NEUTRONIC STUDIES IN SUPPORT TO ADS: THE MUSE EXPERIMENTS IN THE MASURCA FACILITY

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ABSTRACT

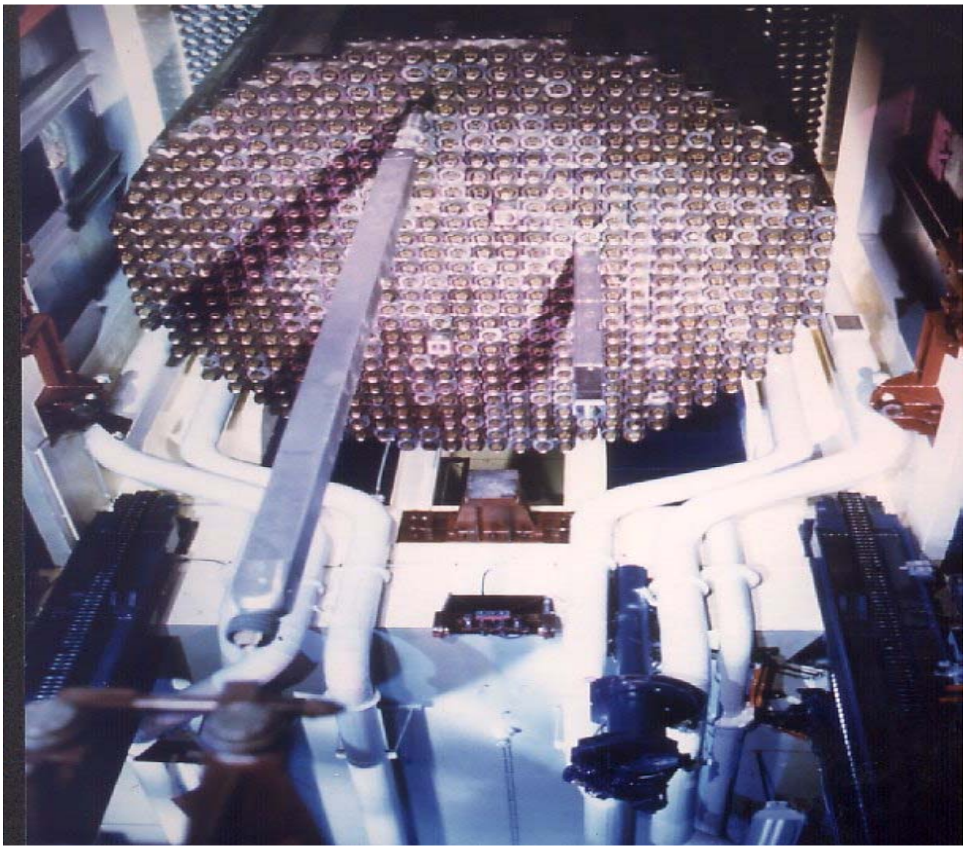
In an ADS, the multiplying medium operates in a sub-critical level with an external spallation source. This operating mode presents physical characteristics needing an experimental validation. The definition and the operation of the MUSE experiments in the MASURCA facility, at Cadarache, represents an essential step in the validation process. These experiments are performed in the frame of a very extensive collaboration: European collaboration through the 5th Framework Program, bilateral collaborations between the CEA (France) and PSI (Switzerland), JAERI (Japan) and DOE-ANL (USA) respectively.

1. INTRODUCTION

The three first phases of the MUSE experiments allowed the neutronic studies of the same sub-critical medium in the presence of a well known external source: (a) ^{252}Cf spontaneous fission source in the MUSE-1 [1] (1995) and MUSE-2 [2] (1996) at the core centre with different axial locations and different sub-critical levels, (aa) (d,t) neutron source produced by a commercial neutron generator in the MUSE-3 [3] (1998) . The availability of the deuterons generator GENEPI (built by the ISN Grenoble) producing both neutron sources from the D(d,n)^{3}He and T(d,n)^{4}He reactions will allow us to largely extend the validation domain, in particular for the reactivity measurements, the kinetic parameters and the eventual coupling effects (use of the AVERY theory on the coupled systems).
As the GENEPI generator can operate from frequencies of 50 to 5000 Hz, one of the important objectives of the MUSE-4 experiments is to test and validate dynamic experimental methods. The pulsed source technique, the transfer function method and adapted Rossi-α and Feynman-α techniques are used to determine the sub critical levels of the configurations and are compared to the precise measurement using the classical Modified Source Multiplication (MSM) Method.
One other aim of the MUSE experiments, performed in the frame of a very extensive international collaboration is to propose a validated reference calculation route (both calculation tools, nuclear data and residual uncertainties). In this way, a comparison of the available tools and data, applied to representative experimental MUSE-4 configurations is also proposed via a benchmark exercise under the auspices of the OECD/NEA[4].

2. THE MASURCA FACILITY

The MASURCA facility is dedicated to the neutronic studies of fast reactors 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 inches) and about 3 meters in height. These tubes are hanged vertically from a horizontal plate supported by a structure of concrete. The core itself can reached 6 000 litres. To built such cores the tubes are introduced from the bottom in order to avoid that the fall of a tube corresponds to a positive reactivity step. The reactivity control is fulfilled by absorber rods in varying number depending of core types and sizes. The control rods 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 and is surrounded by a biological shielding in heavy concrete allowing operation up to a flux level of 10^9 n/cm^2.s. Core and biological shielding are inside a reduced pressure vessel, relative to the outside environment. The limited maximum operating power of the facility is limited to 5kWth. Figure 1 presents a picture of a MASURCA core loading from the bottom.



3. THE GENEPI ACCELERATOR

The GENEPI (GEnérateur de NEutrons Pulsé Intense) accelerator (see Figure2) has been especially formed by ISN Grenoble for the MUSE experiments in the MASURCA facility for brief neutron injections with a very fast intensity decrease. In this way, deuterons impulses are created, then

focalised, accelerated and guided to a deuterium or tritium target. This accelerator is a classical one with a lower mean neutrons production than the same type of
accelerators. The main originality of GENEPI concerns its operating mode based on high ions peak current (50 mA) and a decreasing time of the neutron impulse of some 100 µs. The main characteristics of the ion beam are indicated in the Table I.

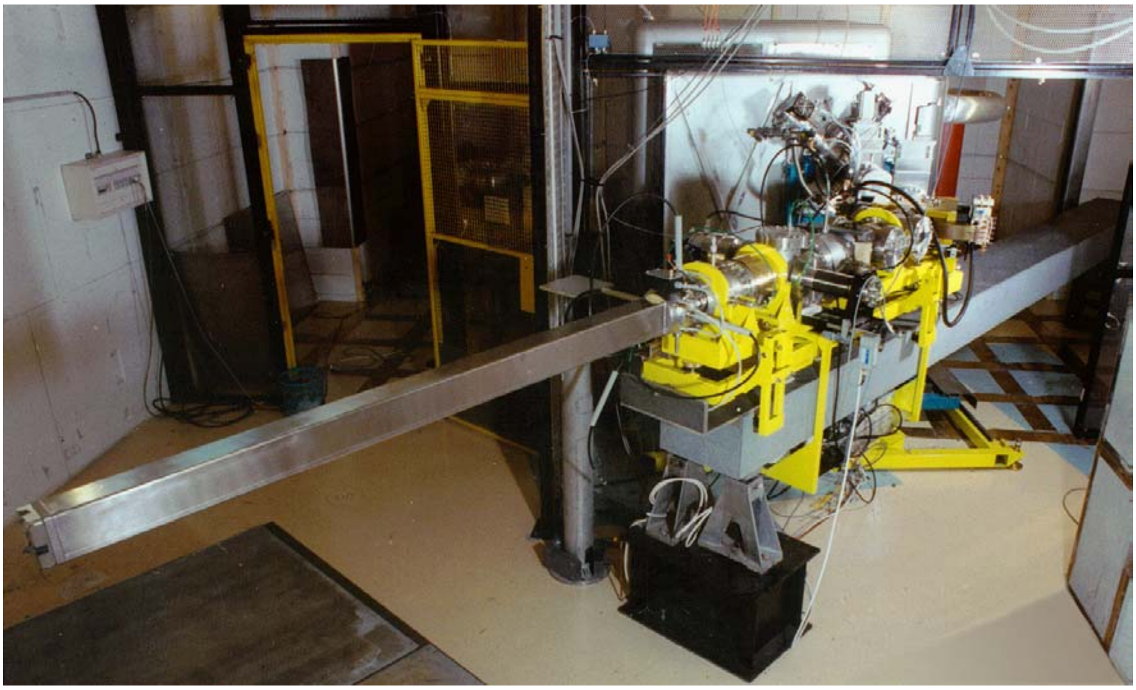


Figure 2. The GENEPI accelerator

TABLE I. Deuterons beam characteristics

Beam energy (keV)	140 to 240
Peak current (mA)	50
Repetition rate (Hz)	10 to 5 000
Minimum pulse duration (10^{-9} s)	700
Mean beam current (µA)	200 (for a duty cycle of 5 000 Hz)
Spot size (mm)	≈ 20 in the diameter
Pulses reproducibility	Fluctuations at 1% level

The characterisation of the neutron production by both deuterium and tritium targets has been performed by the ISN team and is based on the detection by a Si detector of:

- the recoiled protons induced by the (D,d) reaction on the deuterium target and in the magnet chamber due to deuterium implantation, due to deuterium implantation,
- the recoiled protons and alpha particles produced by the (D,t) reaction on the tritium target.

The characterisation of the neutron production yield is based on the activation analysis of ^{58}Ni foils. For the 2,67 MeV neutrons produced by the D(d,n)^{3}He reaction, the ^{58}Ni(n,p)^{58}Co reaction is used. The 14 MeV neutron spectrum produced by the T(d,n)^{4}He reaction is determined by both the ^{58}Ni(n,2n)^{57}Ni and ^{58}Ni(n,np)^{57}Co reactions representative of the neutrons with an energy higher than 13 MeV. For a natural Ni target of about 20 mm diameter (corresponding to a mass of about 580 mg), irradiated during 14 hours at 2 000 Hz with a pulse width of 700 nanoseconds FWHM, the measured neutrons/pulse intensities are indicated in the Table II.

Table II. Neutron intensities

Target characteristics*	Nuclear reaction	Neutrons/s
D in 1 mg/cm2 Ti deposit (Φ 30 mm)	$D(d,n)^3He$	$8.0\ 10^7$
T (1 Ci) in 0,25 mg/cm2 Ti deposit (Φ 25 mm)	$D(t,n)^4He$	$8.5\ 10^9$ **
T (10 Ci) in Ti deposit	$D(t,n)^4He$	Expected : 1.5 to 4.5 10^{10}

*D/Ti or T/Ti atomic ratio is close to 1.5,
**Measurement done after a 50% decrease of the tritium content of the target.

An accurate monitoring of the external neutron source in terms of intensity and pulse form is of prime importance for a good and accurate understanding of the proposed dynamic measurements. The target beam current, the proton and the proton + alpha spectroscopy signals and the proton + alpha time distribution referred to the neutron source pulse will be available for the physicists during the experimental campaigns.

4. EXPERIMENTAL CONFIGURATIONS

During the 2001-2003 period two types of cores will be studied in the MASURCA facility. As the MUSE experiments are based on a parametric approach, the MUSE-4 configurations (2001-2002) are based on the ZONA2 fuel cell (see Fig. 2), representative of a fast Pu burner core (Pu enrichment of ≈ 25% with ≈ 18% content of ^{240}Pu) with sodium coolant. The fuel zone is radially and axially reflected by a stainless steel/sodium (75/25) shielding. The GENEPI deuteron guide will be horizontally introduced at the core mid-plane and the deuterium or tritium target will be located at the core centre (see Fig. 3). To compensate the spatial effect due to the presence of the GENEPI guide in the north part of the loading, the south symmetrical part will be loaded with pure lead (99.99% of Pb) simulating the Pb circulation of the target. To simulate the physical presence of a Pb spallation source, a pure square (10 cm thick) lead zone is placed around the GENEPI target (see Fig. 3).

Six different experimental configurations will be studied:

- a critical one, the GENEPI beam guide introduced but being shut off, in which all the safety, neutron flux level and spectrum measurements will be performed. In this configuration the reactivity scale will be experimentally determined by the classical pilot rod shutdown measurement.
- three successive sub-critical configurations (k_{eff} being successively of about 0.994, 0.97 and 0.95; the SC1, SC2 and SC3 configurations respectively). These three configurations will be obtained by replacing radially some peripheral fuel cells by stainless steel/ sodium cells. The West/East symmetry along the beam guide axis will be preserved.
- two complementary asymmetrical sub-critical configurations, with k_{eff} of about 0.97 and 0.93 obtained from the previous SC1 and SC2 sub-critical configurations, by complete insertion into the fuel zone of the same safety rod. These two last configurations will be of interest in the frame of studying the spatial decoupling effects and the excitation of the high order flux harmonics (the flux tilting effect may be amplified by the external source).

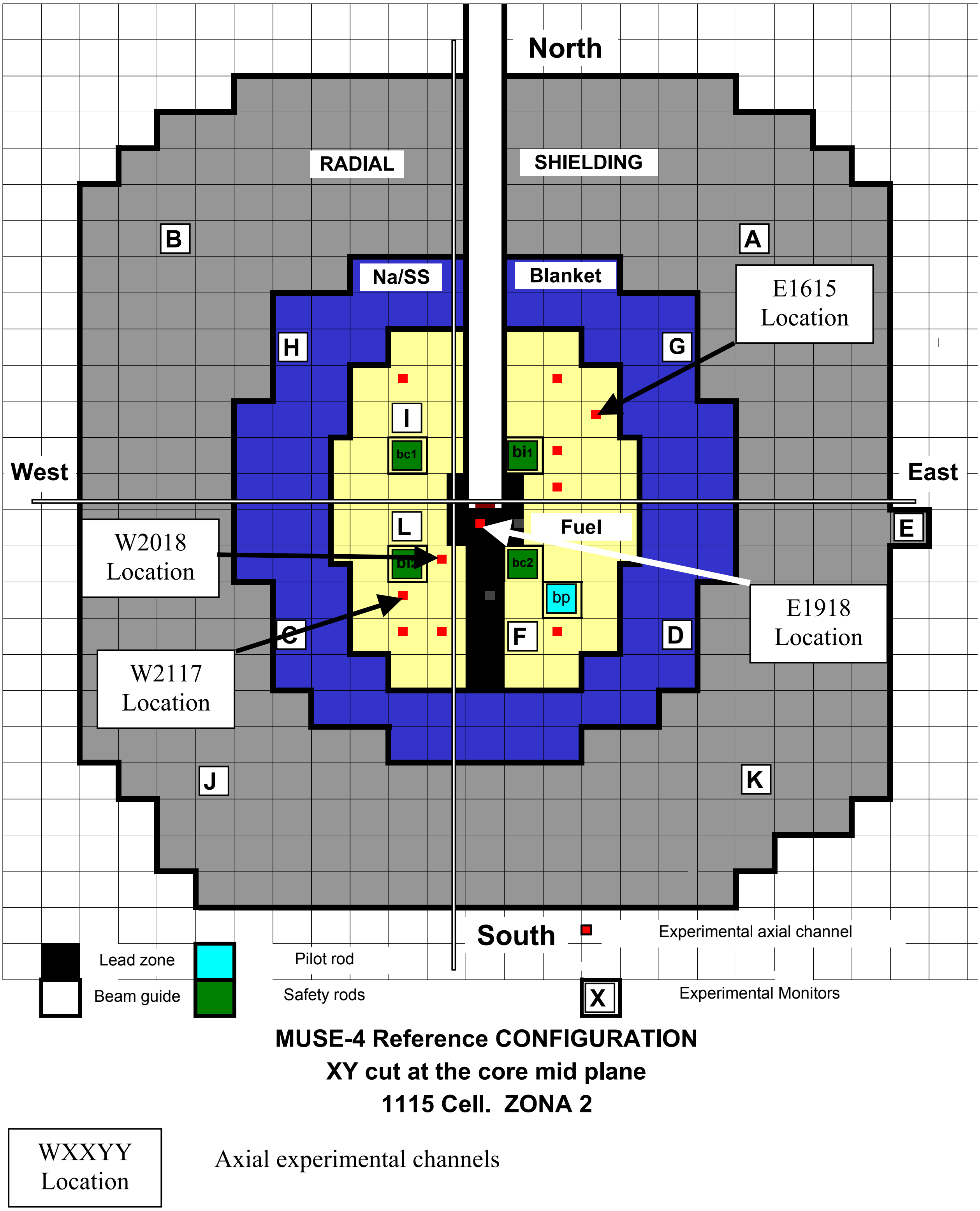


Figure 3. : XY cut of the MUSE-4 reference critical configuration at the core mid-plane

5. EXPERIMENTAL PROGRAM

The experimental program performed during the MUSE-4 experiments must answer to the specific problems associated to the multiplying medium (Mox fuel, Na coolant) in sub-critical situations driven by the GENEPI external source. Thus, we have considered the main following items.

5.1 REACTIVITY CALIBRATION AND KINETIC PARAMETERS

The difficulty of the measurement of the sub-critical level of an ADS is due to the heterogeneous nature of the system in space, energy and time (in the case of a pulsed accelerator). In addition, the classical techniques used in standard critical systems (based in particular on rod drops) for the reactivity calibration cannot be used in these sub critical systems if we keep in mind that the criticality could never be achieved and secondly the presence of control rods is still not determined. In the MASURCA facility, the sub-critical level of the different configurations will be precisely determined by the well-known Modified Source Method after the absolute reactivity calibration by the rod drop technique of the pilot rod.
The second step consists in the test and validation of dynamic experimental methods applied to an ADS, based on the reactor kinetics and neutron–noise theory using time series data as the pulsed neutron source technique, the transfer function measurement and noise measurements based on the Rossi-α and/or Feynman-α techniques for the reactivity levels determination. A specific acquisition system NIKO has been developed in order to achieve these objectives [5].
This point is of crucial interest since without this type of measurements during the MUSE experiments, it will be very difficult to demonstrate the reactivity measurement feasibility in a future operating ADS. All these dynamic methods can be easily validated in the MASURCA facility at very low power and with sub-critical medium characteristics representative of an ADS.
These different techniques, the instrumentation and acquisition systems and their application during the MUSE experiments are precisely described in [5].The noise techniques have been performed for the MUSE-4 reference core (1115 ZONA2 fissile cells) with the pilot rod down. The corresponding reactivity level of this configuration has been determined by the well known MSM method using the twelve fixed ^{235}U monitors located into the core and radial reflector:

$$\rho_{MSM} = -\ 35{,}2 \pm 0{,}2\ ¢$$

The Rossi-α and Feynman-α experimental data series obtained by different monitors located in core and in radial reflector are analysed by a least square fitting method [5] .
For example in the figure 4 is presented the fit of the Rossi distribution for the G and H ^{235}U monitors located in the radial reflector. The Table III gives the fit results for Rossi-α method and for the two monitors G and H located in the radial reflector (see figure 3).

TABLE III . Fit results for the Rossi-α method

Monitors	α_p (s^{-1})	σ_α (%)
(G,G)	8901	1.1
(H,H)	7853	1.4
(G,H)	7555	1.2
(H,G)	7757	1.2

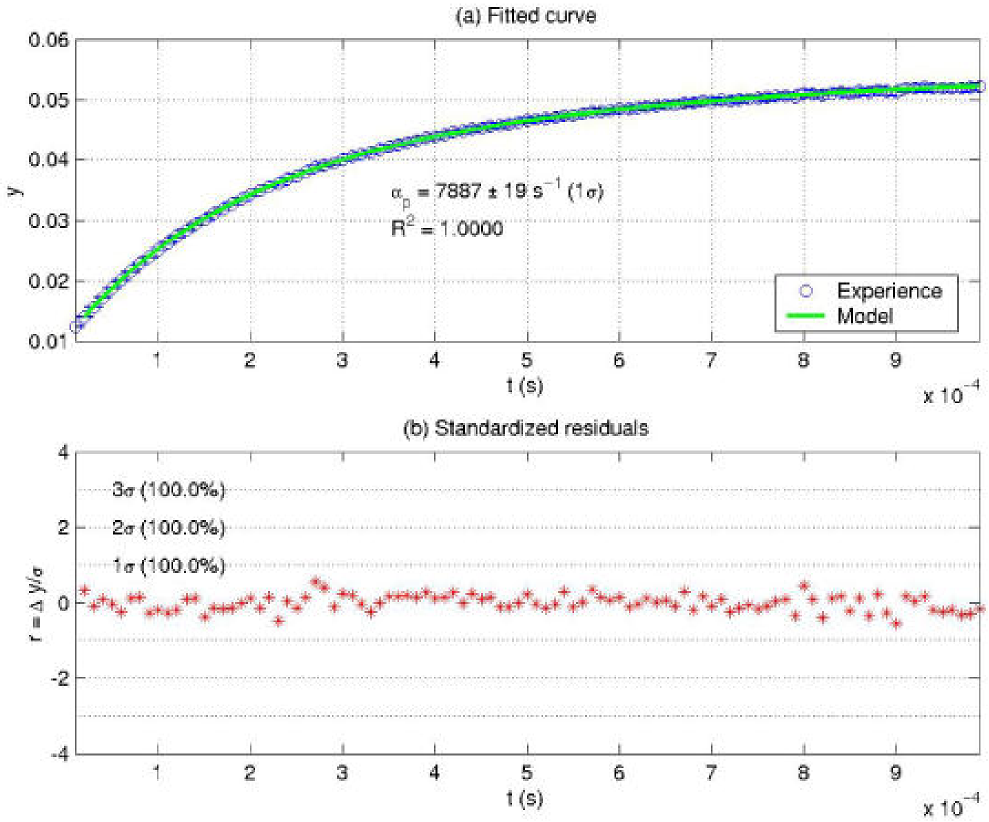


Figure 4 : Rossi-α Measurement – Cross-correlation between the G and H monitors

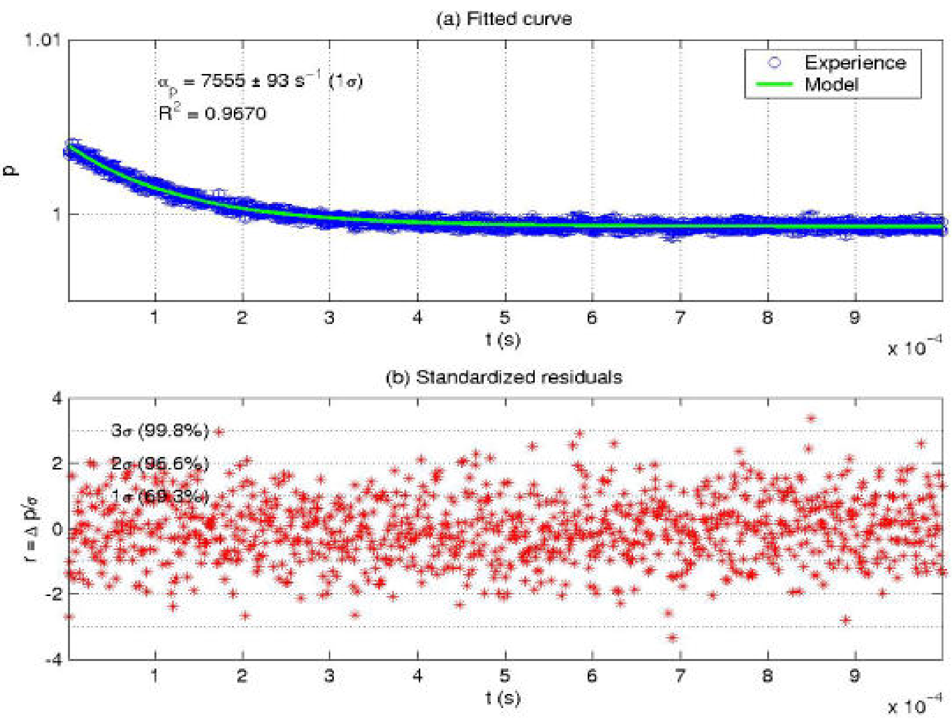


Figure 5 : Feynman-α measurement – Fit of the covariance to mean between the G and H monitors

In Figure 5 is presented the fit of the Feynman distribution for the G and H ^{235}U monitors located in the radial reflector. The Table IV gives the fit results for Feynman-α

TABLE IV . Fit results for the Rossi-α method

Monitors	α_p (s^{-1})	σ_α (%)
(G,G)	8046	0.5
(H,H)	7691	0.5
(G,H)	7850	0.2
(C,C)	8917	2.6
(D,D)	9066	1.6
(C,D)	7891	1.9

From Table IV , a mean $\alpha_{Feynmzan}$ value of 8244 ± 688 s^{-1} can be obtained.

The pulsed neutron source method has been used with the deuterium target, three frequencies of GENEPI varying from 1 to 4 kHz in a SC0 sub-critical configuration with three different rod positions:

- the four safety rods up and the pilot rod up, corresponding to a MSM reactivity level of -1.33 \$ ($\pm$ 0.4%)
- the four safety rods up and the pilot rod down, corresponding to a MSM reactivity level of -1.74 \$ ($\pm$ 0.4%)
- three safety rods up, one safety rod down and the pilot rod down, corresponding to a MSM reactivity level of -12.53 \$ ($\pm$ 1.5%).

The ^{235}U fixed fission chambers (the monitors, see figure 3) have been used in each region of the SC0 loading. The experimental conditions and the experimental data series obtained by different monitors are analysed by a least square fitting method [5].

Figure 6 illustrates the decrease of the GENEPI pulse in the beginning and the approach to the background value at the end of the PNS curve.

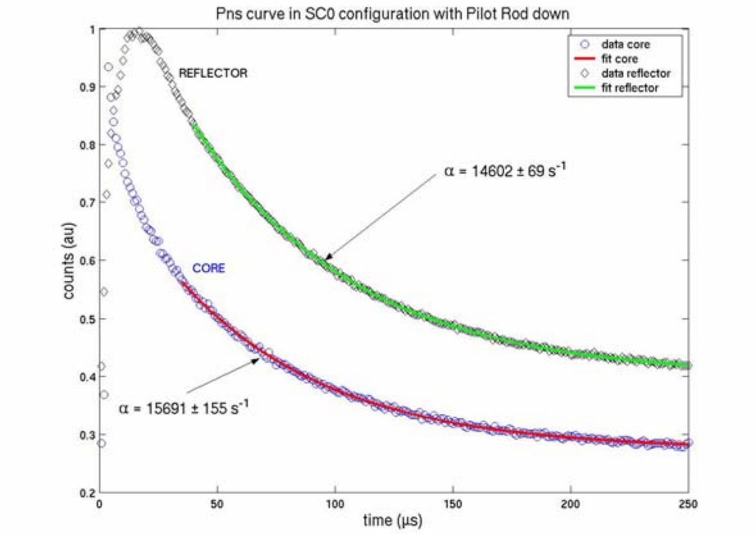


Figure 6. PNS curve in SC0 sub-critical configuration with the safety rods up and the pilot rod down

The following 3 α-values are deduced from measurements in the core region for the three previous rods positions:

$$\alpha_1 = 13018\ s^{-1}\ (\pm 3.5\%) \qquad \alpha_2 = 15578\ s^{-1}\ (\pm 2.5\%) \qquad \alpha_3 = 63664\ s^{-1}\ (\pm 8.6\%)$$

From these three sets of α values we can infer the ratio of β/Λ which is very important, as it is the rate above which the reactor can no longer significantly respond to perturbations. Expressing the reactivity in units of dollars, we can write:

$$\beta/\Lambda = \alpha / (\rho_{\$} - 1).$$

The inferred values of β/Λ are given in Table V.

Table V: Inferred β/Λ values

Configuration	Reactivity ($)	β/Λ (s^{-1})	Uncertainties
Reference MUSE-4 Configuration			
Rossi Measurement	-0.367	5865	8.9 %
Feynman Meas.	-0.367	6031	8.3 %
SC0 MUSE-4 Configuration			
PNS 1	-1.33	5587	3.5 %
PNS 2	-1.74	5665	2.5 %
PNS 3	-12.53	4705	8.6 %

For slightly sub-critical configurations, we can observe a good agreement above the methods. The agreement is well within the assumed uncertainties.
However, for the SC0 MUSE-4 configurations, there is clearly a trend as the configuration is changed in going just slightly sub-critical (-1.74 $) to the case with a safety rod inserted (-12.53 $). The explanation of this effect is still under investigation (problems related to the numerical model used or physical effect related to the detector efficiencies). This point is crucial for the next SC2 and SC3 sub-critical configurations for which reactivity levels will be on several dollars.

5.2 CONTRIBUTION OF THE NEUTRONS OF THE EXTERNAL SOURCE COMPARED TO THE NEUTRONS GENERATED BY FISSIONS

The neutron importance of the external source to the neutron importance of the total fission source: the φ* parameter [8] is an essential parameter as it will determine the maximum intensity of the proton beam for a given sub-critical system (in term of sub-critical level and maximum power of the system).
The contribution of the high energy neutrons to the spatial distribution of the neutron spectrum, implying the presence of transients and gradients which can be important for the determination of the power distribution and the damages on materials (in particular in the fuel subassemblies adjacent to the buffer zone) will be determined by the reaction rate distributions and the associated spectral indices. Small fission chambers (4 mm and 8 mm diameters) with a very extensive list of deposits (^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am and ^{244}Cm) are available in the MASURCA facility. Secondly, measurements will be performed for characterisation of the neutronic spectrum variations by irradiating various types of activation foils (indium, iron, cobalt, nickel, zinc,…) in the regions of interest, principally near the lead/fuel, accelerator/fuel and fuel/reflector interfaces, where the new types of spectral fluctuations are the more important. At a later stage, the currently reported experimental results will also be used, employing a suitable unfolding code, to yield the neutron spectra at certain characteristic locations in the assembly [6]. These

measurements are performed in the different available experimental channels: radial North-South and East-West channels near the core mid-plane and different axial channels as indicated in Figure 3.

Due to the presence of a central lead buffer zone around the GENEPI source having a potential decoupling effect, the spatial distributions of the neutron flux may be potentially sensitive to the introduction of physical perturbations (tiltiness effect). The coupling between different zones of the system may be more or less high (by the mean of the Avery theory on the coupled systems). These coupling (or decoupling) effects may be precisely measured in zero power facility using experimental techniques developed in the past at the ZPPR facility (ANL West).

Some axial reaction rate distributions obtained in the MUSE-4 reference configuration and at different locations are indicated in the following figures 7 - 12.

They are compared to the equivalent one obtained by the ERANOS system using a geometrical simplified model of the loading [7].

Figure7. ^{241}Pu axial relative distribution

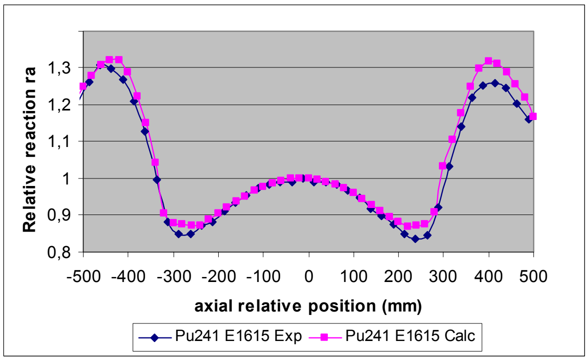


Figure8. ^{240}Pu axial relative distribution

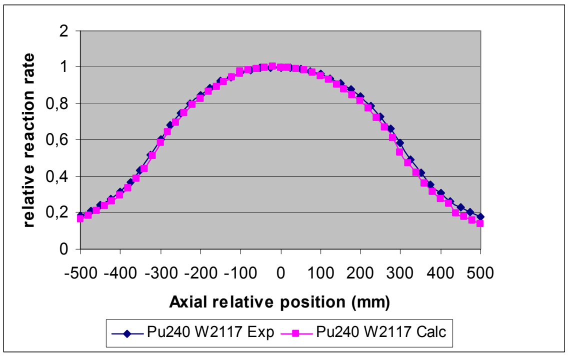


Figure9. ^{238}U axial relative distribution

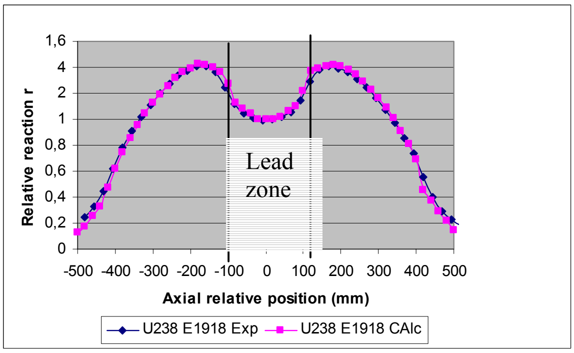


Figure10. ^{239}Pu axial relative distribution

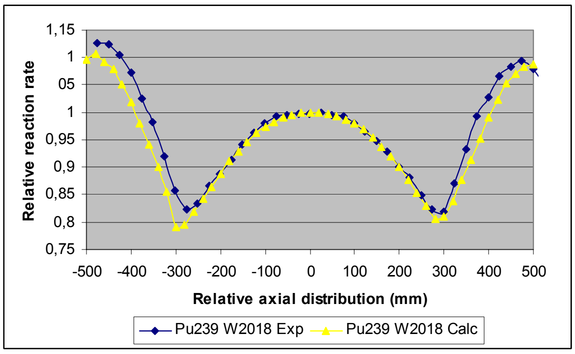


Figure11. ^{233}U axial relative distribution

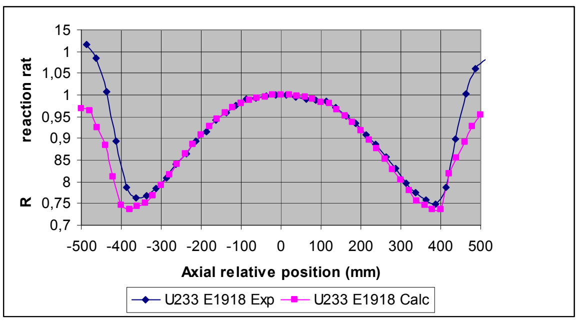
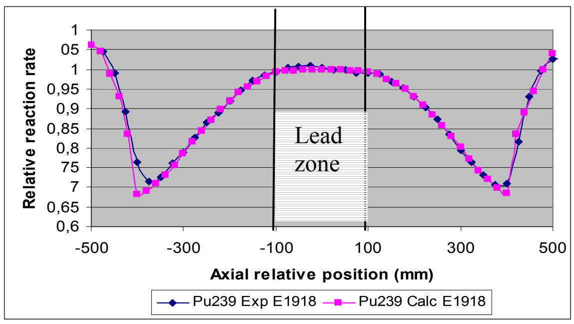


Figure12. ^{239}Pu axial relative distribution



A good agreement is observed for each axial distributions in the central lead and fissile zones. These relative radial and axial distributions will be performed in the SC2 MUSE-4 configuration in presence of the (d,t) neutron source

5.3 PROPAGATION AND STEAMING EFFECTS OF THE SPALLATION SOURCE NEUTRONS

The problems related to the propagation and the streaming of the spallation neutrons induce new characteristics compare to the same in a classical critical power reactor. The transport calculation tools and the nuclear data treating the deep penetration and the activation of the materials far away from the source and the multiplying medium have to be validated. In this way, complementary experiments (the SAD experiments) will be performed at Dubna (Russia) in the frame of the 5th FWP of the European Community, studying different spallation neutron sources (Pb, Pb-Bi, W targets) produced by the 660 MeV protons of the Dubna synchrotron, without and with the presence of a multiplying medium. These experiments will allow to the experimental validation of the spallation neutrons propagation, with a special attention to a “forward” direction (behind the target area). These penetration measurements will be performed in the target, the fuel and the structural materials encountered into an ADS.
Tables VI and VII give the main characteristics of the JINR Phasotron and SAD facility for lead target.

Table VI. Main Parameters of JINR Phasotron

Maximal power of the beam	2.1 kW
Maximal energy of protons	659 ± 0.6 MeV
Energy dispersion	3.1 ± 0.8 MeV
Beam emittance	
Horizontal	π(5.1 ± 2.3) cm.mrad
Vertical	π(3.4 ± 1.4) cm.mrad
Intensity of the extracted proton beam	3.2 μA (2. 10^{13} protons/s)
Number of protons in a pulse	0.8 10^{11}
Frequency of pulses	250 Hz
Microstructure of a pulse	
Bunch length	20 ns
Interval between bunches	70 ns
Number of bunches in a pulse	300
Pulse duration	30 ms

Table VII. Main Parameters of the ADS facility for lead target

Proton beam energy	660 MeV
Beam Power	0.5 kW
Beam intensity	4.762 10^{12} p/s
Neutron intensity	1.51 10^{15} n/s
K_{eff}	0.95
Fission power	15 ÷ 20 kW
Core length of a MoX fuel element	50 ÷ 60 cm
Core diameter (with Pb reflector)	100 cm
Weight of loaded fuel	354 kg

6. CONCLUSIONS

A very extensive experimental program has been defined in support to the neutronic behavior of a multiplying sub-critical medium in presence of a well known external neutron source. This program, begun in 2000, will allow us to develop in particular some experimental techniques to be used for the reactivity control of this type of systems. This techniques based on noise measurements have just begun in the MASURCA facility, and the preliminary experimental results are very encouraging. However, many more such measurements are needed to infer the sub-critical reactivity with a target uncertainty on the order of 5% or less. These necessary measurements will be accumulated till the end of the MUSE-4 program (end of 2003). The neutron flux characterisation in space and energy will be also performed using miniature fission chambers with a very extensive list of deposits and also by mean of activation foils with different energy range activation.
This very extensive set of experimental results will be used to validate the calculation tools and the nuclear data and to propose a reference validated calculation scheme for the design of a future ADS prototype. In this way a calculation benchmark exercise has been proposed and distributed under the auspices of OECD/NEA [4]. From 2003, complementary experiments will be performed in Dubna (Russia) using the JINR phasotron, different targets (Pb, Pb-Bi and W) and a MOX sub-critical assembly at K_{eff} =0.95 (the SAD experiments).

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