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The MUSE-4 Experiment: Prompt Reactivity and Delayed Neutron Measurements

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ABSTRACT - *The use of systems such as Accelerator Driven Systems (ADSs) for incineration of nuclear waste and/or energy production will require monitoring of different parameters which govern the reactor safety. The MUSE-4 experiment performed at CEA Cadarache Centre (France) in the MASURCA reactor coupled to the GENEPI accelerator allows the study of new techniques to perform this monitoring in subcritical medium. We detail two experimental methods to determine the prompt multiplication factor* k_p *and the delayed neutron fraction* β_{eff}*.* k_p *values are obtained from time responses of the core measured with fission chambers after a neutron pulse. We propose a new approach based on the distribution of time intervals between two consecutive events in a fission chain obtained from a MCNP simulation. From the decrease rates of time spectra simulated for different subcriticality levels compared to experimental rates, the determination of the prompt multiplication factor is done. The delayed neutron fraction is obtained by varying suddenly the GENEPI source intensity. The response of a neutron detector immediately before and after the source change allows the determination of the ratio* $\frac{\rho}{\beta_{eff}}$ *between the reactivity and the fraction of the delayed neutrons. We show that these two methods applied for two reactivity levels give finally* β_{eff} *and* k_{eff} *which are found in excellent agreement with expected values.*

I. INTRODUCTION

One of the most important problem with nuclear energy is the management of the large amount of plutonium and minor actinides (MA) arising from the reprocessing of spent nuclear fuels.

A reduction of the potential radiological toxicity of these long lived isotopes before final disposal into deep underground repository can be achieved using dedicated transmutation systems. It could be either a critical or subcritical system (Accelerator Driven System or ADS). Cores with very high MA loading, however, pose crucial problems related to fuel evolution and to small delayed neutron fraction.

In a subcritical system, the reactivity ρ or the effective multiplication coefficient k_{eff} are intrinsic characteristics of the reactor, and govern the safety of the system. It seems likely that any regulatory body will demand that the methods for monitoring the reactivity are well qualified before giving the license to operate the system. In order to investigate the criticality monitoring techniques, during the MUSE-4 (MUSE EC collaboration contract FIKW-CT-2000-00063) experimental program, the MASURCA reactor located at CEA Cadarache (France) has been coupled to the GENEPI neutron generator in order to study the response of a subcritical assembly to an extraneous source of neutrons.

The method which is chosen to measure the prompt reactivity is to study the decrease of the neutron flux following a neutron pulse. This technique giving access to the prompt multiplication coefficient k_p must be associated to a measurement of the effective delayed neutron fraction β_{eff}. To extract β_{eff}, we propose a new method based on the modulation of the external source intensity, and as a consequence, we fully qualify the total effective multiplication coefficient k_{eff}.

II. EXPERIMENTAL SETUP

These experiments were carried out at the MASURCA reactor facility of the CEA Cadarache (France). This small reactor devoted to studies of fast neutron reactors can operate in critical or subcritical configuration by removal of fuel subassemblies. It consists of about 20×20 modular vertical assemblies of 16 square inches. The core central zone (about 60 cm in diameter) is filled with MOX fuel (UO_2, PuO_2) and Na rodlets. The reflector is made of Na and stainless steel and has a thickness of about 25 cm. A thick stainless steel shield is surrounding the reflector. Measurements presented in this paper were obtained for two experimental configurations, the so-called SC0 and SC2 configurations, corresponding to a reactivity level of about -500 pcm[1] and -3000 pcm respectively. A pilot rod (PR) can be inserted or removed from the core, allowing a reactivity change of about 150 pcm.

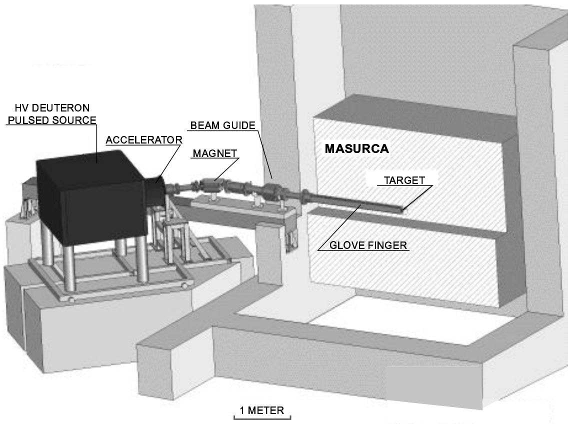

Fig. 1. The GENEPI accelerator coupled to the MASURCA reactor.

The external neutron source was provided by a pulsed deuteron accelerator designed for the MUSE-4 experimental program and built by the LPSC: the GENEPI accelerator. Deuterons are produced by a pulsed duoplasmatron source and accelerated to 220 kV, bent in a magnet chamber in order to remove the deuterium molecular ions, and then guided through a glove finger inserted into the reactor core (in the median plane) on a titanium-tritium target. The characteristics of this deuteron beam are a peak intensity of about 40 mA for a width of less than 1 μs. The repetition rate can vary from a few Hz up to 5 kHz, and when needed sharp frequency changes can be obtained through a programmable generator. It provides about 3.3×10^6 neutrons per pulse by $T(d,n)^4He$ reactions (3.3×10^9 neutrons/s at 1 kHz). A general view of the accelerator coupled to the reactor is shown in Fig. 1.

Measurements of reaction rates were performed with CEA fission chambers (detector 2: ^{237}Np, detectors 1,3,4 : ^{235}U) inserted vertically in the core and in the reflector as shown in Fig. 2 where a cut of the reactor in the median plane is presented. Time spectra performed with these detectors were sampled at 100 ns, but for the results presented in section IV, bins were summed to increase the time binning.

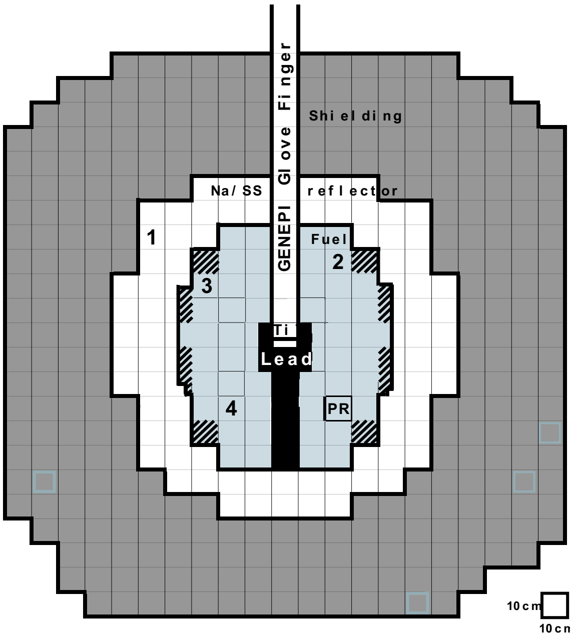

Fig. 2. XY cut in the median plane of MASURCA core in the SC0 configuration. The dashed areas represent the fuel removed for the SC2 configuration.

III. PROMPT MULTIPLICATION k_p MEASUREMENTS

III.A. The method

Usually, the time behavior of the neutron flux in a reactor excited by an extraneous neutrons source is described by solving the point kinetics equations where a neutron induces a fission after an average time ℓ. Thus, neglecting the delayed neutrons and the inherent neutron source, after a pulse the neutron population $N(t)$, in the case of a subcritical reactor, vanishes following an exponential decrease given by the equation :

$$N(t) = N_0 \exp(-\frac{1-k_p}{\ell}t). \tag{1}$$

Nevertheless, for subcriticalities relevant for ADS (i.e. for k_{eff} ranging from 0.95 upto 0.97) , the point kinetics fails to reproduce accurately the decrease of the neutron flux [1]. To understand this failure it is useful to consider the intergeneration time distribution $P(\tau)$ which is defined as the probability for a neutron to give birth to a new one as a function of the time τ elapsed since its birth. With the point kinetics assumptions, averaging all cross sections over energy, space and time, this probability decreases exponentially (Fig. 3). The intergeneration time distribution has been simulated with the MCNP transport code [2] for the MASURCA reactor. It appears clearly that the simulated $P(\tau)$ distribution (also shown in Fig. 3) has a behavior not reproduced by the point kinetics approximation which does not take into account the effect of the neutrons coming back from the reflector and the crossing of the various resonances.

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[1] One pcm unit corresponds to a reactivity of 10^{-5}.

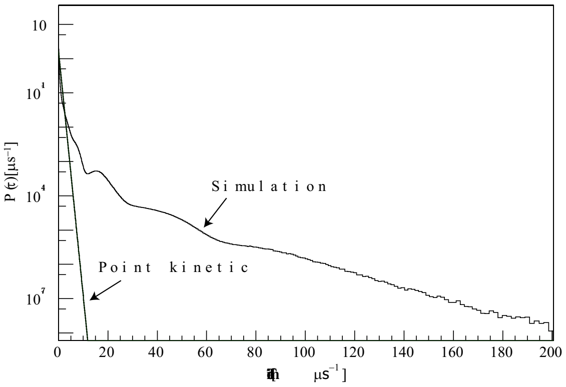

Fig. 3. Simulated $P(\tau)$ distribution compared to the one obtained with the point kinetics approximations.

The time dependence of the neutron population is obtained for any subcriticality level by using the normalized intergeneration time distribution $P'(\tau)$:

$$P'(\tau) = \frac{P(\tau)}{\int_0^\infty P(u)du} = \frac{P(\tau)}{k_p}. \tag{2}$$

The neutron population is calculated by summing the contribution of each generation :

$$N(t, k_p) = k_p P' + k_p^2 P' * P' + k_p^3 P' * P' * P' + .. \tag{3}$$

where the star denotes the convolution operator. The contribution of the i^{th} generation to the neutron population is obtained by convolving i times $P(\tau)$ with itself and weighting the result by a factor k_p^i. To improve the model, the correlation between the time of life of a neutron and the location where it induces a fission must be considered. For instance, old neutrons induce fissions at the peripheral part of the fuel zone. Consequently, the emitted neutrons are more likely to escape the fuel zone. Thus, this correlation is taken into account by introducing the relative importance $I(\tau)$ which measures the ability for a neutron to induce a fission. This quantity has been simulated and is plotted in Fig. 4.

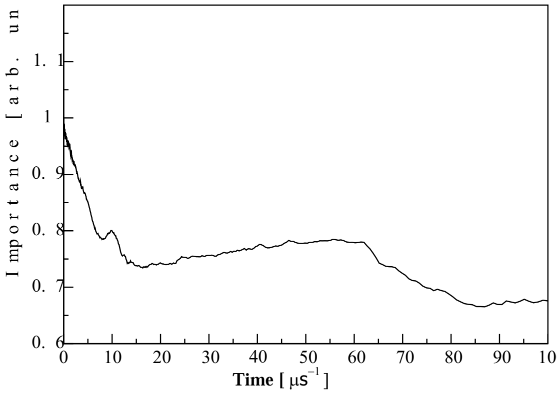

Fig. 4. Importance $I(\tau)$ of the emitted neutrons as a function of the time of life of the neutron inducing the fission.

A new distribution $P''(\tau)$ taking into account this importance can be defined :

$$P''(\tau) = \frac{P(\tau)I(\tau)}{\int_0^\infty P(u)I(u)du}. \tag{4}$$

The $P'(\tau)$ and $P''(\tau)$ distributions are plotted in Fig. 5.

$N(t, k_p)$ is now written as :

$$N(t, k_p) = k_p P' + k_p^2 P' * P'' + k_p^3 P' * P'' * P'' + .. \tag{5}$$

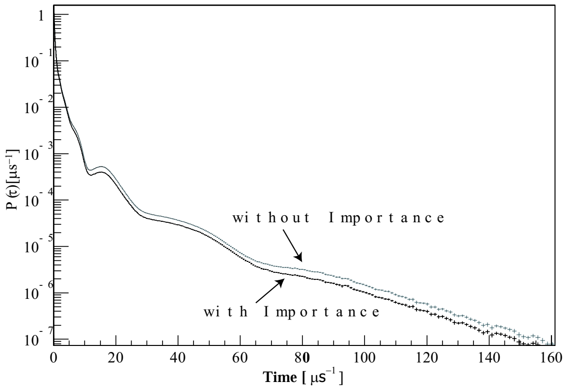

Fig. 5. Normalized intergeneration time distributions $P'(\tau)$ and $P''(\tau)$.

Experimentally, the neutron population decrease is obtained by using fission chambers with different isotopes and consequently different thresholds. The relation between the neutron flux and the counting rates will depend on the detection reaction and on the measurement location. Then, the distribution of time delays between the fission event and the possible detection a neutron $D(\tau)$ must also be obtained by simulation. The neutron population in the reactor is related to the measured quantity $N_m(t, k_p)$ by the relation :

$$N_m(t, k_p) = \int_0^\infty N(s, k_p) D(t - s) ds. \tag{6}$$

Its logarithmic derivative, representing the local slope of the counting rate, is equal to :

$$\alpha(t, k_p) = \frac{1}{N_m(t, k_p)} \frac{dN_m(t, k_p)}{dt} \tag{7}$$

and is compared to the experimental one. Finally, the value of the k_p parameter leading to the $\alpha(t, k_p)$ function fitting the best the experimental decrease rate gives the prompt multiplication factor.

III.B. Results of the Prompt Multiplication Determination

Figure 6 shows the logarithm of the counting rates for several detectors and three reactivity levels (SC0 data are from Ref. 3).

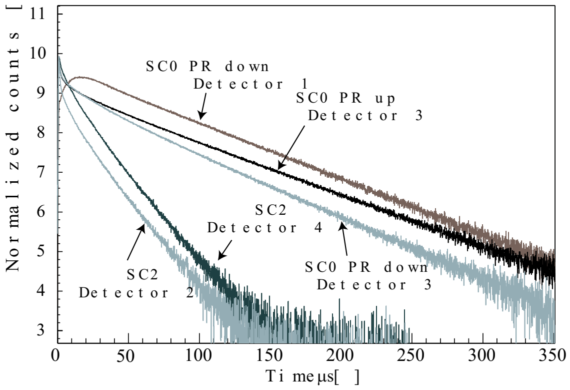

Fig. 6. Logarithm time spectra for three levels of subcriticality and for different detectors (SC0 data from Ref. 3).

TABLE I. Calculated prompt multiplication factors for the three different core configuration

Configuration	Detector	k_p
SC0 PR up	3	0.9913±0.0005
SC0 PR down	3	0.9892±0.001
SC2 PR down	4	0.9674±0.002

As expected, the decrease of the counting rates depends on the reactivity and exhibit sensitivity to reactivity change as small as the one induced by the pilot rod removal ($\simeq$ 150 pcm).

The analysis described in section III has been performed on data obtained in the SC0 configuration with detector 3 and in SC2 configuration with detector 4 : both detectors are ^{235}U fission chambers and are located in the fuel (Fig. 2). The results are shown in Figs. 7 and 8, and the k_p values results are gathered in Table I.

From the measured value of k_p and the average time of life of a neutron (ℓ = 0.6 μs obtained by simulation), it is also possible to deduce the exponential decrease rate $\alpha_{PK} = (1-k_p)/\ell$ expected in the case of the point kinetics approximations (PK). These calculated values are plotted in Figs. 7 and 8.

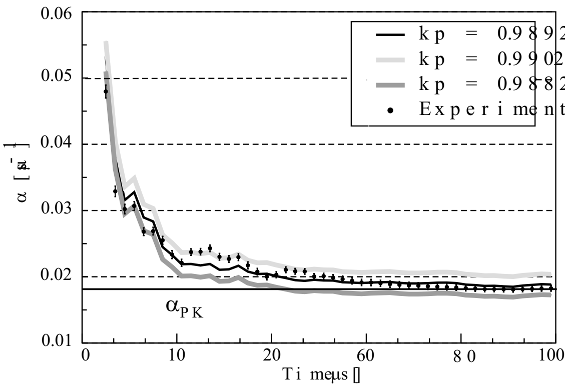

Fig. 7. Measured logarithmic derivative in the SC0 configuration for detector 3.

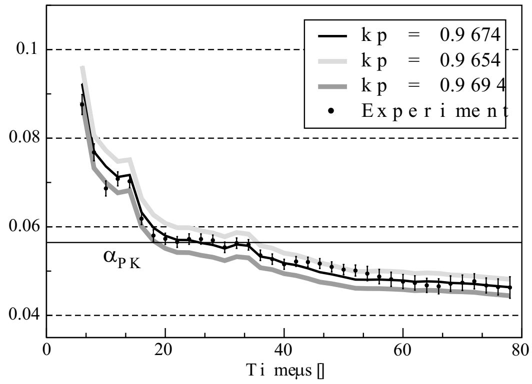

Fig. 8. Measured logarithmic derivative in the SC2 configuration for detector 4.

In the SC0 configuration, after 60 μs, the logarithmic derivative tends to a constant value which is found equal to α_{PK} (Fig. 7). Consequently, for such a subcriticality level ($k_p = 0.9892$), the measurement of the asymptotic decrease rate can be used to determine the prompt multiplication assuming that ℓ can be obtained by simulation.

On the other hand, in the SC2 configuration, the logarithmic derivative (Fig. 8) does not reach an asymptotic value. The calculated α_{PK} is lower than the measured quantity before 20 μs and greater after 30 μs. This behavior can be explained by the fact that the point kinetic assumptions tend to over-estimate the number of fissions occuring at short times in comparison to the fissions occuring at later times (see Fig. 3).

IV. MEASUREMENT OF THE EFFECTIVE DELAYED NEUTRON FRACTION

As discussed in section III, the Pulsed Neutron Source technique gives access to the prompt multiplication factor k_p. However, since only the fraction $(1 - \sum_i \beta_i)$ of the fission neutrons is prompt, the total multiplication factor coefficient k_{eff}, which governs the safety of the reactor is related to k_p by the equation :

$$k_p = \left(1 - \sum_i \beta_i\right) k_{eff}. \tag{8}$$

We have thus developed an experimental procedure to determine the delayed part of the multiplication factor.

IV.A. Overview of the Experimental Method

The method applied is closely related to the “Source Jerk” technique. During an irradiation time (T_{irr}=200 s) much larger than the mean lifetime of the “longest lived” neutron precursor (56 s), the GENEPI generator is operating at a repetition rate F_0 = 4 kHz, thus injecting into the subcritical assembly a neutron source rate S_0 proportional to this frequency. Consequently, the subcritical system is maintained at neutron and precursor populations n_0 and

C_{i0} equilibrium by the extraneous neutron source S_0. In such a case, the neutron balance equation writes:

$$\left(\frac{\rho - \beta_{eff}}{\Lambda}\right) n_0 + \sum_i \lambda_i C_{i0} + S_0 = 0 \tag{9}$$

where Λ is the mean fission generation time, C_{i0} is the equilibrium concentration of the i^{th} delayed neutron precursor , and λ_i is the decay constant of the i^{th} precursor. Let now imagine, for sake of simplicity, that the external source is suddenly switched off. Following this sudden change in the source intensity, the prompt neutron flux dies away quickly and the flux then reduces to the delayed neutron flux decreasing with precursors time constants. Under these conditions, a simple result can be obtained, by merely assuming that the concentration of the delayed neutron C_{i0} does not change over the time of the sudden drop in the flux. The neutron density n_1 immediately after the sudden change in source intensity is given by :

$$\left(\frac{\rho - \beta_{eff}}{\Lambda}\right) n_1 + \sum_i \lambda_i C_{i0} = 0 \tag{10}$$

because the delayed neutron precursor population will not change immediately. These equations and the equilibrium precursors concentrations :

$$C_{i0} = \frac{\beta_i n_0}{\lambda_i \Lambda} \tag{11}$$

lead to the equation :

$$\frac{\rho}{\beta_{eff}} = 1 - \frac{n_0}{n_1}. \tag{12}$$

IV.B. The Actual Procedure

The ratio n_0/n_1 is obtained experimentally as the ratio of detectors counting rates which suffer the following effects :

- the intrinsic source of the reactor gives birth to a constant counting rate due to spontaneous fissions and (α,n) reactions on U an Pu oxides
- the return phase to the high frequency must be adapted to the reactor doubling time (5 s) on pain to cause a safety rod drop. Consequently, the source is not switched-off but varies from a high value F_0 (4 kHz) to a low value F_1 (300 Hz) in order to decrease the time needed to reach F_0 from the low frequency F_1 (Fig. 9).
- the choice of the low frequency F_1 is also based on a physical ground: it corresponds to a time interval of 3 ms between two consecutive neutron pulses. This time distance must be compared to the half-lives of the short lived delayed neutron precursors. Thanks to the weak interaction properties no β emitters in the mass range of the fission products have a half-life shorter than a few tens of milliseconds. As a consequence, even for the shortest-lived delayed neutron precursors, the pulsed irradiation acts as a continuous one.

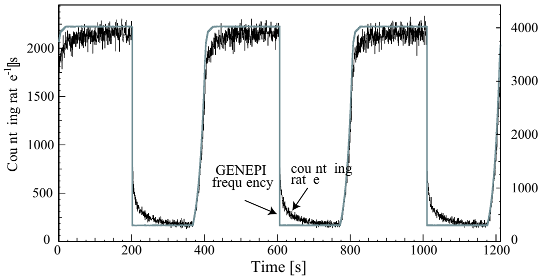

Fig. 9. Source frequency variation cycle (gray line, right scale) and experimental neutrons counting rate (black line, right scale) for three cycles.

Under these conditions, the rates n_0 and n_1 which enter the Eq. (12) are replaced by the quantities R_0 and R_1 obtained by subtracting to the total counting rates a pedestal which consists of the sum of the inherent source and of the equilibrium rate corresponding to the low excitation frequency $F1$ (see figure 10).

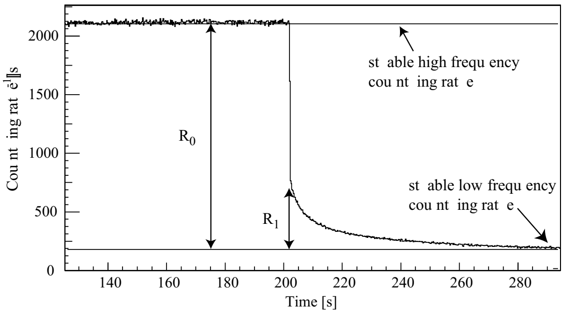

Fig. 10. R_0 and R_1 quantities (summation over all measured transients) obtained with detector 4 in the SC0 configuration.

IV.C. Results

Figure 11 shows, for the two core configurations SC0 and SC2, the results of the source modulation experiment. The two displayed spectra correspond to the sum of all measured transients for a given subcriticality. These data allow us to extract a value of $\frac{\rho}{\beta_{eff}}$ following Eq. (12). With the value of the prompt multiplication factor deduced from the prompt decay analysis (Table I), the Eq. (8) along with the Eq. (12) leads to :

$$\beta_{eff} = \frac{1 - k_p}{1 - k_p \left(\frac{\rho}{\beta_{eff}}\right)_{exp}}. \tag{13}$$

Finally, the effective multiplication factor k_{eff} is calculated for the different configurations and is compared to the value obtained with standard Source Multiplication (SM) methods [4]. All the results and SM values are gathered in Table II.

There is excellent agreement between the SM results and those obtained with our proposed method.

In addition to these results, a careful analysis of the slow decrease (Fig. 11) of the neutron counting will allow

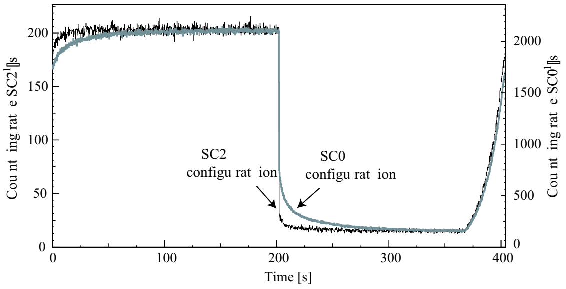

Fig. 11. Experimental counting rates measured with detector 4 for the SC0 configuration (gray line, right scale) and SC2 configuration (black line, left scale).

TABLE II. β_{eff} and k_{eff} values for the SC0 and SC2 configurations the pilot rod down compared to k_{eff} values obtained with standard SM measurements [4] (the k_{eff} values are calculated with the mean value β_{eff}= 328±23 pcm).

Configuration	β_{eff} (pcm)	k_{eff}	k_{eff} (SM)
SC0 PR up		0.9946±0.0005	0.9948±0.0005
SC0 PR down	342±32	0.9925±0.0010	0.9937±0.0005
SC2 PR down	313±34	0.9706±0.0020	0.9716±0.0030

us to measure the distribution of emission times for the delayed neutrons and compare it with the spectrum which can be constructed from the precursor decay data.

V. CONCLUSIONS

In the MUSE project, a pulsed deuteron generator has been coupled to the MASURCA fast reactor to establish a subcritical assembly driven by a pulsed d-T source. We have developed a technique based on the analysis of the prompt decay of the neutron population which follows the external neutron pulse. In addition to the prompt multiplication coefficient measurement, we have also developed and successfully applied a method which allows us to determine the ratio of the absolute reactivity ρ to the fraction of delayed neutron β_{eff}. Together these two complementary measurements give access to the parameters which governs the prompt and the slow kinetics of a subcritical assembly. Thanks to the fact that these methods do not require any calibration measurement in critical configuration, it can be used for the monitoring of a future ADS. Finally, by mean of an external pulsed source excitation, it is possible to characterize any fuel assembly even devoted to critical systems.

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