



BE0000005

SCK • CEN

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

The use of Computed Neutron Coincidence Counting with Time Interval Analysis for the analysis of Fork-measurements on a fresh MOX-LWR fuel assembly under water

Task performed in the framework of the Belgian Support Programme to the IAEA for Safeguards Implementation (task n° A1068) in collaboration with the US Support Programme to the IAEA (task n° A1025) with the participation of the Euratom Safeguards Directorate.

P. Baeten, M. Bruggeman, R. Carchon

June 1998

BLG-770

3 13 / 3 9

11

**The use of Computed Neutron
Coincidence Counting with Time
Interval Analysis for the analysis
of Fork-measurements on a fresh
MOX-LWR fuel assembly under
water**

Task performed in the framework of the Belgian Support Programme to the IAEA for Safeguards Implementation (task n° A1068) in collaboration with the US Support Programme to the IAEA (task n° A1025) with the participation of the Euratom Safeguards Directorate.

P. Baeten, M. Bruggeman, R. Carchon

June 1998

BLG-770

Preface

This task was performed in the framework of the Belgian Support Programme to the IAEA for Safeguards Implementation under task number A1068 in collaboration with US Support Programme to the IAEA for Safeguards Implementation under task number A1025, and with the participation of the Euratom Safeguards Inspectorate.

The task is described by the IAEA as "Calibration of the LWR-MOX fresh fuel underwater neutron coincidence counter (UWCC) incorporating the existing modified fork detector and the improved underwater coincidence counter being developed under US SP task A1025".

In addition to the main objective of the exercise, which was the calibration of the different Fork-detectors, supplementary measurements were performed by SCK•CEN in order to investigate important instrumental parameters and their influence on the calculation of the triples-rate in view of the applicability of multiplicity counting in these measurement conditions. A Computed Neutron Coincidence Counting method (CNCC) in combination with the Time Interval Analysis interpretation model (TIA) was used for these measurements. This method has fargoing diagnostic capabilities compared to conventional electronics. These diagnostics have proven to be very helpful in deciding on the proper working of the detector and can thereby strengthen the confidence in the measurement result.

Abstract

Measurements have been made on MOX-LWR fuel under water. The aim of this study was to investigate the influence of different important parameters on measurement results for various fork-detectors.

Computed Neutron Coincidence Counting (CNCC) with Time Interval Analysis (TIA) was used for this study. The performance of the electronics for the different fork-detectors was studied by investigating the deadtime perturbed zone of the Rossi-alpha distribution in TIA. The measurements revealed anomalies in the performance of the electronics of the IAEA BWR and LANL fork-detector. The IAEA PWR fork-detector showed to work properly and the deadtime parameter was calculated.

The optimal setting for the predelay was investigated and it was found that a predelay of 10 μ s should be considered as an optimum between excluding from analysis data in the deadtime perturbed zone and keeping a high signal-to-noise ratio. For the shift register electronics used with the fork-detectors, only a predelay of 4.5 μ s was used.

The study of the predelay and the deadtime showed that the calculated triples-rate is strongly dependent on these parameters. An accurate determination of the triples-rate in this type of measurements has proven to be quite difficult and requires proper operation of the electronics, a correct predelay and an accurate deadtime correction formalism.

By varying the boron concentration in the water, the change of the decay time of the Rossi-alpha distribution was clearly observed. This change is due to the variation of the thermal multiplication. The variation of this decay time with the boron concentration proves that Böhnel's model for fast neutron multiplication is not valid in these measurement conditions and that a model for fast and thermal multiplication should be used in order to obtain unbiased measurement results.

In all these investigations CNCC with TIA proved to be a valuable tool in which parameter settings can be varied a posteriori and the optimal setting can be determined for each measurement. Moreover the display of the time intervals allows a simple control of the proper performance of the system.

1 Introduction

With the increasing trend to use mixed oxide (MOX) fuel in light water reactors (LWR), there is a necessity to store fresh MOX fuel assemblies in the reactor pool under water. The quantity of Pu in a 17x17 fuel assembly can amount up to 25 kg. Current safeguards regulations require a monthly verification of these fresh MOX assemblies. In order to overcome their inaccessibility, a fork-detector (developed initially for spent fuel verification) has been modified to incorporate ^3He -detectors appropriate to measure the coincident neutron emission from Pu in fresh fuel in the MOX assembly.

Measurements of fresh MOX-LWR type fuel assemblies under water have been made already in the past [1,2,3,4], with various devices on various types of fuel composition.

Besides the main objective of the exercise, the calibration of the different fork-detectors, measurements are performed to investigate several instrumental parameters of the fork-detectors used in the measurement campaign. In the calibration exercise, fixed settings for pre-delay, deadtime and die-away time are commonly used. These settings were determined from previous measurements. When the settings are not optimized or properly chosen, measurement results can be biased. By using Computed Neutron Coincidence Counting (CNCC) [5] combined with the Time Interval Analysis method (TIA) [6], the effect of these parameters on the measured data can be visualized and a more accurate and optimal determination of the different parameters can be obtained.

In measurements on fresh MOX fuel under water, neutron multiplication effects are an important source of measurement bias when not properly corrected for. Commonly, Böhnel's neutron multiplication model is used, but in fact this model is only valid for fast neutron multiplication. Since thermal multiplication is to be expected due to the strong moderating properties of the water, the validity of Böhnel's model is questioned. To investigate this point, the variation of the neutron die-away time was followed as a function of the boron concentration in the water.

In order to investigate whether multiplicity counting, based on the determination of the singles-, doubles- and triples-rate, can be used to obtain the $^{240}\text{Pu}_{\text{eff}}$ -mass in an absolute way e.g. without using a calibration, the LANL multiplicity counter and the Time Interval Analyser board used by SCK•CEN were applied. The use of multiplicity counting in these measurements would offer some advantages :

- no calibration of the instrument is required, which would obviate calibrations such as the one performed in this support task described in reference [7].
- the measurement range and measurement conditions have less impact on the measurement method since to some extent multiplicity counting acts like an autocalibration and is independent of the measurement situation.
- multiplicity counting allows to determine the triples-rate, which can be used to calculate a third unknown.

In order to determine the feasibility of multiplicity counting in fork-detector measurements on fresh fuel under water, CNCC with TIA is used to evaluate the influence of different important parameters on the calculation of the triples-rate. Since the triples-rate in high count-rate

applications is severely perturbed by counting losses due to deadtime effects, the setting of the predelay and the determination of the deadtime parameter are essential to obtain unbiased results.

2 Experimental set-up and equipment

2.1 The installation of the fuel in the water tank

In order to perform the measurements, we used a cylindrical stainless steel container with 1 m diameter and 1.2 m height. MOX fuel pins from the VENUS critical facility were set up in two mock-ups for respectively a PWR 17x17 fuel assembly and a BWR 9x9 fuel assembly. A 17x17 square assembly contains 264 pins (289 positions minus 25 empty places) and has a pitch of 12.6mm, whereas a 9x9 square configuration contains 80 pins (81 positions minus 1 central empty place) and has a pitch of 14.3 mm. The fuel has an active length of 50cm and was positioned at a height of 18.5cm from the bottom of the water tank. The water tank was filled up with water to a height of 76cm.

2.2 Description of the fuel assemblies

The characteristics of the fuel pins of the Venus critical facility used in this experiment are given below. For the updating, nuclear data have been used from reference [8].

The $^{240}\text{Pu}_{\text{eff}}$ mass loading is calculated according to the following expression :

$$^{240}\text{Pu}_{\text{eff}} = 2.52 f_{238} + f_{240} + 1.68 f_{242} \quad [1]$$

with f_i the weight percent of the corresponding Pu isotope i .

The Pu-isotopic composition, updated for 16 February 1998, is given in Table 1.

Isotope	Weight Abundance (%)
Pu-238	0.054
Pu-239	81.218
Pu-240	17.582
Pu-241	0.689
Pu-242	0.456
Am-241	2.432

Table 1 : *Plutonium isotopic composition on 16/2/1998*

This isotopic composition gives an equivalent plutonium-240 mass of $^{240}\text{Pu}_{\text{eff}} = 18.49\%$. The chemical composition of the MOX-LWR fuel rods is given by :

UO₂ - 97.3% of 2% ²³⁵U enrichment,
PuO₂ - 2.7%.

The total weight Pu per pin equals 6.9647g. A PWR assembly contains a maximum of 264 pins resulting in a maximum of 1838.68 g Pu or 36.77 g Pu/cm or 6.798 g/cm $^{240}\text{Pu}_{\text{eff}}$. A

BWR assembly contains a maximum of 80 pins resulting in a maximum of 557.18 g Pu or 11.14 g Pu/cm or 2.06 g/cm $^{240}\text{Pu}_{\text{eff}}$.

2.3 Influence of the boron concentration

To estimate the influence of the boron concentration on the MOX fork measurements, concentrated borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) solutions were added to the water, followed by homogenization and sample taking. For each concentration, a chemical analysis was made, yielding the following values: 530, 909, 1540, 2160 and 2250 ppm.

2.4 The measurement devices

2.4.1 The IAEA fork-detectors

The IAEA fork-detectors (PWR and BWR) consist of a supporting frame containing two square polyethylene arms, the geometry of which is particularly tailored so that it can embrace the fuel assembly. Two ^3He -tubes of 4 atm are placed symmetrically in the polyethylene inserts and no Cd-lining is applied. The two counters are connected to one preamplifier/discriminator (Amptek A-111A). For the electronic signal treatment, the JSR-12 and TIA-board from SCK•CEN were used [7].

2.4.2 The Los Alamos detector

The Los Alamos fork-detector has almost the same main design and characteristics as the IAEA fork-detectors. The LANL fork-detector has however an increased efficiency, since it has two ^3He -tubes per arm instead of one for the IAEA fork-detector and the ^3He -tubes in the LANL fork-detector have a pressure of 7.5 atm. The LANL fork-detector is also lined with a Cadmium-sheet to minimize the detection of thermal neutrons. The two detectors of one arm are connected to one preamplifier/discriminator (PDT 210A). Afterwards, the signals coming from the two preamplifiers are added to give one output signal. For the electronic signal treatment, the multiplicity counter from LANL and the TIA-board from SCK•CEN were used.

2.5 Computed Neutron Coincidence Counting with the Time Interval Analyzer board

A Computed Neutron Coincidence Counting system (CNCC) [5] is composed of two main components: a data acquisition component (Time Interval Analyser board) and a computing component. The acquisition component digitizes the pulse train in a sequence of numbers corresponding to the arrival times of the pulses or the time intervals between subsequent pulses. The computing component, a PC, is used for processing the data representing a digital representation of the pulse train. Data processing via software offers full flexibility in the number and type of quantities which can be measured. Using software modules, different coincidence and multiplicity counting algorithms can be implemented with the same system.

In this section the main features and modes of operation of the TIA acquisition board are discussed. The TIA board referred to is the commercial 16 channel model

GT659-TIA Time Interval Analyser manufactured by Guide Technology, Inc., (San Jose, USA). This TIA board plugs into the ISA slot of an ordinary PC. The standard 128 kB on-board memory of the TIA was upgraded to 2 MByte in order to have larger buffer capacity.

The GT659-TIA allows to continuously measure the arrival times of pulses up to pulse-rates of 2×10^6 pulses/s until memory is full (while accepting bursts of 50×10^6 pulses/s). All arrival times are stored in a fast First-In-First-Out (FIFO) memory. The time-base of the TIA board is 50 MHz which sets the maximum time resolution at $0.02 \mu\text{s}$ which is equal or superior to the resolution commonly obtained with a conventional shift register.

The arrival times of all triggering pulses are represented as 32-bit-numbers in the on-board memory. From these 32 bits, 16 bits are used to identify the channel at which the pulse was detected (16 channels are available). If two pulses arrive simultaneously (or in a time interval smaller than the time resolution of the TIA) in respectively two different channels, then their detection will generate a single time tag and the corresponding bits representing these channels are set high. The remaining 16 bits of the 32 bit representation of a pulse are used to represent the time at which the pulse is detected or is used for a dummy time tag to indicate that there is an overflow of the 16 bit clock counter when no pulses are detected in this period. The FIFO memory stores the arrival times of the triggering pulses according to a back-to-back measurement principle: this means that there is no deadtime between the recording of the end of one time interval, storing the information, and the beginning of the next time interval. This is very important in neutron coincidence counting since deadtime effects severely influence the coincidence and multiplicity counting. When using the software drivers delivered with the TIA board, the bookkeeping of dummy time tags and time calibration, is completely managed by the driver and is invisible to the programmer. We used the C-drivers and subroutines coming with the board to write a measurement programme running under DOS. The architecture of the TIA is shown in Figure 1.

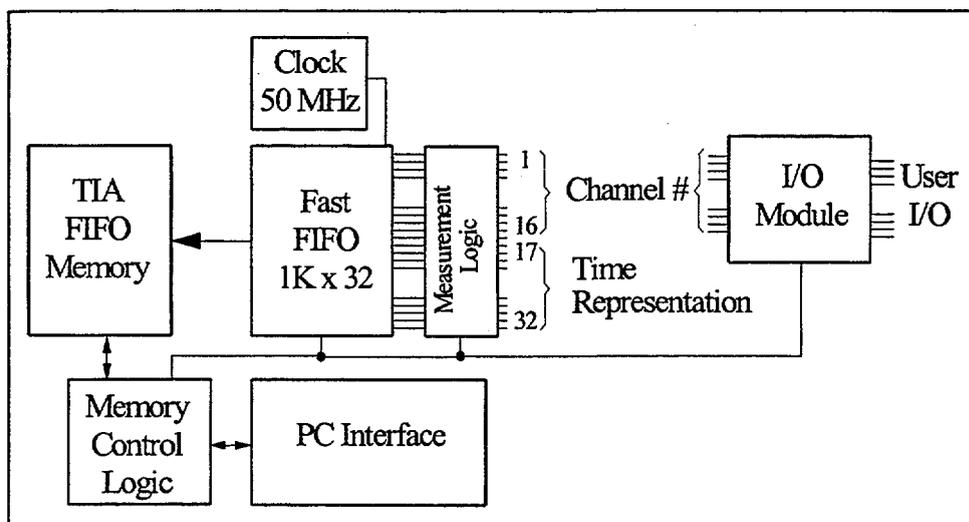


Figure 1 : Architecture of the TIA board, the principal component is a fast FIFO which accepts bursts of 50 Mpulses per second.

Once data is transferred from the FIFO memory of the TIA to the PC memory, software modules can be used to process the dataflow on-line, or data may be stored for processing at a later time in the list mode operation. To calculate the Central Process Unit (CPU) time actually needed to do on-line processing of the incoming data, the acquisition time to store the data in the PC memory and the subsequent processing time have to be known. The CPU time devoted to data processing, however is a function of the specific software used to implement the coincidence counting algorithms. The CPU time devoted to this specific task is also a function of the CPU performance index of the PC. We use a Pentium 200 MHz which allows a transfer of a data block representing 1024 pulses from the TIA-board to the PC memory in 21 ms with 16 channels enabled.

Figure 2 gives the relative measurement time, this means the ratio of the actual measurement time needed to acquire and process a pulse train divided by the effective time corresponding to the time length of this pulse train, as a function of the mean pulse rate. For on-line processing this ratio is ideally smaller than 1 requiring that the software processing of the data is faster than the incoming pulse rate. The curves shown on Fig. 2 are for a CNCC algorithm based on a multiplicity selective Rossi-alpha technique, called Time Interval Analysis (TIA) [6] which will be briefly explained in the following paragraph. The curves indicated with MC(600 μ s) and MC(300 μ s) are for multiplicity counting (TIA) with a time window of 600 μ s and 300 μ s respectively. The curves indicated as CC are for coincidence counting (Shift Register) in time windows of respectively 300 μ s and 600 μ s. Figure 2 shows that on-line CNCC with this technique is applicable up to count-rates of 30 kpulses/s.

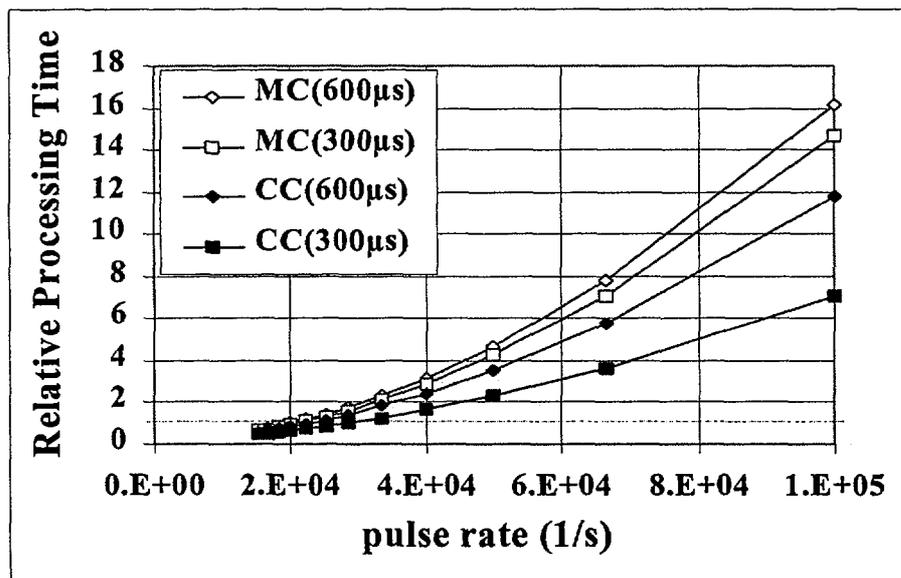


Figure 2 : Relative Processing Times for a 200 MHz Pentium computer for the implementation of different algorithms: CC= coincidence counting (SR), MC = multiplicity counting (TIA) for respectively (300 and 600 μ s).

Since the average count-rate of a measurement performed with the Fork-detectors in this measurement campaign, always well exceeded the 30kpulses/s, the reading and processing time exceeded several times the time length of the pulse train. The on-board memory allows

to store 2Mbyte of pulse information, which is continuously read out by the computer. The memory is filled faster than it is read out and the measurement stops when the memory is full.

The data is then transferred to the computer. During this time the measurement is stopped and restarts when the on-board memory has been emptied. This limits the use of CNCC with a

TIA-board to low count-rate applications and suggests that for high count-rate applications a hardware version of the vital software modules has to be developed.

However, CNCC with Time Interval Analysis offers several advantages with respect to conventional hardware and dedicated electronics. It facilitates the access to different instrumental parameters (deadtime, die-away time,..), allows a more optimal parameter setting (pre-delay, ..) and offers improved diagnostic capabilities. Also in other nuclear applications [8,9], Time Interval Analysis has proven to be an excellent technique to determine more accurately the deadtime parameter and to detect anomalies in electronic performances. The different interesting aspects of CNCC will be illustrated in the following paragraphs. In the next paragraph, the Time Interval Analysis method (TIA) which is used in connection with CNCC will be briefly explained.

3. The Time Interval Analysis method (TIA)

The theoretical background of the Time Interval Analysis method based on Rossi-alpha distributions has already been explained in another paper [6] and only the main principles will be reproduced here.

The time intervals recorded with the TIA board allow to compute and visualise what is known as the Rossi-alpha distribution for the detected pulse train. The Rossi-alpha distribution gives the distribution of time intervals between a pulse –which is assumed to arrive at time zero– and all its neighbour pulses coming at later times and laying in a predefined time window W . Under the assumption that the neutron population decay is mono-exponential, it has the following form:

$$S_1(t) = A_1 + R_1 e^{-\frac{t}{\tau}} \quad (t \geq W) \quad (2)$$

with :

- A_1 : the time independent component expressing the accidental coincidence count-rate,
- R_1 : the amplitude (count-rate) due to real coincidences,
- τ : the die-away time of the detector assembly.

The "R + A" and "A" counts commonly measured with a shift register (SR), are time integrated quantities obtained from the distribution described by the equation (1). The SR electronics however does not allow to visualise $S_1(t)$ nor to analyse the detailed time behaviour of this function. From the Rossi-alpha distribution recorded with the TIA the real coincidence count-rate can be obtained in a similar way as with the SR via time integration, but can also be

computed by mathematically fitting the curve $S_1(t)$. Via a non-linear fitting, the parameters A_1 , R_1 and τ can be directly determined.

In quite a similar way a two-dimensional Rossi-alpha distribution can be defined and computed from an actual pulse train. The two-dimensional Rossi-alpha distribution registers only detected pulse multiplets with a pulse multiplicity equal to or exceeding 3 (triple correlation). The time distribution of the pulse multiplets is recorded with two time axis and two equal time windows

W . A pulse multiplet will only be recorded when the condition is met that the time interval between a triggering pulse and a second pulse is smaller than W and the time interval between this second pulse and a third pulse is also smaller than W . The first condition is measured on a time axis t_1 , the second on a time axis t_2 . The mathematical expression for the two-dimensional Rossi-alpha distribution as a function of the time parameters t_1 and t_2 is -under the assumption of a mono-exponential decay of the neutron population- given by:

$$S_2(t_1, t_2) = A_2 + C_2(e^{-\frac{t_1}{\tau}} + e^{-\frac{t_2}{\tau}} + e^{-\frac{t_1+t_2}{\tau}}) + R_2 e^{-2\frac{t_1}{\tau}} e^{-\frac{t_2}{\tau}} \quad (3)$$

with

- A_2 : the count-rate due to accidentally correlated pulse multiplets,
- C_2 : the count-rate due to pulse triplets or higher order pulse multiplets of mixed origin e.g. containing a correlated pulse pair accidentally time-correlated with a singlet,
- R_2 : the count-rate due to real coincident pulse multiplets,
- τ : the die-away time as given in equation (2).

The two-dimensional Rossi-alpha distribution is also computed from the digitized pulse train and is represented as a two-dimensional distribution. At the end of the measurement, this distribution is analysed making use of the value of τ obtained from the analysis of $S_1(t)$ and a least-squares fitting of the parameters A_2 , C_2 and R_2 from $S_2(t_1, t_2)$.

The quantities R_1 and R_2 together with the measured total count-rate allow to build a system of three equations from which the fission-rate and two other unknowns e.g. the multiplication factor and the (α, n) -neutron production-rate can be inferred [6]. From the fission-rate, the $^{240}\text{Pu}_{\text{eff}}$ -mass can be derived.

4 Deadtime effects observed with TIA for the different fork-detectors

4.1 Determination of the deadtime parameter with TIA

In high count-rate applications and multiplicity selective coincidence counting techniques, counting losses due to deadtime effects are an important source of measurement bias when not properly corrected for [9]. A deadtime correction formalism was developed for TIA [9]. All deadtime correction procedures make use of a deadtime parameter δ , describing the average minimum time between two events required to count two events as two separate pulses.

Methods based on Time Interval Analysis [10,11] have become an interesting tool for the determination of deadtime parameters. Using CNCC with TIA, the deadtime parameter of a single measurement chain assembly can easily be determined from the deadtime perturbed zone in the one-dimensional Rossi-alpha distribution of a random source by the following expression [9] :

$$\delta = \left(1 - \frac{\int_0^t S_1(t, \delta) dt}{S_1(\delta)t} \right) \cdot t \quad [4]$$

with : $S_1(t, \delta)$: the observed one-dimensional Rossi-alpha distribution in the presence of deadtime effects,
 $S_1(\delta)$: the constant count-rate of the one-dimensional Rossi-alpha distribution outside the deadtime perturbed zone,
 t : time arbitrarily chosen after the end of the deadtime perturbed zone.

The deadtime effects for the three different fork-detectors used in the measurement campaign are investigated.

4.2 Deadtime effects in the IAEA PWR and BWR fork detectors

Figure 3 represents the one-dimensional Rossi-alpha distribution for respectively the IAEA PWR and BWR fork-detector in a small time window starting at $t=0$.

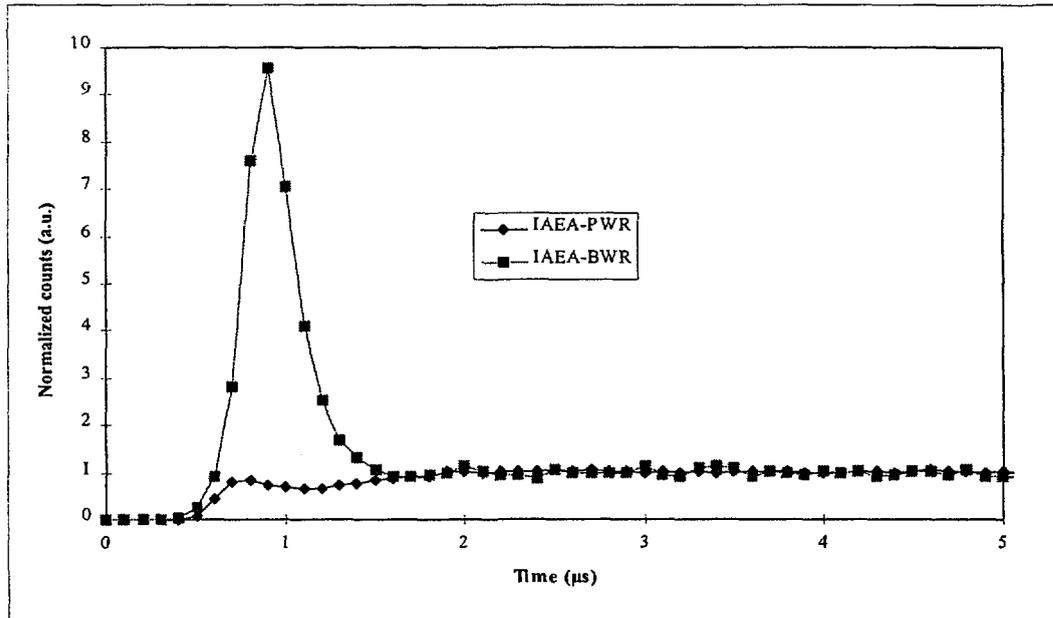


Figure 3 : *Deadtime effects in the 1-D Rossi-alpha distribution for the IAEA PWR and BWR fork-detector*

Figure 3 shows that the deadtime perturbed zone for the IAEA PWR fork-detector is characterized by a smooth transition from zero to the constant value after approximately $2\mu\text{s}$. This evolution in the deadtime perturbed zone is to be expected because :

- for a single chain detection circuit no counts are registered in the 1-D Rossi-alpha distribution when two neutrons are detected very close together in time,
- a continuous and smooth transition from zero to the constant count-rate exists, since the actual pulse shape is not constant in time and shows partial overlapping of pulses.

The investigation of the deadtime perturbed zone for the IAEA PWR fork-detector suggests that the detector and associated electronics are working properly. The deadtime parameter for the IAEA PWR fork-detector calculated with expression (4) equals $\delta=0.68\mu\text{s}$. To correct for counting losses due to deadtime effects, this deadtime parameter should be used in combination with the deadtime correction formula derived in reference [9].

From Figure 3, it can be seen that deadtime effects for the IAEA BWR detector are quite different. A large spike (anomaly) can be observed in the deadtime perturbed zone. The presence of this spike clearly indicates that something is wrong with the detector and/or associated electronics. From experience we know that the presence of such a spike in the deadtime perturbed zone can mostly be attributed to double pulsing occurring in the preamplifier/discriminator. The double pulsing results from a distortion of the pulse shape in such a way that the same pulse triggers twice. A typical distorted pulse-shape is represented in Figure 4.

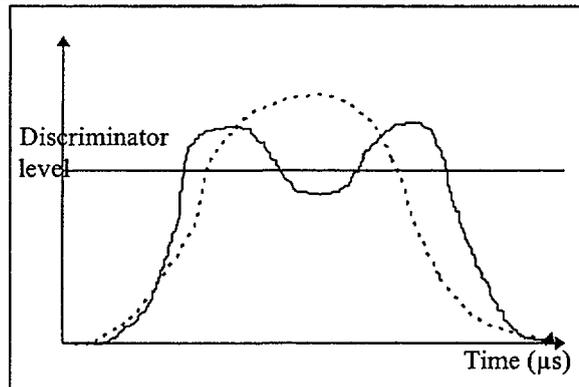


Figure 4 : *Ideal and distorted analogue pulse-shape*

Figure 4 shows that the distorted analogue pulse will cause twice a leading edge triggering at the discriminator level, resulting in two separate TTL-pulses which are only about $1\mu\text{s}$ separated in time. The pulse-distortion often results from a saturation of the preamplifier/amplifier.

A possible cause of this problem was later identified as being the replacement of the original ^3He -tubes of the BWR fork-detector by ^3He -tubes delivered by the Euratom Inspectorate. Although the tubes from the Euratom Inspectorate had other characteristics, the amplifier gain was never adjusted. In the scope of the calibration exercise, it was however decided not to change the amplifier gain/discriminator level, since measurements were already performed in the past with this detector and these electronic settings.

Double-pulsing not only has an effect in the deadtime perturbed zone of the Rossi-alpha distribution, but also distorts the Rossi-alpha distribution at times $t \gg \delta$, since the Rossi-alpha distribution is in fact an autocorrelation function. When indeed a second event occurs some considerable time after the double pulsing event, the time interval between those two events will be counted twice instead of once due to the almost negligible time between the two triggers of the double pulse event. Since different combinations of normal events and double pulse events are encountered in a real pulse train, the exact behaviour of this effect cannot exactly be predicted or calculated. Hence, no correction can be applied and the magnitude of

the effect cannot easily be estimated. Therefore a predelay which eliminates the spike from the data used in the analysis will not solve the problem, since the effect of double pulsing still remains present at later arrival times in the Rossi-alpha distribution.

When calibrations and actual measurements are performed in the same conditions, the effect has limited consequences. When however absolute measurements are the objective, the elimination of the spike, by adjusting the gain of the associated electronics, is a *conditio sine qua non* to obtain unbiased measurement results.

No deadtime parameter can be calculated IAEA BWR fork-detector, since the deadtime perturbed zone is too much distorted by the presence of the spike.

4.3 Deadtime effects in the LANL fork-detector

The deadtime perturbed zone of the one-dimensional Rossi-alpha distribution for the LANL fork-detector is represented in Figure 5.

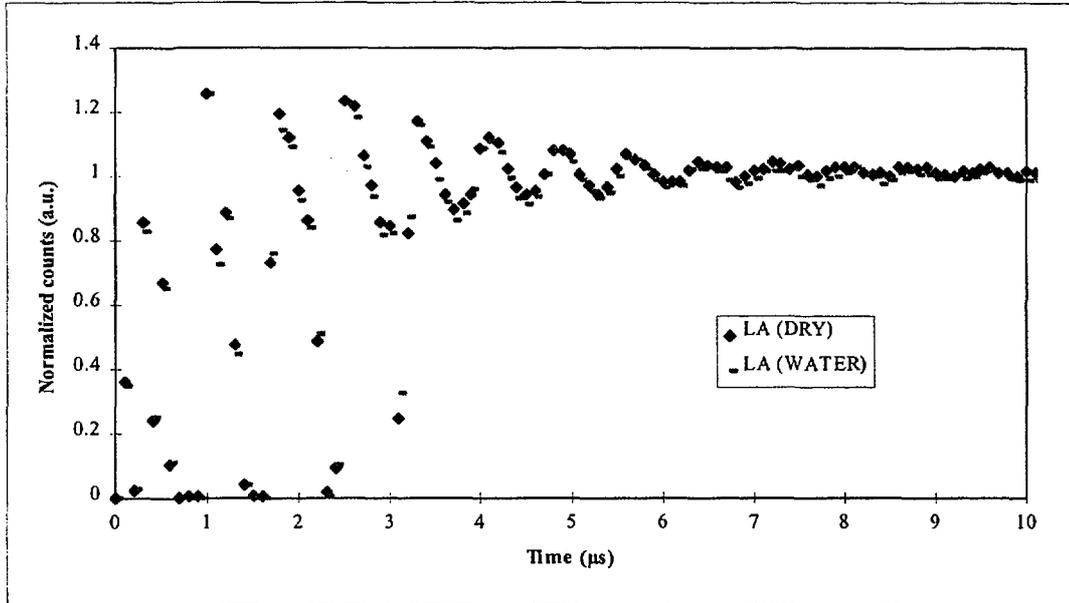


Figure 5 : *Deadtime effects in the 1-D Rossi-alpha distribution for the Los Alamos fork measured in a dry environment and under water*

The LANL fork-detector was once used in a dry environment (empty tank) and a second time under water. Figure 5 immediately shows that both experiments give the same typical behaviour in the deadtime perturbed zone. The observed evolution of the Rossi-alpha distribution in the deadtime perturbed zone has a very peculiar shape corresponding to a damped oscillation. No direct explanation can be given for this peculiar shape and further investigation is needed to determine its cause. Since the LANL fork-detector has two separate preamplifier/discriminators and the deadtime between two separate detection chains can be considered negligible compared to the deadtime of an individual chain, counts can be expected even for very small interval times. Although some counts exist very close to the time origin, the observed behaviour does not correspond to the expected one measured in other experiments [9]. Again these effects indicate that the electronics are not working properly. Electronic adjustments to obtain an appropriate signal should be envisaged in order to guarantee unbiased measurement results.

Since the analysis of the behaviour of the Rossi-alpha distribution in the deadtime perturbed zone does not corresponds with the expected behaviour, it has no sense calculating an equivalent deadtime parameter.

5 Study of the die-away time as a function of the boron concentration

Another important parameter is the die-away time describing the neutron die-away in the detection process. The die-away process is commonly considered to be mono-exponential. If this approximation is valid, the one-dimensional Rossi-alpha distribution is described by expression (2) and the die-away time of the detector assembly equals the decay time τ .

We will now investigate how the decay time changes when the boron concentration in the water is varied. Figure 6 represents the decay time as a function of the boron concentration in the water for respectively the LANL and IAEA PWR fork-detectors.

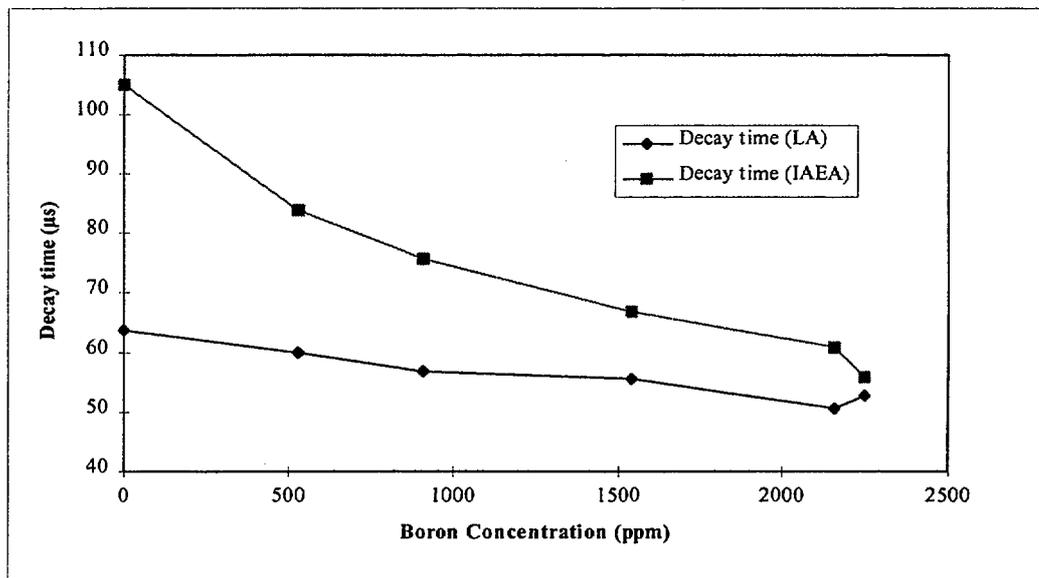


Figure 6 : Evolution of the decay time as a function of boron concentration (ppm) for the LANL and IAEA PWR fork-detector

For both detectors the observed decay time decreases as a function of the boron concentration. Since the decay time does not remain constant, it means that the assumptions made in equation (2) are not valid. The model expressed by equation (2) is based on the fact that there exists only fast multiplication [12]. In these measurements, thermal multiplication exists since neutrons are moderated in the water or polyethelene and then provoke thermal induced fissions. The thermal induced fissions are responsible for thermal multiplication which introduces an additional time delay between the detection of correlated neutrons resulting from induced fission chains.

From Figure 6 it can be seen that the decay time for the IAEA PWR detector is always larger than for the LANL detector which is due to the fact that the IAEA detector has no cadmium-lining. Detection assemblies without cadmium-lining still detect thermal neutrons, which have a thermal neutron lifetime. The increase of the boron concentration increases the thermal

absorption by the boron which decreases the mean thermal neutron lifetime and hence shortens the observed decay time. The decay time of the IAEA fork-detector decreases with approximately 50%, where the decay time of the LANL detector is only reduced by 20% when 2200 ppm boron is added to the water. The smaller decrease in die-away time for the

LANL-detector results from the fact that thermal multiplication effects only influence the observed die-away time through the detection of fast neutrons generated by thermal fissions, whereas for the IAEA-detector thermal multiplication effects are much more pronounced through the detection of thermal neutrons. At the maximum boron concentration, both detectors tend to show the same decay time. This is to be expected since thermal multiplication is strongly suppressed and the decay time is determined mainly by the polyethylene surrounding the detector.

If one fixed die-away time is used to represent the decay time independent of the boron concentration, an additional measurement bias will occur. Therefore, the actual decay time for every measurement will have to be monitored. CNCC with TIA allows to visualize the 1-D Rossi-alpha distribution from which one can inspect the observed decay to determine whether it is monoexponential. For the LANL fork-detector, a monoexponential behaviour of the neutron die-away process was observed with a decay time which is a function of the boron concentration. The die-away process for the IAEA fork-detector was found not to be monoexponential, which is due to detection of thermal neutrons. Since Böhnel's model for fast multiplication is not consistent with the observed behaviour of the die-away process, a multiplication correction based on Böhnel's model will be biased. The new model for fast and thermal multiplication [13,14] developed at SCK•CEN uses two exponentials where the decay times of the exponentials are respectively the instrumental die-away time of the neutron counter and the decay time of the thermal neutron population. Since the relative importance of both exponentials and the decay time of the thermal neutron population changes as a function of the boron concentration, a mono-exponential with varying decay time can be observed. This will especially be true when both decay times are of the same order of magnitude, which is to be expected in these measurement conditions. Hence, the new model for fast and thermal multiplication is much more consistent with the measurements, which will result in a more accurate multiplication correction. The implementation of this model in routine measurements will however still demand additional research on the specific quantities to be measured and the approximations to be made.

6 The predelay setting for the LANL fork-detector

Conventional coincidence techniques mostly use a fixed predelay to eliminate deadtime effects. Commonly, a predelay of $4.5 \mu\text{s}$ is chosen. Figure 7 represents the normalized 1-D Rossi-alpha distribution after subtraction of the accidental count-rate for measurements with different boron concentrations. The Rossi-alpha distribution was normalized with respect to the area under the curve.

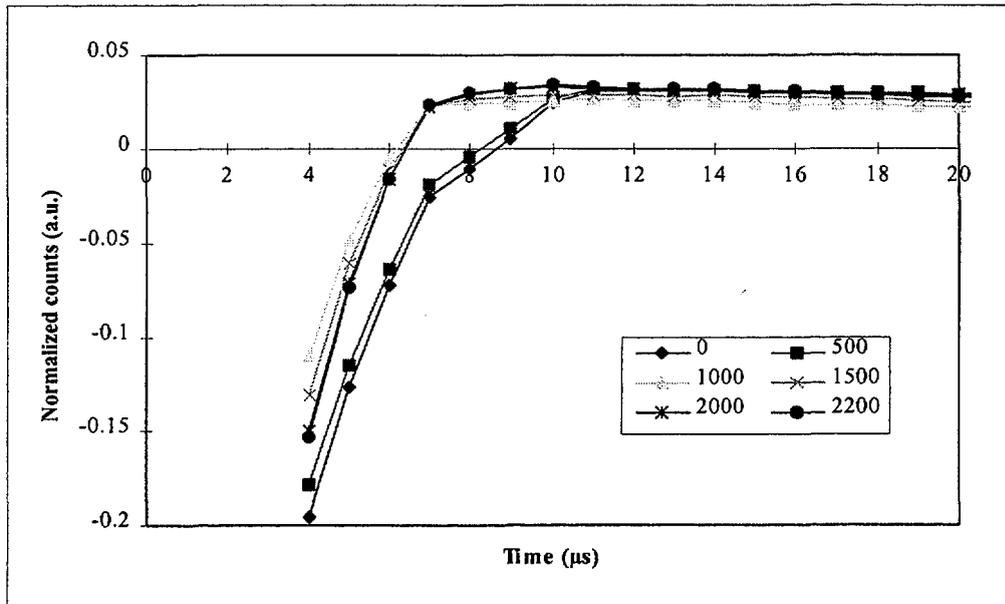


Figure 7 : *Deadtime perturbed zone of the normalized 1-D Rossi-alpha distribution for different boron concentrations with LANL fork-detector*

Figure 7 shows that the deadtime perturbed zone which should be excluded from analysis by the use of a predelay can strongly vary depending on the measurement conditions. If e.g. a predelay of $4.5 \mu\text{s}$ is used, a large negative contribution to the total real-rate will exist and the obtained real-rate will be underestimated. The choice of an accurate predelay which is large enough to exclude the deadtime perturbed region is therefore essential to guarantee unbiased measurements results. From Figure 7 it was concluded that a predelay of about $10 \mu\text{s}$ should be considered as an optimum between excluding a deadtime perturbed zone and keeping a high signal-to-noise ratio. For the two-dimensional Rossi-alpha distribution, the same predelay of $10 \mu\text{s}$ can be used since the extent of the deadtime perturbed zone for the two time axis t_1 and t_2 of the 2-D Rossi-alpha distribution is the same as in the case of the 1-D Rossi-alpha distribution.

It should again be noted that the use of CNCC plays an important role in obtaining a good estimate for the optimal predelay setting.

7 Determination of the triples-rate as a function of different parameter settings

In conventional fork-measurements on fresh fuel under water, coincidence counting is used to determine a calibration curve which relates the measured reals-rate to the $^{240}\text{Pu}_{\text{eff}}$ -mass. When multiplicity counting is envisaged, the triples-rate should also be measured. In this paragraph, the influence of different parameters on the determination of the triples-rate is studied in order to evaluate the future feasibility of using multiplicity counting.

Figure 8 shows the calculated triples-rate as a function of boron concentration for different values of the deadtime parameter and predelay.

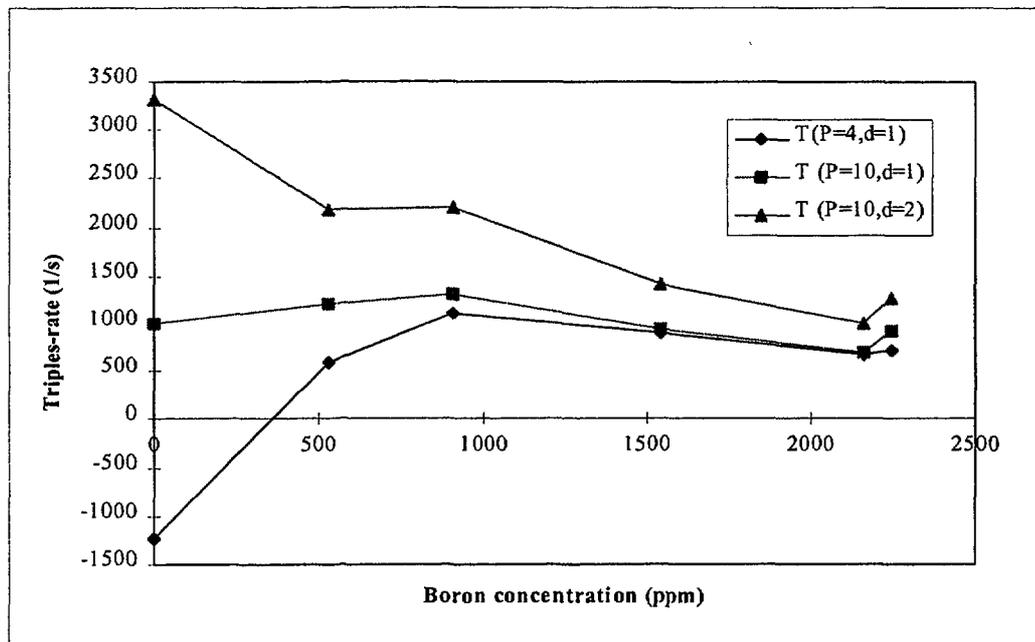


Figure 8 : Triples-rate as a function of boron concentration for different values of the deadtime parameter (d) and predelay time (P)

Figure 8 indicates that the calculated triples-rate strongly depends on the predelay and deadtime parameter. A predelay of $10 \mu\text{s}$ is necessary to obtain a positive value of the triples-rate at the lowest boron concentration. Figure 8 shows that the actual value of the deadtime parameter has a significant influence on the determination of the triples-rate. Therefore, an exact measurement of the deadtime parameter is necessary.

The fact that the calculated triples-rate strongly depends on the setting of the predelay and the deadtime suggests that an accurate determination of the triples-rate is not obvious and that further investigation and optimisation is necessary.

Again CNCC proved its usefulness in investigating the influence of different parameter settings. The flexibility of CNCC with TIA by setting the different parameters a posteriori makes it a lot more attractive and even superior to conventional techniques where dedicated electronics and a priori parameter settings are used.

8 Conclusions

Measurements have been made on MOX-LWR fuel under water and the performance of the fork-detectors and the influence of parameter settings on measurement results were investigated.

The measurement aspects observed with Computed Neutron Coincidence Counting system (CNCC) with Time Interval Analysis (TIA) are reported. The performance of the electronics for the different fork-detectors was studied by investigating in more detail the deadtime perturbed zone of the Rossi-alpha distribution. The investigation pointed out that the IAEA BWR and LANL fork-detector showed anomalies which were attributed to the malfunctioning of the electronics. The IAEA PWR fork-detector was found to work properly and the deadtime parameter could be measured.

Deadtime effects also define the predelay to be used in coincidence counting. It was experimentally verified with TIA that a predelay of 10 μ s should be used.

Different parameter settings for the predelay and the deadtime showed that the calculated triples-rate is strongly dependent on these settings. An accurate determination of the triples-rate in this type of measurements was estimated to be quite difficult and in order to use multiplicity counting in these conditions, additional research and optimisation is necessary.

By varying the boron concentration in the water, a change in decay time of the Rossi-alpha distribution was observed. This change is due to variation of the thermal multiplication. Böhnel's model for fast multiplication was found not to be consistent with the measurement results and a model involving fast and thermal multiplication should be used in these measurement conditions .

In all these investigations CNCC with TIA proved to be a very interesting tool. The visual information associated with this method has proven to be very helpful in identifying the proper working of the electronics. The way in which coincidence counting data is stored in TIA allows reevaluation of the doubles- and triples-rate with different predelays and allows to chose the most favourable settings.

References

- [1] A.J. Nelson, G.E. Bosler, R.H. Augustson, L.R. Cowder, *Underwater Measurement of a 15x15 MOX PWR-Type Fuel Assembly*, LA-11850-MS (ISPO-316) (1990).
- [2] G.E. Bosler, R.H. Augustson, L.B. Cowder, A.J. Nelson, *Underwater NDA Measurements on Fresh MOX Fuel Assemblies*, Proceedings 31th Annual Meeting INMM (1990).
- [3] R. Carchon, P. De Baere, B.G.R. Smith, A. Vandergucht, Y. Abushady, Y. Kulikov, A. Rachev, H.T. Schreiber, *Measurement of a fresh MOX-LWR type assembly under water*, SCK•CEN internal report BLG-633 (1991).
- [4] R. Carchon, P. De Baere, B.G.R. Smith, A. Vandergucht, Y. Abushady, Y. Kulikov, A. Rachev, H.T. Schreiber, *Measurement of a fresh MOX-LWR type assembly under water*, Proceedings 13th ESARDA Symposium on Safeguards and Nuclear Material Management - Avignon, France (1991).
- [5] M. Bruggeman, P. Baeten, W. De Boeck, R. Carchon, *Computed Neutron Coincidence Counting : Feasibility and Demonstration*, 19th ESARDA Symposium on Safeguards and Nuclear Material Management, Montpellier, France (1998)
- [6] M. Bruggeman, P. Baeten, W. De Boeck, R. Carchon, *Neutron coincidence counting based on time interval analysis with one- and two-dimensional Rossi-alpha distributions: an application for passive waste assay*, Nucl. Instr. and Meth. in Phys. Res. A 382, 511-518 (1996)
- [7] R. Carchon et al., *Measurement of fresh MOX-LWR type fuel assemblies under water, Calibration of IAEA PWR and BWR fork detectors*, SCK•CEN internal report BLG-766 (1998)
- [8] M. S. Krick, *Algorithms and software for data acquisition and analysis using thermal neutron coincidence counters within the IAEA's IFSS/NCC system*, LA-UR-88-1301, ISPO 256 (1988).
- [9] P. Baeten, M. Bruggeman, R. Carchon, *Single- and multi-deadtime parameter corrections of one- and two dimensional Rossi-alpha distributions for time interval analysis in neutron coincidence counting*, Nucl. Instr. and Meth. in Phys. Res. A 390, 345-358 (1997)
- [10] E. Schönfeld, H. Janssen, *Precise measurement of dead time*, Nucl. Instr. and Meth. in Phys. Res A 339, 137-143 (1994)
- [11] D. Schmidt, H. Klein, X. Haihong, *Time Interval Measurements and Deadtime Corrections in Coincidence Experiments*, PTB-report ISBN 3-89701-151-4 (1998)

-
- [12] K. Böhnel, *The effect of multiplication on the quantitative determination of spontaneously fissioning isotopes by neutron correlation analysis*, Nucl. Sc. and Eng. 90, 75-82 (1985)
- [13] P. Baeten, M. Bruggeman, R. Carchon, *Predictions of the neutron coincidence count-rate for a fresh UO₂-assembly with MCNP and a generalized multiplication correlation model*, SCK•CEN internal report BLG-764 (1998)
- [14] P. Baeten, M. Bruggeman, R. Carchon, *A generalized multiplication correlation model for the description of fast and thermal neutron multiplication in Neutron Coincidence Counting and Time Interval Analysis*, submitted to Nucl. Instr. and Meth. in Phys. Res. A (1998)