THE MUSE-4 EXPERIMENT:
PROMPT REACTIVITY AND NEUTRON SPECTRUM MEASUREMENTS

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ABSTRACT

In the case of the use of ADS for incineration of nuclear waste and energy production a better knowledge of the ways to monitor the different reactor parameters is required. To do so, the MASURCA fast neutron reactor in different subcritical configurations has been coupled to a deuteron accelerator producing a pulse of neutrons in the middle of the core. We performed both dynamic and spectroscopic measurements. Firstly, the time response of the core after a pulse is measured with a ^{235}U fission chamber and a ^{3}He proportional counter. We show that for a core close to criticality the neutron population behaves as predicted by the point kinetics theory. On the other hand, for subcriticality level relevant for ADS, the evolution of the neutron population is not a pure exponential and thus the point kinetics cannot be used to deduce the prompt multiplication factor. So we propose a new approach based partly on MCNP simulations and with less restrictive assumptions than those of the point kinetics. This method allows a determination of different prompt k values which are in good agreement with the expected ones.

Spectroscopic measurements are also performed with a ^{3}He proportional counter. From the specific response of the detector to monoenergetic neutrons it is possible to reconstruct the neutron energy spectrum at the detector location, which is found in good agreement with the simulated one below 0.6 MeV. Above this energy some studies are in progress to improve the detector response.

These very preliminary results will be completed by further tests and experiments planned till the end of 2003.

1. INTRODUCTION

In the field of the new interest for accelerator driven systems (ADS), new experiments are taking place at the MASURCA facility (CEA Cadarache, France) which consists of a small fast neutron reactor coupled to a deuteron accelerator (called GENEPI) creating a pulsed neutron source inside the reactor core. This reactor, operating at different subcritical levels allows the investigation of neutronic properties of such a medium and more particularly of its dynamic behaviour.

In ADS two multiplication factors can be defined. k_s is the multiplication factor of the source neutrons and is depending both on the source and the reactor caracteristics: it can be deduced from the total power of the reactor, but not so easily regarding to the tricky definition of a source neutron. The other factor which can be considered is the effective multiplication factor k_{eff} corresponding to the multiplication of the stabilized fission distribution many generations after the source has been turned off. It is an intrinsic characteristic of the reactor and it governs its safety. Operating a subcritical reactor will require to monitor this k_{eff} value. We explore here a way to determine the subcriticality level of the core from dynamic measurements performed in the MASURCA core submitted to source pulses and from related simulations. More precisely the measurement concerns the prompt multiplication factor k_p as the β_{eff} value can be measured separately and is less essential here.

Finally we also show preliminary results concerning an attempt of neutron spectrometry in the reactor.

2. EXPERIMENTAL SET-UP

2.1 REACTOR

The reactor consists of about 21x23 modular vertical 4"x4" tubes. The central zone (~60 cm in diameter) is filled with MOX (UO_2, PuO_2) and Na rodlets, and is surrounded by a 25 cm Na and stainless steel reflector and a thick shield. The deuteron pulsed beam provided by the accelerator (250 kV) is brought in the middle of the core by mean of a horizontal glove finger ended by a TiD or TiT target (figure 1). The beam peak intensity is about 50 mA for a width of less than 1μs, and the repetition rate can vary from a few Hz up to 5 kHz, providing (with the TiD target) about 4.10^4 neutrons per pulse (~4.10^7 n/s at 1 kHz). The core configuration for the measurements corresponds to $k_{eff} = 0.994$ with all control rods up (value obtained from MCNP simulations made with a detailed description of the reactor [1]), and when one rod is inserted it has been measured to 0.960±0.004 (MSA measurements [2]), the detailed composition of the control rod being not enough accurately known at the moment to perform the corresponding simulation.

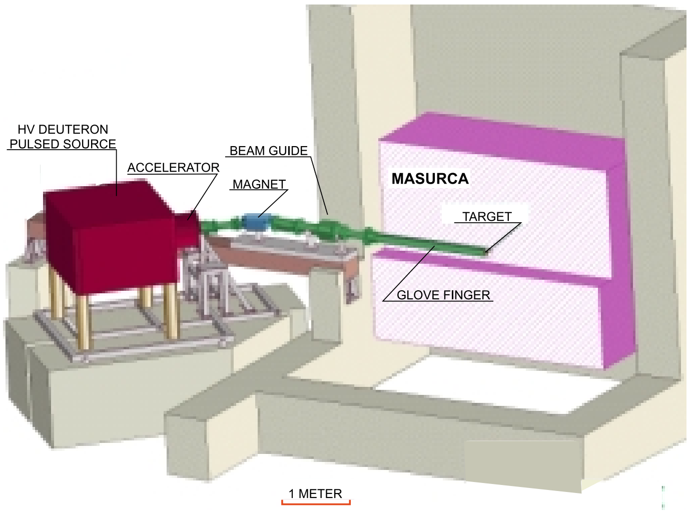

Figure 1. MASURCA reactor facility coupled to the pulsed neutron source "GENEPI".

2.2 DETECTORS

Time and energy spectra are measured by mean of a fission chamber and a ^{3}He proportional counter inserted in vertical 1" channels in the core. Signals are recorded with a 12 bit flash-ADC, working with a 10 MHz clock (100 ns/channel) and synchronized on the neutron pulsed source. The fission chamber has a U5 deposit (about 1 mg). The ^{3}He detector is filled with about 10 mb of ^{3}He and 6 b of Ar (and a few mb of CO_2). For spectrometry in the fuel zone this detector is shielded from γ-rays with a 1" blanket of Pb over the whole fuel zone length. Detector locations are shown in figure 2 on the transversal section (median plane).

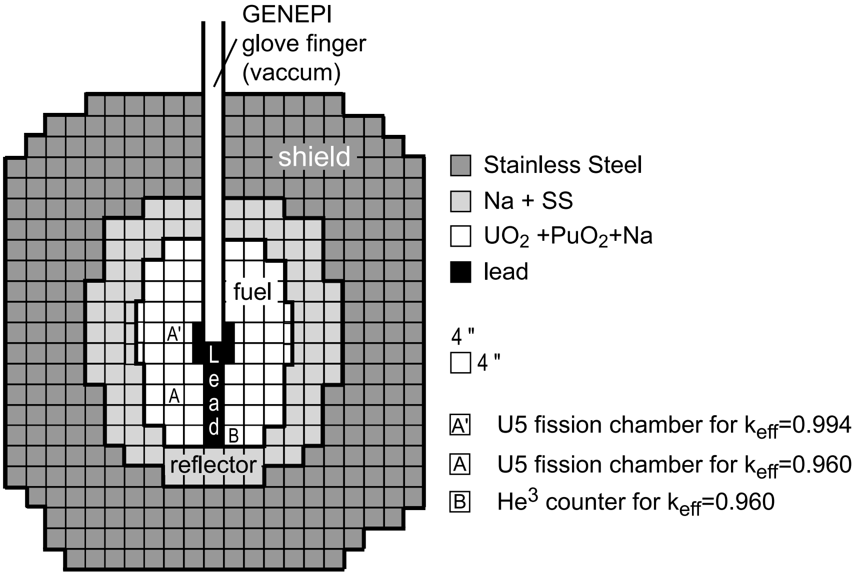

Figure 2. Detector locations in the core: transversal section in the median plane.

3. DYNAMIC RESULTS

3.1 LIMIT OF THE POINT KINETICS MODEL

When a pulsed neutron source is injected into the core those neutrons initialise fission chains and thus the neutron flux is suddenly increased above its intrinsic value. After a sufficiently large number of collisions these neutrons represent an additional flux with a spectral and spatial distribution close to the flux of the already existing neutron population.

One can assume that in those new chains each neutron creates k_p neutrons in the next generation after an average time l called the generation time. The value of l can be estimated through a MCNP simulation: for a stabilized fission source l is found equal to 0.58 µs. Under this assumption the decay of the neutron population follows a pure exponential decrease

$$N(t) = N_0 \exp(-\alpha t) \tag{1}$$

with $\alpha = (1-k_p)/l$.

The decrease of the neutron population can be obtained by measuring the reaction rate of a detector located in the core.

Figure 3 shows the logarithmic time spectra recorded with a fission chamber in the fuel zone for subcriticality levels of 0.994 and 0.960 for a repetition rate of the pulsed source of 2 kHz. Are also shown the polynomial fits of the spectra.

When the reactor is close to the criticality ($k_{eff} = 0.994$), after a few microseconds the curve behaves as a pure exponential with a slope α close to 0.016 μs^{-1}. From this value we can calculate $k_p = 1-\alpha l = 0.990 \pm 0.001$ to be compared to the k_p value also simulated $k_p = 0.991$.

For a subcriticality level relevant for ADS, namely 0.960, shown in figure 3, the slope of the logarithmic decrease is clearly time dependent. This behaviour shows the limit of validity of the point kinetics model.

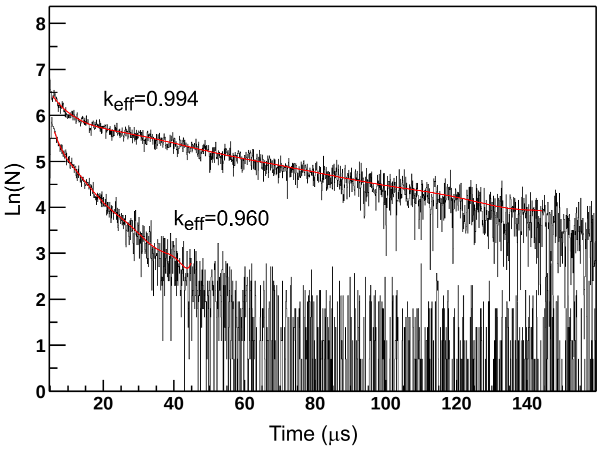

Figure 3. Logarithmic time spectra obtained with a U5 fission chamber in the fuel zone of MASURCA for two subcriticality levels $k_{eff} = 0.994$ and $k_{eff} = 0.960$. Plain curves are polynomial fits of the spectra.

3.2 A MORE SOPHISTICATED MODEL

To explain the failure of such a simple model for subcritical levels, we must pay attention to the distribution of neutron generations after several microseconds. When the multiplication factor is low, neutrons from the first generations become relatively more important than the ones of the later generations since these last generations induce less and less neutrons. Subsequently the lifetime of the early neutrons, much greater than the average generation time l, has to be taken into account. We propose a more sophisticated model where we do not assume anymore that each neutron creates another one at an average time l, but gives birth to a neutron in the next fission generation with a time distribution called $P(\tau)$, τ being the time elapsed since its own birth by fission. That distribution can be easily obtained by Monte-Carlo simulation for a stabilized neutron source and is shown in figure 4.

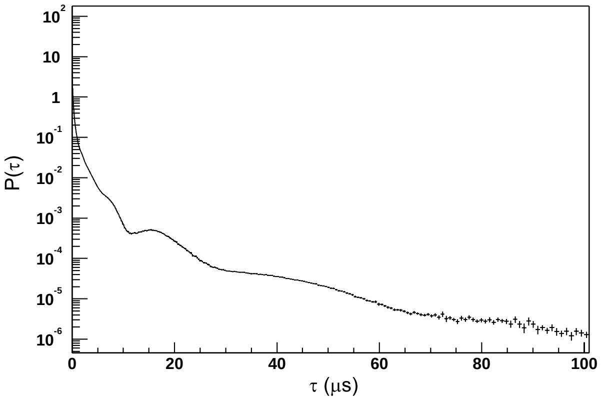

Figure 4. Fission generation time distribution $P(\tau)$ provided by a MCNP simulation.

From that definition we deduce that

$$\int P(\tau)d\tau = k_p \tag{2}$$

and thus we can normalise $P(\tau)$ to $k_p = 1$. With that normalised distribution $P'(\tau)$, we have access to the number of neutrons in the core at any time for any k_p value, summing the contribution of each generation:

$$N_{kp}(t) = k_p P'(\tau) + k_p^{\ 2} P'(\tau)*P'(\tau) + k_p^{\ 3} P'(\tau)*P'(\tau)*P'(\tau) + \ldots \tag{3}$$

where * denotes the convolution operator. The decrease rate $\alpha_{kp}(t)$ can then be calculated for different k_p values from the logarithmic derivative:

$$\alpha_{kp}(t) = \frac{1}{N}\frac{dN}{dt} \tag{4}$$

and compared to the $\alpha(t)$ obtained from the experimental $N(t)$ spectrum, the one fitting the best the experiment giving the k_p value of the reactor. This method has been applied to the spectra shown in figure 3 but also to the time spectrum measured with the ^{3}He counter at $k_{eff} = 0.960$ shown in figure 5. The $\alpha(t)$ curves obtained from the fits of these spectra are shown together with relevant calculated $\alpha_{kp}(t)$ curves in figure 6. With the U5 chamber the k_p values of the core are found bounded by 0.990 and 0.993 for the assembly close to the criticality, and by 0.955 and 0.960 in the other case. They are in rather good agreement with respectively the k_p simulated value 0.991 and the one calculated with $k_p = k_{eff}(1 - \beta_{eff}) = 0.960(1 - 0.003) = 0.957$.

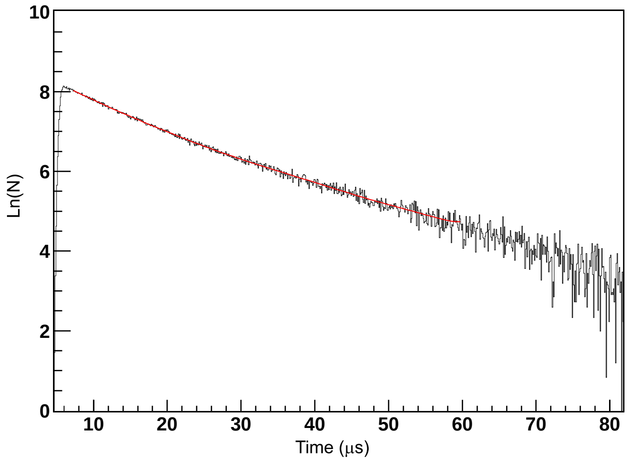

Figure 5. Logarithmic time spectrum obtained with a ^{3}He counter in the fuel zone of MASURCA for $k_{eff} = 0.960$. Plain curve is a polynomial fit of the spectrum.

The $\alpha(t)$ obtained from the ^{3}He counter exhibits a slight different behaviour compared to the U5 data. This can be explained by the location of the counters: the U5 chamber is in the middle of the fuel zone while the ^{3}He counter is close to the reflector and thus submitted to more low energy neutrons. To improve measurements in such locations the use of detectors with energy threshold (like U8 chamber for instance) is required.

This method is very promising as it can give the k_p value from a measurement made in the first tens of microseconds after the pulse, where the counting rate is still high. It is not necessary to reach an asymptotic behaviour of $\alpha(t)$, which may be not accessible to experiment. Moreover it is clearly seen that the α value given by the point kinetics model (0.073 μs^{-1}) is not in agreement with the behaviour of the experimental $\alpha(t)$.

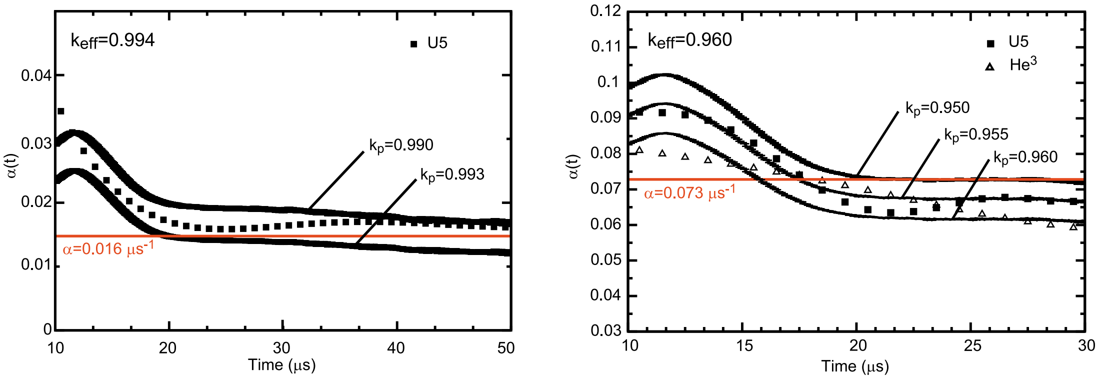

Figure 6. Logarithmic derivatives of the fits of the experimental time spectra compared to several $\alpha_{kp}(t)$ calculated by the proposed method.

More details about this method and its robustness can be found in [3].

4. NEUTRON SPECTROMETRY IN THE REACTOR

Neutron spectrometry in fast neutron reactors is not trivial considering spectra are continuous, ranging up to a few MeV and especially because the neutron flux is very large even in a small research reactor (about 10^6 n/cm^2/s). Classical time of flight methods cannot be applied here essentially because neutron transport outside the core is most of the time impossible, and the use of a time-energy relation between the neutron energy E_n and its tof is not as simple in a reactor as in an inert medium. Spectrometry based upon the detection of recoil protons from elastic scattering processes with hydrogen in plastic or organic scintillators can be done but it requires space which is sorely lacking in measurement channels. The recoil proton energies can be directly measured in a proportional gas counter. But a neutron of a given energy will induce a recoil proton energy distribution due to the recoil angle distribution. Moreover the presence of hydrogen in a fast reactor is not desirable. Finally, in proportional counters it is also possible to measure the energy of particles induced by neutron on light nuclei reactions, the particles sharing the energy released by the reaction Q and the incident neutron energy. We decided to use a ^{3}He proportional counter whose energy calibration is easier due to the thermal neutron peak at Q = 764 keV. But the response of such counters to monoenergetic neutrons is not really ideal. The peak corresponding to the collection of the total kinetic energy of the induced proton and triton is associated to a plateau due to wall effect in the counter and subsequent partial energy collection. This wall effect is reduced by increasing the counter pressure, but cannot be entirely suppressed for fast neutrons. In the response, one has to consider also the structure arising from a competing reaction occurring in the counter which is the elastic scattering of neutrons by ^{3}He. The probability of this reaction becomes greater than that of the (n,p) reaction above 100 keV, and gives a recoil ^{3}He distribution ending at $3/4E_n$ which cannot be neglected above 1 MeV as both responses superimpose. The typical response of such a counter is illustrated in figure 7 for 1 MeV incident neutrons.

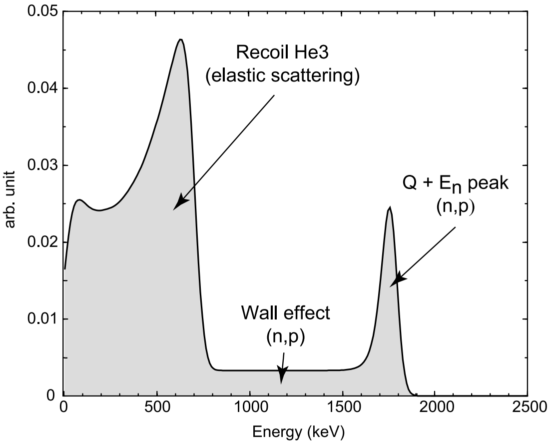

Figure 7. Typical response spectrum of ^{3}He proportional counter to 1 MeV monoenergetic neutrons.

To extract a neutron energy spectrum from the deposited energy spectrum obtained with this counter one has to modelize the response as a function of neutron energy and to build the associated matrix M for the energy range of interest. To achieve this, spectra with monoenergetic neutrons have been obtained at a Van de Graaff accelerator (CEN-Bordeaux-Gradignan, France) from 200 keV up to 1.5 MeV. Detector responses have been fitted (and combined to simulations for recoil ^{3}He distributions) and parametrized, the two reaction contributions being weighted according to their respective cross sections. The matrix Mij elements (i for the neutron energy and j for the deposited energy) with a 10 keV energy binning are then calculated (by extrapolation above 1.5 MeV). Figure 7 represents $\boldsymbol{M_i}$ for $i=100$. The neutron spectrum $\boldsymbol{E}$ whose size is $imax$ can be extracted from the deposited energy spectrum $\boldsymbol{R}$ whose size is $jmax$ by an iterative subtraction method,

$$(\boldsymbol{R})_1 = (\boldsymbol{R})_0 - \boldsymbol{M_{imax}} \,.\, E_{imax} \tag{5}$$

where $(\boldsymbol{R})_0$ is the experimental spectrum, $(\boldsymbol{R})_1$ the spectrum obtained after the first iteration, and E_{imax} satisfies $M_{imax,jmax} \,.\, E_{imax} = (R_{jmax})_1$. At rank k we have:

$$(\boldsymbol{R})_k = (\boldsymbol{R})_{k-1} - \boldsymbol{M_i} \,.\, E_i \tag{6}$$

with $i= imax\text{-}k$, $j=jmax\text{-}k$, and E_i satisfying $M_{i,j} \,.\, E_i = (R_j)_k$. This method has been applied to a measurement performed in the fuel zone for $k_{eff}=0.97$. The result, shown in figure 8 is compared to the neutron spectrum simulated with the Monte Carlo code MCNP-4C. The overall agreement is rather good up to 600 keV, which represents about 75% of the flux. However around 450 keV an underestimation is seen which is inherent to our subtraction method which fails to fully reproduce the flux depression due to the oxygen resonance around 400 keV: it induces an overestimation for a few following lower energy bins. The extraction method is still being improved. We aim to be less dependent upon the flux structures and to be able to measure neutron spectra up to higher energies. This technique will allow us to validate of our simulations in a subcritical medium.

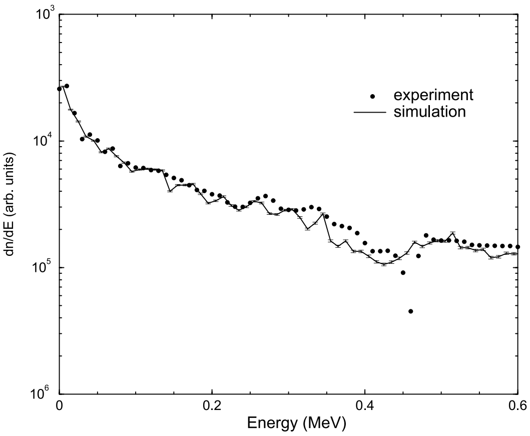

Figure 8. Neutron spectrum in the fuel zone simulated with MCNP for $k_{eff} = 0.97$ compared to the spectrum measured with a ^{3}He counter.

CONCLUSIONS

After having shown the failure of the point kinetics model to reproduce the k_p value typical of an ADS system, we proposed a more sophisticated model to obtain k_p from experiment by introducing the generation time distribution $P(\tau)$. From this simulated distribution and successive convolutions it is possible to calculate the time evolution of the neutron population for any value of k_p and to compare their logarithmic derivative to the experimental reactor response to a pulsed source. With this method the measured k_p values are found in good agreement with the expected ones. Especially it allows to obtain k_p in a time range where the decrease rate $\alpha(t)$ of the neutron population has not yet reached its asymptotic value. We also highlighted the importance of the choice of the detector in such measurements, which should be sensitive to fast neutrons, when its location in the reactor is too close to the reflector.

Concerning the neutron spectrometry, promising results are found with a ^{3}He proportional counter and the reconstruction of its response in the major part of the spectrum (i.e. below 600 keV). A work is in progress to improve the flux extraction above this energy where the detector response has been extrapolated.

These are very first results but all these techniques will be tested and improved in several different experimental conditions in the immediate future during the following of the experimental MUSE programme planned till the end of 2003.

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