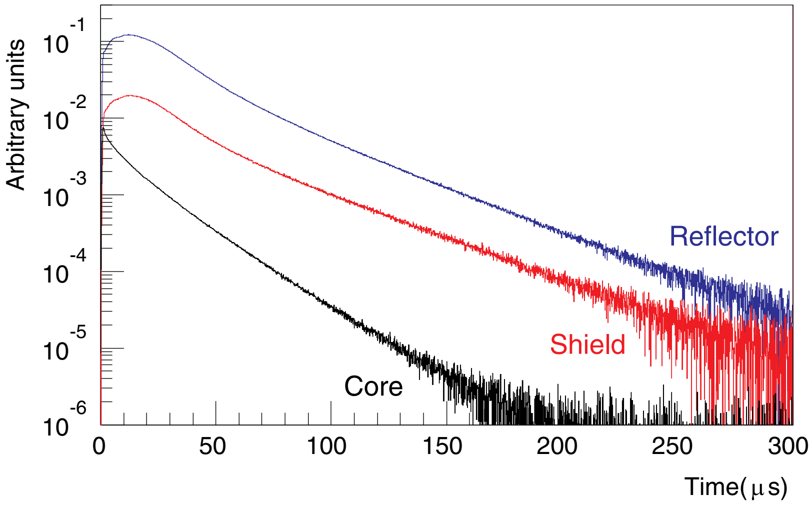

Fig.3 Reduced times histograms after the insertion of a 14 MeV neutron pulse in the SC2 configuration, 4 SR up (not inserted) PR down, of the MUSE-4 experiment.

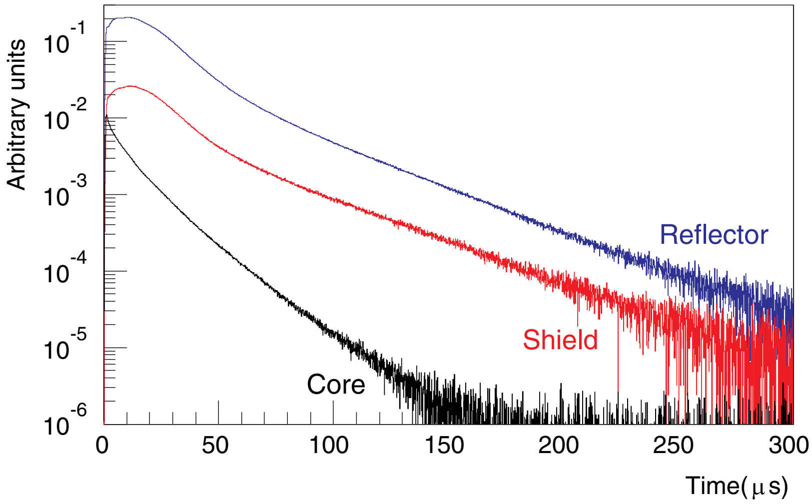

Fig.4 Reduced times histograms after the insertion of a 14 MeV neutron pulse in the SC0 configuration, 3 SR up SR-1 down (inserted), of the MUSE-4 experiment.

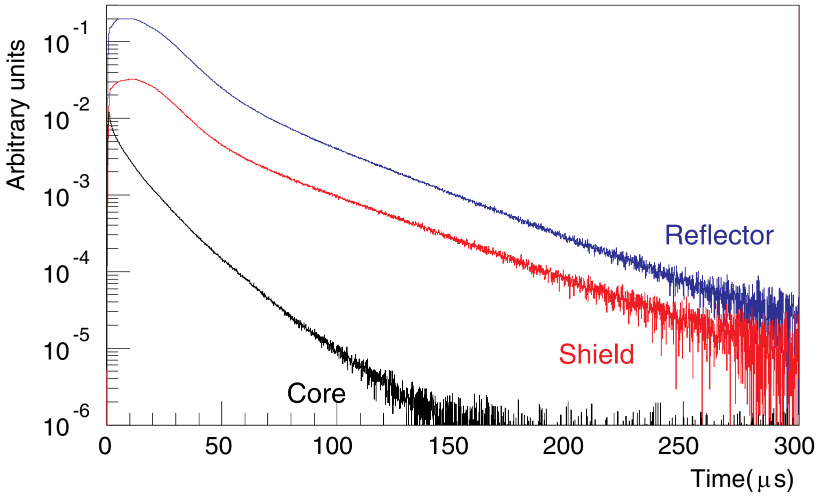

Fig.5 Reduced times histograms after the insertion of a 14 MeV neutron pulse in the SC0 configuration, 3 SR up SR-2 down (inserted), of the MUSE-4 experiment.

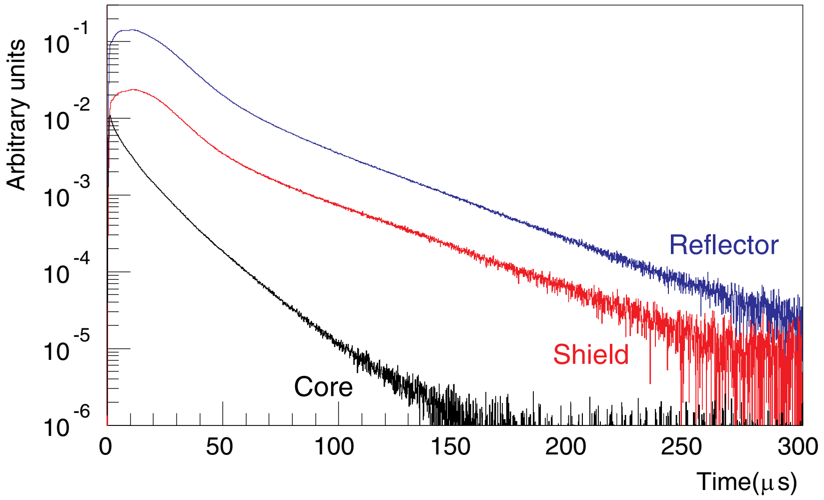

Fig.6 Reduced times histograms after the insertion of a 14 MeV neutron pulse in the SC3 configuration, 4 SR up (not inserted) PR down, of the MUSE-4 experiment.

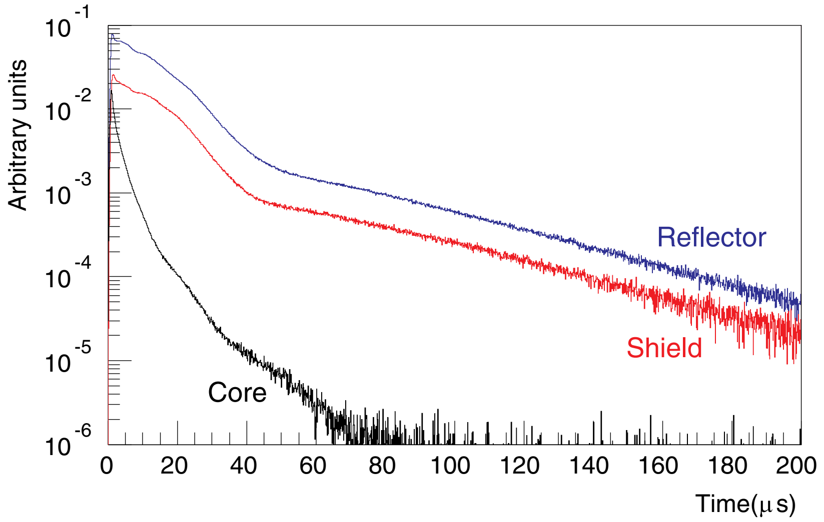

Fig.7 Reduced times histograms after the insertion of a 14 MeV neutron pulse in the SC2 configuration, 4 SR down (inserted), of the MUSE-4 experiment.

Inspecting Figure 3 to 6, two different evolutions are observed for largely subcritical configurations: the core detector on one hand and reflector and shield detectors on the other. The core detector shows an evolution nearly, but not quite, exponential, after the stabilization of the flux (about 50 μs after the pulse). In fact, at long times it can be observed that a small slower evolution appears. On the other hand, the reflector and the shield detectors observe a flux evolution, which has a complex shape and finishes in an exponential evolution with a very slow decay constant compared with the predicted by the point kinetic model. It is interesting to note that the decay constant observed at long times in the reflector and shield are very similar in all the largely subcritical configurations, despite the different reactivity levels.

Last, Figure 7, which is a deep subcritical configuration shows that even here, the long time decay constants are very similar to the other configurations. The core detector shows more clearly the second component in this configuration.

The results previously shown, indicate that the point kinetic model is a good approximation in configurations close-to-criticality, where the system fairly behaves as a point kinetic reactor. Nevertheless, in the MUSE experiments at 9 or more dollars subcritical, this model is no longer precisely followed.

However, the point kinetic model can be improved using the theory of coupled reactors developed by Avery [4]. To describe the previous measurements at MASURCA, we have assumed a model with two systems (core and reflector-shield – 3 regions) and three energy groups (fast, epithermal and thermal) with strong coupling. When physical conditions are imposed, this leads to a description of the flux response with three decay constants, which must be the same for the two systems.

The detailed description of this model will be presented somewhere else, here we will restrict to present the obtained results. We can however indicate that for subcritical configurations, the decay constant with highest absolute value is very closely related with the prompt decay constant of the coupled reactor, and in first approximation can be considered to as the equivalent to the α value in the point kinetic model for a simple reactor. The lowest decay constant, in absolute value, is related with the low energy neutron lifetime in the second system, which is not multiplicative, so it is independent of the reactivity of the system, as it is observed in figures 3 to 7.

4. Logarithmic derivative (shape) method for reactivity determination

According to the point kinetic model of the Boltzman equation with one group of delayed neutrons, in a subcritical system where the neutron generation time, Λ, and the decay constant of the one-group delayed neutrons, λ, hold the condition $\Lambda << 1/\lambda$, the neutron flux, $\phi(t)$, after and instantaneous neutron source, will have a time evolution of the form:

$$\phi(t) \approx \frac{s}{\rho\alpha}\left(\beta_{eff}\,\lambda' e^{-\lambda' t} + \rho\alpha e^{-\alpha t}\right)\phi_0 \tag{1}$$

Where $\alpha = (\rho - \beta)/\Lambda$ is the prompt decay constant, ρ is the reactivity of the system (in absolute value), β_{eff} is the effective delayed neutron fraction, *s* is the number of neutrons inserted by the source and $\lambda' = (\lambda\rho)/(\alpha\Lambda)$.

At short times after the source pulse (or at equilibrium, between two pulses of a long train of periodic pulses with repetition period much shorter than λ') the first term is in good approximation constant. Equation (1) shows that the reactivity of the system can be estimated by means of the decay constant of the single exponential left, by fitting a constant plus an exponential to the progressive decay of a detector counting rate.

This method can be directly applied to the SC0 close-to-criticality configurations. Good agreement is found among the detectors of a same region, better than 1%, with a small trend among regions smaller than 10%. In table 2 the average of the core detectors is quoted.

As previously explained, a more complex model is required for subcritical configurations. To extract the reactivity from the detectors counting rate time dependence, a simultaneous fit of all the nine detectors to the sum of three exponentials has been used. For the fit we have imposed that the decay constants of the exponentials are the same for the 9 detectors and that the shape of detectors in each region is also identical. The constrained model achieves an excellent description of the data[1] and provides a single estimation of the α for the coupled reactor. The fit is applied to the reduced time histograms (after subtraction of the constant level) in the range of times following the local and spectral effects, where the core is approaching its asymptotic behavior ($t > 50\ \mu s$). Beside the large number of parameters in the fit, the fitting procedure is very stable versus the fitting procedure itself and time range of fitting (variations usually smaller than 5%). The reactivity can be extracted from this α and the kinetic parameter β/Λ, obtained in other experiments. The result from these fits for all the clean configurations (without safety rods inserted) are included in table 2. The introduction of one or several safety rods in the system modifies substantially the neutron generation time and special corrections, under evaluation by simulation, are required to interpret the shape of this data. The results of the fits for these perturbed configurations are not included in this paper.

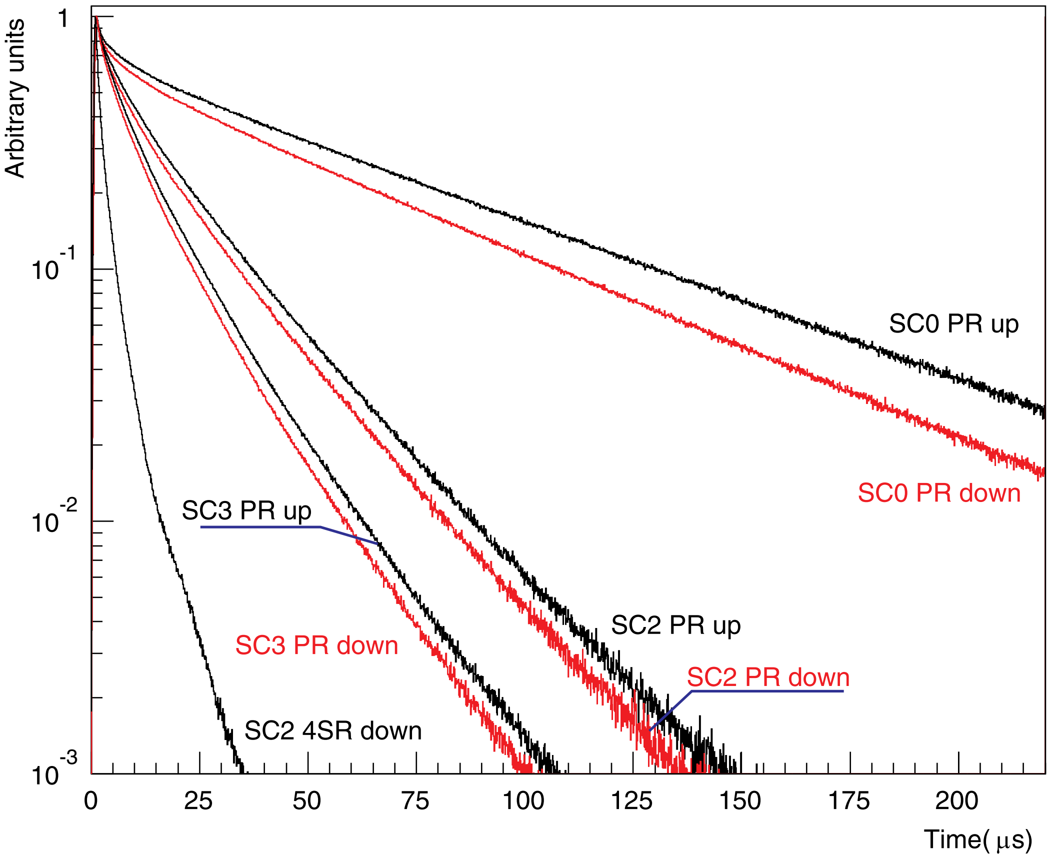

Fig.8 Reduced times histogram of a core detector after the insertion of a 14 MeV neutron pulse for all the MASURCA symmetric configurations (showing the difference between pairs with the pilot rod, PR, inserted or not).

---

[1] The normalized deviation (deviations/statistical error) follow a normal distribution of center 0 and standard deviation 1 and do not show significant dependence as a function of time or detector.

The uncertainty in the determination of the reactivity by this method is close to 7% for the subcritical configurations (SC2 and SC3), however it is possible to detect smaller variations of the reactivity. Figure 8, shows the reduced times histograms of the core detector “F” for all the symmetrical configurations, including three pairs where the criticality level was slightly changed by the insertion of the pilot rod (the weight of the pilot rod is about 0.40-0.45$ between SC0 and SC2). By visual inspection, one can distinguish different decay slopes for these pairs of experiments. The sensitivity lost in the common fit can be recovered by independent 1-exponential fits to each single core detector in a fixed decay time range. The results for the insertion of the PR in SC2 vary from 0.3$ to 0.6$, depending on the time range, and with a consistency between the core detectors better than 5% for a fixed time range. In the case of SC3 the PR effect is evaluated between 0.2$ to 0.6$, depending on the time range, with the same consistency between detectors as in SC2. In these individual detector fits the absolute value of α and of the reactivity can be largely biased, but the changes of reactivities can detected end evaluated with a sensitivity of up to 0.17$ (60 pcms) at reactivities as large as 14$ (K_{eff} close to 0.95).

5. Areas ratio method for reactivity determination

Another method used to analyze the pulsed neutron source experiments was the area method. Developed by Sjöstrand [3], is based in the decomposition of the time response of the neutron flux after a neutron pulse in two parts, the flux due to the prompt multiplication and the rest of the flux, created by the delayed neutrons emitted after the fission and their multiplication. Thus, if the complete space-time decomposition of the Boltzman equation is assumed, the two contributions hold the relation:

$$\frac{A_p}{A_d} = \frac{\rho}{\beta_{eff}} \tag{2}$$

Where A_p is the prompt neutron population integrated in time, and A_d is the delayed neutron population integrated in time. Table 1 shows the results obtained using this area method in a selected subgroup of the measurements performed.

Table 1 Reactivity in dollars obtained by the area method in selected configurations of the MASURCA core (the value of β_{eff} is estimated experimentally as 335 pcms).

Detector		SC0 4SR up PR down	SC2 4SR up PR down	SC0 3SR up SR1 dwn	SC3 4SR up PR down	SC2 4SR up PR dwn[a]	$\Delta\rho$ 2kHz-1kHz	SC2 4SR up PR up	$\Delta\rho$ PR dw-up
F	Core	1.98	8.99	11.82	13.53	8.97	-0.02	8.50	0.49
I		1.99	9.18	14.07	14.76	9.23	0.05	8.82	0.36
L		2.00	9.36	12.83	14.65	9.38	0.02	8.90	0.46
G	Reflector	2.02	9.33	12.96	14.81	9.38	0.05	8.87	0.46
H		2.00	9.16	12.63	14.18	9.21	0.05	8.73	0.43
M		2.00	9.15	12.68	14.31	9.18	0.03	8.70	0.45
N		1.98	9.36	12.06	13.88	9.38	0.02	8.92	0.44
A	Shield	2.00	9.32	12.52	14.40	9.23	-0.09	8.81	0.51
B		2.01	9.26	12.71	14.42	9.27	0.01	8.89	0.37

[a] Using a frequency of 2kHz in the pulsed source (vs. reference frequency of 1kHz)

The statistical uncertainty is in all cases lower than 0.1%. In addition the comparisons of experiments in the same configuration in different days and with different frequencies we observe a reproducibility typically better than 0.5%, and in all cases better than 1%. Furthermore, comparing configurations with and without the pilot bar inserted, the difference is independent of the detector within 1% deviations from the mean and with the values in excellent agreement with the expected weight of the PR. All these comparisons allow to expect an uncertainty on the reactivity determination from each detector of the order of 1%. From these results we assign an uncertainty of 0.5% to the average of the different detectors.

However, we observe small but systematic and significant difference between detectors in each largely subcritical configuration. These deviations are lower than 1% for the SC0 close to critical configurations, and reach in the worse case 6% when the system is 14$ subcritical. Finally we observe a large deviation on the “I” core detector in the configuration SC0 when we inserted the SR1, very close to this detector (for this reason this detector is ignored in the average for this configuration). These two effects indicate the possible presence of small space or localized spectral effects in the evaluation of the reactivity by the area method. This point is discussed in another paper presented to this meeting [5].

6. Comparison between methods for reactivity determination

Table 2 shows the comparison between the two methods of analysis for all the clean configurations (no safety rod inserted). The shape-based method provides a precision of about 1% for close-to-criticality configurations and 7% for the subcritical, whereas the area method provides resolutions close to 0.5% for all the configurations. We have, however, indicated before that we can detect variations close to 1% in reactivity by the shape method but with substantial bias on the absolute value of the reactivity.

Comparing the values obtained with the two methods, we observe a very good agreement for close-to-criticality and SC2 configurations. However, for the SC3 configurations, the reactivities obtained for the slopes method seem smaller than with the area method. We are now investigating the possibility of small changes in the kinetic parameter, β/Λ, to explain this difference.

Table 2 Reactivity in dollars obtained by the area and slopes methods in six configurations of the MASURCA core. To convert α to reactivity, the experimental value $\beta/\Lambda = 5690\ s^{-1}$ has been used.

	SC0		SC2		SC3	
	PR up	PR down	PR up	PR down	PR up	PR down
Shape	1.52 ± 0.02	1.93 ± 0.02	8.7 ± 0.5	9.0 ± 0.5	11.7 ± 0.8	12.3 ± 0.8
Area	1.59 ± 0.01	2.00 ± 0.01	8.79 ± 0.05	9.23 ± 0.05	13.77± 0.07	14.33± 0.07

7. Conclusions

A large database of experimental information of the kinetic behavior of the MASURCA zero-power fast ADS system has already been collected. This includes three basic configurations from nearly critical down to $K_{eff} = 0.95$. For each configuration two sub-configurations with the PR inserted or not have been explored. In addition there are a few (more than 4) perturbed configurations with 1 or several safety rod inserted. For each of these configurations at least 10 detectors had been recorded including ^{235}U fission and ^{237}Np detectors, in experiments with several frequencies for the external neutron source, GENEPI.

These experiments are allowing to improve our understanding of the physics and kinetics of subcritical systems. These results are being used to test different methods to evaluate the reactivity, that do not require reaching criticality, a must for the operation of the industrial ADS foreseen for transmutation of nuclear wastes.

Two methods are presented in this paper. The first one is based on the shape of the counting rate decay after an instantaneous neutron pulse (equivalent to a short/fast source variation). The main characteristics of this method are: a rather global behavior for core detectors, hopefully representative of the asymptotic reactor behavior, and the strong dependency of the reactivity evaluation on the neutron generation time. A coupled reactors model has been successfully compared with this experimental information. A complex fitting procedure is required to extract a reliable value of the α parameter and the associated reactivity.

The second method is the Sjöstrand area method. This method is very precise and mainly sensitive to the global neutron multiplication, and insensitive to the neutron generation time. However slight spatial and local spectral effects are indicated by the data, although, in any case, only at few percent level. In this sense the two methods looks to be complementary.

The difference between the 2 methods is smaller than 5% for SC0 and SC2 configurations ($|\rho|$ < 9$), and reaches 15% for the SC3 configuration, 14$ subcritical. These differences are being investigated with detailed MC simulations. In addition, the results of the two methods will be compared with measurements based on more standard Modified Source Multiplication techniques (that however require a critical reference).

Acknowledgements

The authors wish to thank the EC and ENRESA for their support to this work, the first within the MUSE4 share cost action of the 5th Framework Program and the second in the collaboration agreement with CIEMAT for the study of the transmutation of long lived isotopes. We also want to thank all the personnel of CEA and CNRS that has made this experiment possible by the setup and operation of MASURCA and GENEPI. Finally we want to thank all our collaborators of the MUSE EU project for the fruitful discussions.

References

1) M. SALVATORES et al., “MUSE-1: A First Experiment at MASURCA to Validate the Physics of Sub-Critical Multiplying Systems Relevant to ADS”, Proc 2nd Int Conf on Accelerator-Driven Transmutation Technologies and Applications", Kalmar, Sweden, Vol 1, p 513 (1996).
2) E. Gonzalez-Romero et al., “Pulsed Neutron Source measurements of kinetic parameters in the source-driven fast subcritical core MASURCA”. InWor for P&T and ADS'2003, Mol, Belgium (2003).
3) N. G. Sjöstrand. “Measurements on a subcritical reactor using a pulsed neutron source”. Arkiv Fysik, 11, 233 (1956).
4) R. Avery, “Theory of coupled reactors”, Proc. 2nd Int. Conf. on Peaceful uses of Atomic Energy, Geneva, Switzerland, 182-191 (1958)
5) M. Carta et al., “Reactivity assessment and spatial time-effects from the MUSE kinetics experiments”, PHYSOR 2004, Chicago, Illinois, April 25-29, 2004.