SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ÉTUDE DE L'ÉNERGIE NUCLÉAIRE

# MEASUREMENT OF A FRESH MOX-LWR TYPE FUEL ASSEMBLY UNDER WATER

## Comparison of the Euratom and LANL Fork devices

Task performed in the frame of the Belgian Support Programme to the IAEA for Safeguards Implementation (Task n° A414) with the support of the International Safeguards Division of the Office of Arms Control and Nonproliferation of the US Department of Energy.

R. Carchon, W. De Boeck (•)
G.P.D. Verrecchia (○), G.E. Bosler (□)
Y. Kulikov (■)

September 1994

• SCK•CEN - Mol (Belgium)
○ EURATOM - Safeguards Inspectorate (Luxembourg)
□ LANL - Los Alamos National Laboratory (USA)
■ IAEA - Department of Safeguards (Vienna)

BLG 654

# MEASUREMENT OF A FRESH MOX-LWR TYPE FUEL ASSEMBLY UNDER WATER

## Comparison of the Euratom and LANL Fork devices

Task performed in the frame of the Belgian Support Programme to the IAEA for Safeguards Implementation (Task n° A414) with the support of the International Safeguards Division of the Office of Arms Control and Nonproliferation of the US Department of Energy.

R. Carchon, W. De Boeck (•)
G.P.D. Verrecchia (○), G.E. Bosler (□)
Y. Kulikov (■)

September 1994

• SCK•CEN - Mol (Belgium)
○ EURATOM - Safeguards Inspectorate (Luxembourg)
□ LANL - Los Alamos National Laboratory (USA)
■ IAEA - Department of Safeguards (Vienna)

BLG 654

## Table of Contents

## List of Tables

**List of Figures**

## Abstract

Measurements have been made on LWR-MOX fuel under water with two devices: the modified LANL Fork detector and the modified Euratom Fork detector.

The aim of the exercise was to make a comparison of both devices in measuring the same fuel and to compare their normalized sensitivity.

The opportunity was taken to use multiplicity measurements to complete the shift-register measurements.

The boron content was varied, and the influence of absorbers and poisons was investigated.

This task was performed in the frame of the Belgian Support Programme to the IAEA for Safeguards Implementation under task number A 414 in collaboration with US-DOE and Euratom Safeguards Inspectorate.

## 1. Introduction

With the use of mixed oxide (MOX) fuel in light water reactors (LWR), there is an intention to store fresh MOX fuel assemblies in the reactor pool under water, before they are loaded in the reactor. The quantity of Pu in a 17x17 fuel assembly can amount to 25 kg.

This material could become inaccessible for verification. In order to overcome this safeguards inconsistency, a Fork detector for spent fuel measurement has been modified to incorporate the detectors appropriate to measure the neutron emission from Pu in fresh fuel in the MOX assembly.

Measurements of fresh MOX-LWR type fuel assemblies under water have been made in the past, by two devices: the LANL modified Fork detector on a 15x15 fuel assembly and the Euratom system on a 17x17 PWR fuel assembly.

Both experiments revealed a different normalized sensitivity, although the same neutron detectors were used.
During the IAEA review of the LANL report, a proposition was made for a comparison between the Euratom and the Los Alamos Fork detectors on the same fuel and with the same experimental conditions.

In October 1993 both the Euratom and the Los Alamos Fork detectors were used to assay a fresh MOX-type fuel assembly in a 17x17 configuration, composed of fuel from the VENUS critical facility.

In all experiments an adapted Fork-type detector was used wherein fission chambers were replaced by $^{3}$He tubes. Shift-register electronics from Euratom and LANL and the LANL multiplicity counter were used, revealing total neutrons, real coincidence neutrons, and, where relevant, multiplicity neutrons. The influence of removing pins and adding poison rods was investigated.

The boron concentration in the water was increased from 0 to approximately 2200 ppm with one intermediate step at 1500 ppm. The influence on totals and reals was examined.

Under real conditions, it is necessary to remove fuel from the storage rack, either partially or completely.

Equipment and experimental setup are described in Chapter 2.
Both systems have been tested to gain an idea of the performance of the system under field conditions.
Fuel from the VENUS critical facility of SCK•CEN was used, as described in Chapter 3, and a full account of the experimental results is given in Chapter 4.

## 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 stainless steel container 1 m in diameter and 1.2 m in height. MOX fuel pins from the VENUS critical facility were set up in a mock-up simulating a real 17x17 LWR fuel assembly. The characteristics of the fuel are given in Chapter 3.

In order to assure the safety of the operation, the $k_{eff}$ of the system was calculated with the SCALE-2 computer code. A 17x17 square configuration (Fig. 3), containing 264 pins (289 positions less 25 empty places) and having a pitch of 12.6 mm, yielded a $k_{eff} = 0.727 \pm 0.004$. Although the calculation yielded confidence in the safety of the undertaking, criticality was approached gradually, see Fig. 1, to assure that the subcritical state was maintained [1].

The evolution of the neutron count rate, emitted by the fuel assembly as the water level increased, is given in Fig. 1. The node at 16 cm is caused by the positioning of the $BF_3$ counter at the bottom of the assembly. If the $BF_3$ counter is placed at the middle of the assembly, a smoother graph [2,3] is obtained.
It is clear that, if the water is sufficiently high, the curve stabilizes, because the neutron count rate is no longer affected.

This procedure was followed to start the exercise, and in the follow-up, when any change in the pin configuration was made.

### 2.2. The equipment: the modified Fork detector

#### 2.2.1. The Euratom Fork detector

To make the Euratom detector we started with the existing Fork II detector, routinely used for the verification of irradiated fuel [4], and made a number of modifications as in the 1990 exercise [2]:

- the relatively insensitive fission chambers (Centronic type FC167, 0.12 c/n*cm$^2$*s) have been replaced by $^3$He counters (Reuter-Stokes type RS-P4-0805-223, 20 c/n*cm$^2$*s). The two $^3$He tubes are placed symmetrically in the polyethylene inserts and no Cd shielding is applied. Two pairs of counters are wired separately (representing an adequate performance check), but both signals can be added and treated together, improving count rate and statistics.

- a gross gamma measurement is no longer required, so the ionization chambers were removed.

- it was decided to readjust the discriminator settings of the original AMPTEK A-111A's and to adjust them for the lower output pulse of the $^3$He counters. They were moved inside the Fork II head. The lead shield for the preamplifiers was no longer required, so the shield and stainless steel covers were replaced by two blind flanges.

- signals were transmitted to the HLNCC electronics shift-register, and totals and reals count rates were obtained.

Data are produced as in the traditional HLNCC experiment. This electronics is used throughout the measurements.

- a general view of the electronic connections is given in Fig. 2.

### 2.2.2. The LANL Fork detector

For the LANL detector, the Fork version #1 [5] was chosen.

This detector contains nonstandard polyethylene inserts not wrapped in cadmium and two $^{3}$He tubes per detector arm. The system is completed with a $^{252}$Cf detector to determine the boron concentration of the water bath based on a well-defined, well-calibrated source-to-detector configuration that is not dependent on the pin configuration of a fuel assembly and that uses an external source. In this Fork #1 detector different $^{3}$He counters and similar AMPTEKs have been used as in the Euratom Fork detector to result in a similar identical configuration.

The detectors are of the type Reuter-Stokes type RS-P4-0806-207 having 18 c/n*cm$^{2}$*s.

## 2.3. The electronics used for signal treatment

For the electronic signal treatment, the JSR-11 from Euratom and the JSR-12 and multiplicity counter from LANL were used.

Multiplicity electronics provide the same data as a conventional shift-register coincidence module (JSR-11 or JSR-12) and, in addition, provide multiplicity distributions. The multiplicity measurements record the number of times each neutron multiplicity occurs in the coincidence gates. For example, if seven neutron pulses are in a coincidence gate when another neutron arrives then "1" is added to the counter that tallies multiplicities of seven. A multiplicity distribution is measured for the real-plus-accidental coincidence gate and for the accidental coincidence gate. The accidental gate measures random coincidences that must be removed from the real-plus-accidental coincidences to obtain the real multiplicity coincidences. A computer attached to the multiplicity module processes the data and generally uses only three numbers, namely, totals (singles), doubles, and the sum of all multiplicities higher than two. The additional information can be used for three parameter calibration. During this exercise we used the multiplicity module to collect data. The multiplicity data are not used in this report, but can be the subject of another report.

## 3. Description of the fuel assemblies

The fuel pins of the VENUS critical facility were used in this experiment and the characteristics are given in Table 1.

For this experiment a mock-up of a 17x17 array of pins was used. The grid has a pitch of 12.6 mm and is made in such a way that the pins can be easily removed (pin removal experiments) or replaced (absorber and poison rod experiments) or both.

The mock-up was positioned in a stainless steel cylindrical tank (diameter 1 m, height 1.2 m, water level 0.8 m).

The total quantity of Pu in the 17x17 assembly amounted to 1.805 kg.

## 4. Experimental results

### 4.1. Die-away time

The gate length of 128 μs was used, based on the measurements made in the 1990 exercise [2,3]. The die-away time of the system was not determined again, and there was no reason that it would have changed.

### 4.2. Influence of the high voltage on the neutron detector

The influence of the high voltage setting on the Euratom fork has not been investigated again, but based on the measurements of the 1990 exercise [2,3] the working voltage was set at 1650 V.
The influence of the high voltage on the neutron detector response was investigated for the LANL fork detector. Two high voltages of 1200 V and 1275 V were used with a zero boron concentration, whereas in the case of a 2200 ppm boron concentration, the voltage was extended to 1300 V and 1350 V as well. The results are given in Tables 2 and 3 for the different moderator configurations of zero and 2200 ppm boron.
The working voltage for the LANL fork was 1250 V.

Different configurations such as a full assembly, a full assembly with 4 pins missing, and a full assembly with 16 pins missing were used.

The voltage settings for the two devices as described yielded results that gave good comparison between the two Fork systems, both in reals coincidence count rate and in total neutron count rate.

### 4.3. Measurements in unborated water

#### 4.3.1. Calibration experiment

The only configuration used was the 17x17 mock-up with the 25 locations for control rods empty, as shown in Fig. 3, corresponding to commercially available assemblies.

Measurements with the Euratom system and the JSR-11 electronics on the full assembly, with 4 pins removed (Fig. 4) and with 16 pins removed (Fig. 5), were used to fit curves of fuel mass against reals coincidence count rate.

The experimental data concerning pin removal are given in Table 4. Removing four pins results in an increased thermalization process, increasing the reactivity of the assembly, resulting in a higher totals and reals count rate than the full 17x17 assembly. By removing 16 pins, the thermalization process also increases but balances with the diminished mass of Pu. This reduces the totals and reals count rate. In general the more central are the pins that are removed, the lower will be the effect per pin on the reals coincidence count rate.
The effect apparently is not linear but seems to depend on the location from which pins are removed.

The effective $^{240}$Pu linear density and the corrected reals rate were used to perform a DEMING curve fitting of the following form:

$$y = a1\ x + a2$$

where y is the reals coincidence rate and x is the $^{240}Pu_{eff}$ mass loading, given by the expression

$$^{240}Pu_{eff} = 2.52\ f_{238} + f_{240} + 1.68\ f_{242}$$

with $f_i$ the weight percent of the corresponding Pu isotope i. The combination of the Euratom Fork detector with the LANL multiplicity electronics system yielded similar values as displayed in Table 5.

The fitting parameters are taken from the 1990 exercise because they cover a much broader mass range, so these values are:

$$\begin{aligned} a1 &= 2.2185 \pm 5.4584E\text{-}2 \\ a2 &= -1.3949 \pm 3.2109E\text{-}1 \end{aligned}$$

The calibration parameters have been used to calculate the $^{240}Pu_{eff}$ mass, taking the multiplication corrected reals Rc as experimental values. The differences between calculated and declared values amount to ± 0.2%.

The 17x17 configuration has a very close Rc normalized to $^{240}Pu_{eff}$ density of 2.00 c/s/g/cm for the Euratom Fork. This value was moreover confirmed during the Euratom inspections on real size fuel.
Table 2 makes clear that the LANL measurement system yields similar values within a normalization constant, if no boron is present, but also with 2200 ppm boron, as seen in Table 3.

### 4.3.2. Absorber and poison effects

The influence of absorber and poison pins was investigated as well. We used AgInCd, $B_4C$, and pyrex pins that were introduced in the 17x17 mock-up as displayed in Fig. 6.
The results are given in Table 6 for the Euratom case in combination with the JSR-11 electronics and in Table 7 in combination with the multiplicity electronics.

The percentage reduction in the reals count rate is given in Table 8. The absorption process depends on the absorbers used and the reduction in the reals count rate. Pyrex has the lowest influence, (3% for 16 pins). Boron carbide ($B_4C$) provokes the most pronounced effect (10% for 16 pins).

## 4.4. Measurement in borated water

### 4.4.1. Pin removal experiment

The previous experiments, described in paragraph 4.3., were based on pin removal and

absorber rod influence in demineralized water.
The pool water, in actual reactors, contains approximately 2200 ppm boric acid, used to partially reduce neutron multiplication in the storage pond.

To estimate the influence of the boron concentration on the MOX Fork performance, concentrated boric acid solutions were added to the tank, followed by homogenization and sample taking. Target boron concentrations of 1500 ppm and 2200 ppm were in reality 1487 ppm and 2192 ppm as a result of chemical analysis. The influence of adding boron to the water is shown in Table 9.

Besides sample taking and chemical analysis, an independent NDA check could be used to verify the boron concentration of the pool. Those propositions are made elsewhere [5], consisting of either the use of detector type #2 that contains a bare $^{3}$He and a Cd-wrapped $^{3}$He chamber (similar to the Fork detector for spent fuel) or the use of a Cf source kept at a fixed distance from a $^{3}$He detector.
These methods were not applied in the described experiment.

All totals T and reals R and calculated multiplicity M and corrected reals rate Rc values are considerably affected by boron. The multiplication correction procedure [2,3,5]is the same as for unborated water, but a boron adjustment factor is determined from a calibration measurement, so that

$$Rc = R/r.M.f(B).$$

All these factors are given in Table 9 for the Euratom Fork in combination with the JSR-11 electronics system. The Rc value is used in the calibration equation to obtain an estimate of the $^{240}$Pu$_{eff}$ mass loading. At a 2200 ppm boron concentration the multiplication corrected reals count rate is reduced to half its value. This confirms the results from the experiment in 1990 [2,3].

For measurements in borated water, multiplication corrected reals count rates can be used effectively to determine the $^{240}$Pu$_{eff}$ mass loading in fresh MOX-LWR fuel assemblies. Results are given in Table 10.

A removal of 16 pins (6% of the assembly) results in a reduction of 4.1% for the corrected reals rate in demineralized water and 7.2% in a boric acid concentration of 2200 ppm in the case of the Euratom Fork and the JSR-11 electronics system.
These results confirm the 1990 exercise [2,3].

### 4.4.2. Absorber and Poison rods

The influence of added absorber and poison rods is given in Table 11. The reduction in the total count rate in the borated condition (2200 ppm) with 16 absorbers in the configuration shown in Fig. 6 is 13.5% for AgInCd, 17.0% for $B_4C$, and 6.1% for pyrex.
For the Euratom Fork in combination with the JSR-11 electronics, the multiplication corrected reals count rate Rc is more sensitive to absorber rods in demineralized water than to water with a boron concentration of 2200 ppm.

## 5. Conclusion and recommendations

An effort has been made to resolve the discrepancy in the normalized sensitivity of the LANL and Euratom modified Fork detectors, instruments that measure MOX-LWR fuel under water. Both Forks can easily be converted from the spent fuel configuration to the fresh fuel configuration within one hour. The instruments were brought together for an intercomparison test with a mock-up of VENUS fuel, simulating a 17x17 commercial PWR assembly.

The effects of fuel pin removal and the addition of neutron poison rods were investigated in water with an increasing boron concentration. Euratom and LANL shift register electronics were used as well as the LANL multiplicity counter, and yielded similar results.
A normalized corrected reals count rate of 2.00 c/s/g/cm was found for the Euratom Fork. These results confirmed the values obtained during the earlier experiments and also during the Euratom inspections on real size fuel.

The LANL Fork gave a confirmation of values obtained with the Euratom Fork. Different $^3$He counters were used in the LANL Fork, compared to the 1990 exercise. Agreement has been reached for both instruments on the same fuel.

The differences between the normalized corrected reals count rate of the Euratom and LANL Fork detectors that was found in the 1990 exercise, referred to different fuels that were used: VENUS fuel in the Euratom case and LANL fuel in the LANL case.
A definite answer to the mentioned differences can only be obtained by a test of both Forks on LANL fuel unless computer simulations could be made.

The removal of a number of pins corresponding to a 6% decrease in Pu content is clearly detectable based on evaluating the multiplication corrected count rates and confirming earlier measurements.

A correction coefficient can be established to account for the boron concentration in water. This correction factor does not fully coincide with that obtained in the 1990 exercise, and could require some further investigation.

Measurements on different fuel assembly configurations show very close values of multiplication corrected reals rates normalized to the linear specific weight of plutonium.

The effects of absorber-poison rods in the fuel assembly have been investigated for 3 cases: AgInCd, $B_4C$, and pyrex. Boron carbide ($B_4C$) has the highest neutron absorption effect, while pyrex has the lowest absorption effect. This is true as well for 0 ppm and 2200 ppm boron.

Poison rods obviously reduce the detector response, while limited pin removal increases this response. This effect disappears after multiplication correction.

## References

[1] S. Glasstone & A. Sesonske, "Nuclear Reactor Engineering", Van Nostrand Reinhold Co - 3rd Ed. (1981).

[2] 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", BLG 633 (May 1991).

[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", Proc. 13th ESARDA Symposium on Safeguards and Nuclear Material Management - Avignon, France, 14-16 May 1991.

[4] P. De Baere, R. Carchon, B.G.R. Smith, G.P.D. Verrecchia, "The construction of Fork detectors for irradiated fuel assemblies", Proc.11th ESARDA Annual Symposium on Safeguards and Nuclear Material Management - Luxembourg (1989).

[5] 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).

[6] G.E. Bosler, R.H. Augustson, L.B. Cowder, A.J. Nelson, "Underwater NDA Measurements on Fresh MOX Fuel Assemblies", Proc. 31th Annual Meeting INMM (1990).

[7] N. Ensslin, "A simple self-multiplication correction for In-Plant Use", Proc. 7th ESARDA Annual Symposium on Safeguards and Nuclear Material Management - Liège (1985).

## Acknowledgement

We acknowledge the help of J. Gerits in the preparation of the experimental set-up and the boric acid solutions and for assuring the editing of this report.
Thanks are due to H. Geens and L. Truyens for making the Venus fuel available and for preparing the poison rods.
The SCALE-2 calculations of the $k_{eff}$ of the experimental set-up were performed by G. Minsart.

## Appendix: multiplication correction formalism

Multiplication correction was applied, using the Ensslin formalism [7], in the following way :

$$Rc=\frac{R}{CF}$$

$$CF=M*r$$

$$r=\frac{R/T}{\rho_0}(1+\alpha)$$

$$\rho_0=0.0043$$

$$\alpha=\frac{134f_{238}+0.38f_{239}+1.41f_{240}+0.013f_{241}+0.02f_{242}+26.9f_{Am}}{(2.54f_{238}+f_{240}+1.69f_{242})\,10.2}$$

$$\alpha=0.6596$$

$$A=2.062(1+\alpha)=3.4220$$

$$AM^2+BM+C=0$$

$$B=1-A=-2.4220$$

$$C=-r$$

The numerical values can be found in the different Tables.

# TABLES

**Table 1: FUEL CHARACTERISTICS**

Pu isotopics/rod

| Isotope | 15 November 1966 | | 26 October 1993 | |
|---|---|---|---|---|
| | (g) | (wt%) | (g) | (wt%) |
| Pu-238 | 0.005 | 0.068 | 0.004 | 0.056 |
| Pu-239 | 5.547 | 79.247 | 5.543 | 81.073 |
| Pu-240 | 1.204 | 17.197 | 1.200 | 17.557 |
| Pu-241 | 0.213 | 3.044 | 0.059 | 0.858 |
| Pu-242 | 0.031 | 0.445 | 0.031 | 0.456 |
| Am-241 | | 0.075 | | 2.274 |
| Isotopic Composition (wt%) | U-234 | | 0.016 | |
| | U-235 | | 2.002 | ± 0.005 |
| | U-236 | | 0.013 | |
| | U-238 | | 97.970 | |
| Stoichiometry | | | 2.046 | ± 0.005 |
| Chemical Composition (wt%) | $UO_2$ | | 97.300 | |
| | $PuO_2$ | | 2.700 | ± 0.030 |
| Weight per rod (g) | U | | 5.000 | |
| | Pu | | 7.000 | |
| Fuel diameter (cm) | | | 0.902 | ± 0.004 |
| Fuel length (cm) | | | 50.000 | ± 0.500 |
| Cladding | | | SS 304 | |
| Cladding thickness (cm) | | | 0.038 | ± 0.002 |
| Linear Pu density (mg/cm) | | | 136.760 | |

## Table 2: Measurements with the LANL Fork device as a function of voltage setting
## October 1993 Exercise in Mol, Belgium
## LANL Fork & JSR-12

| Description | Number of Pu rods | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No boron, full assembly, 1200 V | 264 | 15912.04 | 4.21 | 1100 | 8.57 | 36.10 | 6.67 | 26.71 | 3.1687 | 84.6339 | 13.00 | 6.49 | 2.70 | 1.9494 |
| No boron, four pins missing, 1200 V | 260 | 15902.82 | 4.2 | 1143.28 | 8.57 | 35.56 | 6.57 | 27.78 | 3.2235 | 89.5369 | 12.77 | 6.38 | 2.77 | 1.9446 |
| No boron, 16 pins missing, 1200 V | 248 | 15553.38 | 4.16 | 1148.35 | 8.38 | 33.92 | 6.26 | 28.53 | 3.2614 | 93.0356 | 12.34 | 6.19 | 1.13 | 1.9708 |
| No boron, full assembly, 1275 V | 264 | 17766.45 | 4.44 | 1395.12 | 9.57 | 36.10 | 6.67 | 30.34 | 3.3510 | 101.6685 | 13.72 | 6.81 | -2.20 | 2.0582 |
| No boron, four pins missing, 1275 V | 260 | 17753.31 | 4.44 | 1420.06 | 9.57 | 35.56 | 6.57 | 30.91 | 3.3784 | 104.4094 | 13.60 | 6.76 | -2.94 | 2.0714 |
| No boron, 16 pins missing, 1275 V | 248 | 17391.81 | 4.4 | 1433.6 | 9.38 | 33.92 | 6.26 | 31.85 | 3.4236 | 109.0348 | 13.15 | 6.56 | -4.67 | 2.0993 |

## Table 3: Measurements with the LANL Fork device as a function of voltage setting for 2200 ppm boron
## October 1993 Exercise in Mol, Belgium
## LANL Fork & JSR-12

| Description | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Full assembly, 2200 ppm boron, 1200 V | 6849.82 | 3.38 | 213.85 | 4.52 | 36.10 | 6.67 | 12.06 | 2.2636 | 27.3044 | 13.03 | 4.16 | 2.46 | 1.1747 |
| Full assembly, 2200 ppm boron, 1275 V | 7677.07 | 0.44 | 269.66 | 0.62 | 36.10 | 6.67 | 13.57 | 2.3757 | 32.2408 | 13.92 | 4.40 | -3.52 | 1.2545 |
| Full Assembly; 2200 ppm boron, 1300 V | 7683.11 | 6.53 | 270.82 | 9.25 | 36.10 | 6.67 | 13.62 | 2.3791 | 32.4009 | 13.91 | 4.40 | -3.46 | 1.2537 |
| Full assembly, 2200 ppm boron, 1350 V | 10249.34 | 4.13 | 209.29 | 6.72 | 36.10 | 6.67 | 7.89 | 1.9124 | 15.0878 | 23.08 | 6.88 | -65.48 | 2.0806 |

## Table 4: Measurements with the Euratom Fork device in the calibration exercise

October 1993 Exercise in Mol, Belgium

Euratom Fork & JSR-11

| Description | Number of Pu rods | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No boron, full assembly | 264 | 15884.29 | 4.2 | 1071.47 | 8.52 | 36.10 | 6.67 | 26.06 | 3.1349 | 81.7027 | 13.11 | 6.54 | 1.91 | 1.9670 |
| No boron; four pins missing | 260 | 15882.11 | 0.89 | 1080.2 | 1.81 | 35.56 | 6.57 | 26.28 | 3.1462 | 82.6769 | 13.07 | 6.52 | 0.73 | 1.9898 |
| No boron; sixteen pins missing | 248 | 15577.42 | 4.16 | 1103.62 | 8.38 | 33.92 | 6.26 | 27.37 | 3.2029 | 87.6726 | 12.59 | 6.30 | -0.63 | 2.0099 |

## Table 5: Measurements with the Euratom Fork device and multiplicity counter

October 1993 Exercise in Mol, Belgium

Euratom Fork & Multiplicity counter

| Description | Number of Pu rods | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No boron, full assembly | 264 | 15905.60 | 3.77 | 1057.18 | 10.23 | 36.10 | 6.67 | 25.68 | 3.1148 | 79.9883 | 13.22 | 6.59 | 1.21 | 1.9824 |
| No boron; four pins missing | 260 | 15892.61 | 4.06 | 1089.16 | 7.51 | 35.56 | 6.57 | 26.48 | 3.1567 | 83.5846 | 13.03 | 6.50 | 0.97 | 1.9845 |
| No boron; sixteen pins missing | 248 | 15591.49 | 3.4 | 1125.51 | 4.39 | 33.92 | 6.26 | 27.89 | 3.2293 | 90.0673 | 12.50 | 6.26 | 0.02 | 1.9952 |

## Table 6: Measurements with the Euratom Fork device and JSR-11 with poison and absorber rods

### October 1993 Exercise in Mol, Belgium

### Euratom Fork & JSR-11

| Description | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No boron, full assembly | 15884.29 | 4.2 | 1071.47 | 8.55 | 36.10 | 6.67 | 26.06 | 3.1349 | 81.7027 | 13.11 | 6.54 | 1.91 | 1.9670 |
| No boron, full assembly, 16 Ag-In-Cd pins | 11519.03 | 3.5 | 434.67 | 6.19 | 36.10 | 6.67 | 14.58 | 2.4472 | 35.6789 | 12.18 | 6.12 | 8.20 | 1.8273 |
| No boron, full assembly, 16 B4C pins | 10801.14 | 3.46 | 364.52 | 5.8 | 36.10 | 6.67 | 13.04 | 2.3369 | 30.4711 | 11.96 | 6.02 | 9.69 | 1.7943 |
| No boron, full aasmbly, 16 pyrex pins | 13263.89 | 3.04 | 630.6 | 7.13 | 36.10 | 6.67 | 18.37 | 2.6966 | 49.5330 | 12.73 | 6.37 | 4.50 | 1.9095 |

## Table 7: Measurements with the Euratom Fork device and multiplicity counter with poison and absorber rods

### October 1993 Exercise in Mol, Belgium

### Euratom Fork & Multiplicity counter

| Description | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No boron, full assembly | 15905.60 | 3.77 | 1057.18 | 10.23 | 36.10 | 6.67 | 25.68 | 3.1148 | 79.9883 | 13.22 | 6.59 | 1.21 | 1.9824 |
| No boron, full assembly, 16 Ag-In-Cd pins | 11532.70 | 3.21 | 447.98 | 7.74 | 36.10 | 6.67 | 15.01 | 2.4769 | 37.1733 | 12.05 | 6.06 | 9.09 | 1.8075 |
| No boron, full assembly, 16 B4C pins | 10813.95 | 4.34 | 376.82 | 2.83 | 36.10 | 6.67 | 13.46 | 2.3678 | 31.8789 | 11.82 | 5.96 | 10.65 | 1.7729 |
| No boron, full assembly, 16 pyrex pins | 13268.51 | 2.12 | 648.93 | 0.71 | 36.10 | 6.67 | 18.90 | 2.7292 | 51.5716 | 12.58 | 6.30 | 5.50 | 1.8873 |

## Table 8: Reduction of the corrected reals count rate due to absorber pins

| | Euratom Fork + JSR-11 | Euratom Fork + Multiplicity counter |
|---|---|---|
| AgInCd | 7.6 % | 9.7 % |
| B4C | 9.6 % | 11.8 % |
| pyrex | 3.0 % | 5.1 % |

## Table 9: The influence of boron addition in the water

### October 1993 Exercise in Mol, Belgium

### Euratom Fork & JSR-11

| Description | Measured Boron Concent. (ppm) | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Corrected Reals Rate divided by Effective Pu-240 | Boron factor f(B) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No boron, full assembly | 0 | 15884.29 | 4.2 | 1071.47 | 8.55 | 36.10 | 6.67 | 26.06 | 3.1349 | 81.7027 | 13.11 | 6.54 | 1.9670 | 1.000 |
| 1500 ppm boron, full assembly | 1500 | 7782.90 | 2.94 | 273.22 | 4.19 | 36.10 | 6.67 | 13.56 | 2.3751 | 32.2146 | 8.48 | 4.45 | 1.2721 | 0.647 |
| 2200 ppm boron, full assembly | 2200 | 6705.46 | 2.73 | 195.8 | 3.61 | 36.10 | 6.67 | 11.28 | 2.2030 | 24.8542 | 7.88 | 4.18 | 1.1816 | 0.601 |

## Table 10: Measurements with the Euratom Fork and JSR-11 in borated water (removing 4 and 16 pins)

**October 1993 Exercise in Mol, Belgium**

**Euratom Fork & JSR-11**

| Description | Number of Pu rods | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2200 ppm, full assembly | 264 | 6711.75 | 2.73 | 190.35 | 3.61 | 36.10 | 6.67 | 10.96 | 2.1772 | 23.8573 | 7.98 | 4.23 | 36.63 | 1.1967 |
| 2200 ppm, four pins missing | 260 | 6587.56 | 2.71 | 185.07 | 3.54 | 35.56 | 6.57 | 10.85 | 2.1689 | 23.5430 | 7.86 | 4.17 | 36.46 | 1.1972 |
| 2200 ppm, sixteen pins missing | 248 | 6071.75 | 2.6 | 159.83 | 3.27 | 33.92 | 6.26 | 10.17 | 2.1131 | 21.4913 | 7.44 | 3.98 | 36.44 | 1.1874 |

## Table 11: The influence of absorber and poison rods in borated water

**October 1993 Exercise in Mol, Belgium**

**Euratom Fork & JSR-11**

| Description | Totals Rate (c/s) | Totals Rate Error (c/s) | Reals Rate (c/s) | Reals Rate Error (c/s) | Pu Linear Density (g/cm) | Effect. Pu-240 Linear Density (g/cm) | r | M | CF | Corr. Reals Rate (c/s) | Calculated Effective Pu-240 (g/cm) | Effective Pu-240 Mass Diff. (%) | Corrected Reals Rate divided by Effective Pu-240 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2200 ppm boron, full assembly | 6705.46 | 2.73 | 195.8 | 3.61 | 36.10 | 6.67 | 11.28 | 2.2030 | 24.8542 | 7.88 | 4.18 | 37.31 | 1.1816 |
| 2200 ppm, full ass., 16 B4C pins | 5568.28 | 2.49 | 109.56 | 2.99 | 36.10 | 6.67 | 7.60 | 1.8852 | 14.3315 | 7.64 | 4.07 | 38.88 | 1.1466 |
| 2200 ppm, full ass;, 16 Ag-In-Cd pins | 5799.34 | 2.54 | 126.09 | 3.12 | 36.10 | 6.67 | 8.40 | 1.9595 | 16.4608 | 7.66 | 4.08 | 38.78 | 1.1489 |
| 2200 ppm, full ass., 16 pyrex pins | 6298.76 | 2.65 | 148.9 | 3.39 | 36.10 | 6.67 | 9.13 | 2.0248 | 18.4939 | 8.05 | 4.26 | 36.14 | 1.2076 |

# FIGURES

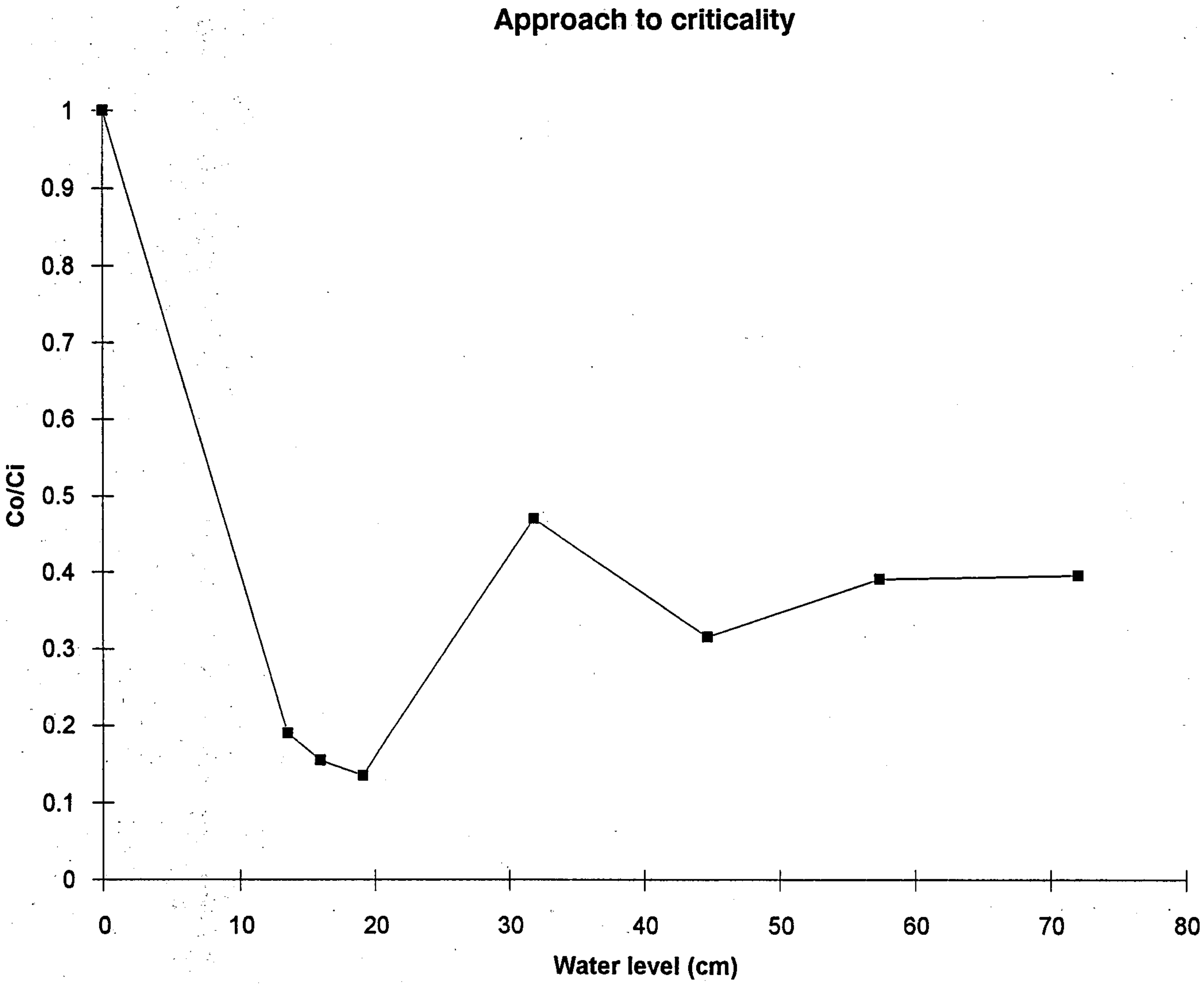

Fig. 1: Approach to criticality

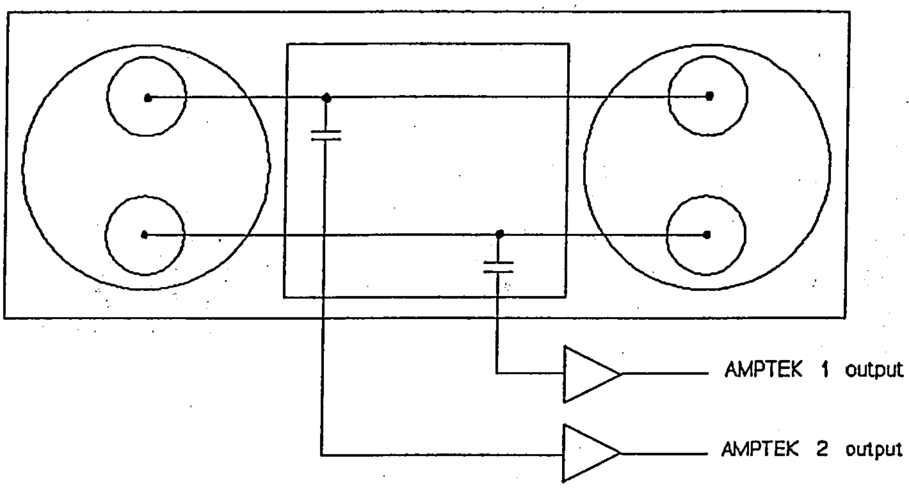

Fig. 2 : Electronic connections from the $^3$He counters to the AMPTEKs

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | | |
| 3 | | | | | | X | | | X | | | X | | | | | |
| 4 | | | | X | | | | | | | | | | X | | | |
| 5 | | | | | | | | | | | | | | | | | |
| 6 | | | X | | | X | | | X | | | X | | | X | | |
| 7 | | | | | | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | | | | | | |
| 9 | | | X | | | X | | | X | | | X | | | X | | |
| 10 | | | | | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | | | | | | |
| 12 | | | X | | | X | | | X | | | X | | | X | | |
| 13 | | | | | | | | | | | | | | | | | |
| 14 | | | | X | | | | | | | | | | X | | | |
| 15 | | | | | | X | | | X | | | X | | | | | |
| 16 | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | | | | | | |

**X** = Empty fuel pin location (simulating control rod thimble)

Fig.3 : 17 X 17 configuration (264 pins)

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | | |
| 3 | | | | | | X | | | X | | | X | | | | | |
| 4 | | | | X | | | | | | | | | | X | | | |
| 5 | | | | | | | | | | | | | | | | | |
| 6 | | | X | | | X | | | X | | | X | | | X | | |
| 7 | | | | | | | O | | | | O | | | | | | |
| 8 | | | | | | | | | | | | | | | | | |
| 9 | | | X | | | X | | | X | | | X | | | X | | |
| 10 | | | | | | | | | | | | | | | | | |
| 11 | | | | | | | O | | | | O | | | | | | |
| 12 | | | X | | | X | | | X | | | X | | | X | | |
| 13 | | | | | | | | | | | | | | | | | |
| 14 | | | | X | | | | | | | | | | X | | | |
| 15 | | | | | | X | | | X | | | X | | | | | |
| 16 | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | | | | | | |

**X** = Empty fuel pin location (simulating control rod thimble)

**O** = Removed pins

Fig. 4: 17 X 17 configuration with 4 pins removed (260 pins)

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | | |
| 3 | | | | | | X | | | X | | | X | | | | | |
| 4 | | | | X | | | | | | | | | | X | | | |
| 5 | | | | | | | | | | | | | | | | | |
| 6 | | | X | | | X | | | X | | | X | | | X | | |
| 7 | | | | | | | O | O | O | O | O | | | | | | |
| 8 | | | | | | | O | | | | O | | | | | | |
| 9 | | | X | | | X | O | | X | | O | X | | | X | | |
| 10 | | | | | | | O | | | | O | | | | | | |
| 11 | | | | | | | O | O | O | O | O | | | | | | |
| 12 | | | X | | | X | | | X | | | X | | | X | | |
| 13 | | | | | | | | | | | | | | | | | |
| 14 | | | | X | | | | | | | | | | X | | | |
| 15 | | | | | | X | | | X | | | X | | | | | |
| 16 | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | | | | | | |

**X** = Empty fuel pin location (simulating control rod thimble)

**O** = Removed pins

Fig. 5: 17 X 17 configuration with 16 pins removed (248 pins)

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | | |
| 3 | | | | | | @ | | | @ | | | @ | | | | | |
| 4 | | | | @ | | | | | | | | | | @ | | | |
| 5 | | | | | | | | | | | | | | | | | |
| 6 | | | @ | | | X | | | X | | | X | | | @ | | |
| 7 | | | | | | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | | | | | | |
| 9 | | | @ | | | X | | | X | | | X | | | @ | | |
| 10 | | | | | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | | | | | | |
| 12 | | | @ | | | X | | | X | | | X | | | @ | | |
| 13 | | | | | | | | | | | | | | | | | |
| 14 | | | | @ | | | | | | | | | | @ | | | |
| 15 | | | | | | @ | | | @ | | | @ | | | | | |
| 16 | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | | | | | | |

**X** = Empty fuel pin location (simulating control rod thimble)
**@** = Poison rods ( AgInCd, Pyrex, B4C )

Fig.6 : 17 X 17 configuration (264 pins), with 16 poison rods