Method to Calibrate Fission Chambers in Campbelling Mode

Benoit Geslot, Troy C. Unruh, Philippe Filliatre, Christian Jammes, Jacques Di Salvo, Stéphane Bréaud, and Jean-François Villard

***Abstract*—Fission chambers are neutron detectors which are widely used to instrument experimental reactors such as material testing reactors or zero power reactors. In the presence of a high level mixed gamma and neutron flux, fission chambers can be operated in Campbelling mode (also known as "fluctuation mode" or "mean square voltage mode") to provide reliable and precise neutron related measurements. Fission chamber calibration in Campbelling mode (in terms of neutron flux) is usually done empirically using a calibrated reference detector. A major drawback of this method is that calibration measurements have to be performed in a neutron environment very similar to the one in which the calibrated detector will be used afterwards. What is proposed here is a different approach based on characterizing the fission chamber response in terms of fission rate. This way, the detector calibration coefficient is independent from the neutron spectrum and can be determined prior to the experiment. The fissile deposit response to the neutron spectrum can then be assessed independently by other means (experimental or numerical). In this paper, the response of CEA-made miniature fission chambers in Campbelling mode is studied. A theoretical model of the signal is used to calculate the calibration coefficient. The model's input parameters come from statistical distribution of individual pulses. Supporting measurements were made in the CEA Cadarache zero power reactor MINERVE and results are compared to an empirical Campbelling mode calibration. The tested fission chamber calibration coefficient is roughfly 2 10^{-26} A^2/Hz/(c/s). Both numerical and empirical methods give consistent results, however a deviation of about 15% was observed.**

***Index Terms*—Calibration, Campbelling mode, fission chamber, neutron detector.**

I. Introduction

IT is generally accepted that fission chambers can be used in three operation modes. At low neutron fluxes, the fission rate in the fissile deposit is low enough and fission products induced pulses are scarce (i.e., the average delay between two pulses is much larger than the pulse duration). They can be counted so as to obtain an event rate closely related to the detector fission rate: this is known as "pulse mode". With the increasing of the neutron flux, pulses inside the chamber overlap and can no longer be individually processed anymore. An indirect parameter related to the fission rate must be estimated, namely the average current delivered by the detector in "current mode" or the current variance in so-called "Campbelling mode". Indeed, if the process underlying neutron detection is Poissonian, Campbell has demonstrated that both signal mean and signal variance are strictly proportional to the event rate [1].

The Campbelling mode is of great interest as it drastically decreases the disturbance of gamma rays on fission chamber neutron signal [2], [3]. It is also used to process fission chambers signal on a wide measurement range (over 10 decades) [4], [5].

Campbell theorems have been generalized to higher order statistics [6], [7]. This, for instance, can be useful to get additional information on the detection process quality [8], [9].

Recently, a new approach was developed to model fission chamber signal [10]. It gives n-th order cumulants and spectra formula by using a model based on a random vector describing detector pulses (pulse shapes, deposited charge, etc.)

Our purpose here is to apply the same fission chamber modeling approach to detector calibration in Campbelling mode (i.e., for the second order). This work was done in the framework of the research activities in fission chamber modeling conducted at CEA Cadarache [11] and also in the frame of a collaboration between CEA and Idaho National Laboratory.

The problem posed by fission chamber calibration is described in Section II. General formulas adapted for our measurement setup are given in Section III. In Section IV the experimental setup used to validate our method is presented. We chose to irradiate a CEA-made miniature fission chamber in the zero power pool reactor MINERVE (Cadarache, France). Major experimental results will then be presented and discussed in Section V.

II. Fission Chamber Calibration

Fission rate R of a detector fissile deposit composed of N fissile atoms can be related to the neutron flux Φ and to the overall fission cross section $\bar{\sigma}$:

$$R/N = \bar{\sigma} \cdot \Phi \tag{1}$$

By calculating the fission cross section, one can derive the on-line neutron flux. Inversely, by knowing the neutron flux, one can have access to an estimate of the fission cross section.

In the case of a detector with a thick fissile deposit, it is necessary to introduce an additional coefficient k_a to take into account the signal loss due to self-shielding (i.e., neutron flux level

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B. Geslot, P. Filliatre, C. Jammes, S. Bréaud, J.-F. Villard, and J. Di Salvo are with the CEA, DEN, Cadarache, SPEx/LDCI, F-13108 S-Paul-lez-Durance, France (e-mail: benoit.geslot@cea.fr).

T. C. Unruh is with the Idaho National Laboratory, INL, Idaho Falls, ID 83415 USA (e-mail: Troy.Unruh@inl.gov).

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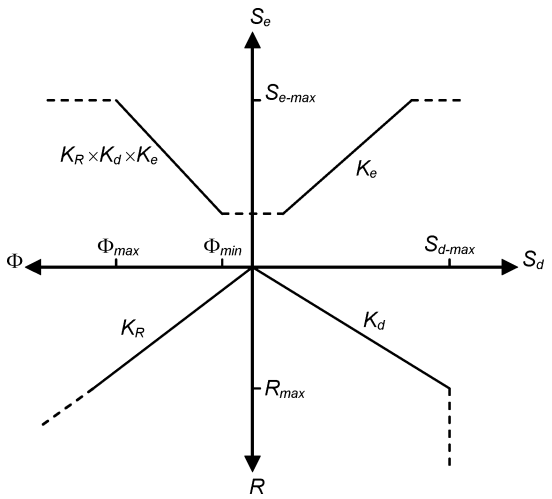

Fig. 1. A general and theoretical fission chamber calibration diagram. Calibration curves are to be read in log-log. Dotted lines represent lower and upper levels (i.e., beyond the operational range).

depression mostly due to neutron absorption) and auto-absorption (accounted for by the stopping of fission products inside the deposit). Consequently, under the assumption that the "lost" fission products are not statistically different from the other fission products that contribute to the signal, an "active fissile mass" composed of N_a fissile atoms can be defined as: $N_a = k_a \times N$. So, the "active fission rate" can be defined as $R_a = N_a \cdot \bar{\sigma} \cdot \Phi$. R_a is obviously the only quantity that is directly accessible to the measurement. Determining the self-absorption factor is not our purpose here and will be done elsewhere [12]. In consequence, it will be assumed in the following that k_a is equal to 1 (i.e., $R = R_a$).

Fig. 1 exhibits a general diagram describing several calibration coefficients. The relation between R and Φ allows us to use a coefficient K_R that depends solely on the neutron properties of the fissile deposit. A second coefficient K_d is used to link the fission rate to signal S_d generated inside the detector. K_d depends solely on the chamber response (gas mixture, pressure and geometry). Lastly, K_e links detector signal S_d to measurement S_e and is related to the electronic system.

III. Calibration Method in Campbelling Mode

In Campbelling mode, S_d is the average amplitude of the power spectrum density of the output current within a certain frequency range. S_d is expressed in A^2/Hz and so K_d is expressed in A^2/Hz/(c/s). K_d can be understood as the fission chamber response to an average fission product emitted by the fissile deposit.

According to the second Campbell theorem, it is known that coefficient K_d is related to the second order statistics of individual pulses occurring in the detector. We also know how to link the signal spectrum to the physical parameters of the detector [10]. Two random variables are to be taken into account. The first and most important one is the charge created in the detector by a single fission product. The second one is the current pulse shape at the detector ouput. As fission products can have a wide variety of paths through the detector fill gas, pulse shapes parameters may also vary signigicantly (in particular the pulse width). As small detectors are studied here (meaning that the inter-electrode gap is much smaller than the fission product range in the gas), it is possible to neglect the pulse shape variation.

One can show that the detector calibration factor is expressed as:

$$K_d = \left(\bar{Q}^2 + \sigma_Q^2\right) \cdot \frac{\Delta T}{F_2 - F_1} \cdot \int_{F_1}^{F_2} |FT[\bar{h}]|^2 dF, \qquad (2)$$

where FT is the Fourier transform operator, $\bar{Q}$ (in C) and σ_Q^2 (in C^2) are the first two moments of the collected charge statistics, $\bar{h}$ (expressed in s^{-1}) is the function describing the average pulse shape at the output of the detector and $\mathrm{F_2}$–$\mathrm{F_1}$ is the measurement frequency range (in Hz). The normalization factor $\Delta\mathrm{T}$ (in s) is equal to the pulse function temporal support. It accounts for the pulse sampling, i.e., the number of points in the pulse.

The proposed calibration method is based on acquiring individual pulses at the output of a fast broadband amplifier. The voltage signal has to be directly proportional to the current delivered by the detector. The signal to noise ratio has to be high enough for the pulse discrimination not to drastically modify the statistical distributions of relevant parameters. Terms of (2) are calculated and reconstructed afterwards by straightforward numerical processing.

IV. Experimental Setup

MINERVE is a pool type ZPR operated by CEA Cadarache. The facility is dedicated to experimental programmes in support of the French nuclear industry and to improve neutron cross sections databases. Its maximum power is 100 W. Two irradiation channels are available to test fission chambers in a nearly thermal neutron flux (about 10^8 n/cm^2/s at maximum power).

Our test detector is a miniature cylindrical CF4 type fission chamber manufactured at the Cadarache Fission Chamber Workshop [12]. This detector (FC 2247) houses a 250 μg deposit of enriched uranium (98.5% U-235). An estimation of the deposit thickness is 0.6 μm. The detector outer diameter is 4 mm and the electrode gap is 0.5 mm. The fill gas is pure argon at 12 bars.

Measurements in Campbelling mode were acquired using a new acquisition system called the Fast Neutron Detector System (FNDS). This system has been developed and qualified in the framework of the Instrumentation Joint Laboratory between CEA and SCK·CEN [14].

FNDS acquisition system is sketched on Fig. 2. Its front end is a fast broadband current amplifier. The transimpedance of about 32.5 k Ω (current to voltage conversion gain) is constant over the amplifier frequency bandwidth (5 kHz–150 MHz). The variance measurement is taken on a frequency range spanning from 20 kHz to 300 kHz (analog pass-band filter, 8th order) and the acquisition frequency is 1 MHz. The electronics gain has been calibrated using synthesized signals: K_e is about 10^{15} Ω^2. Hz.

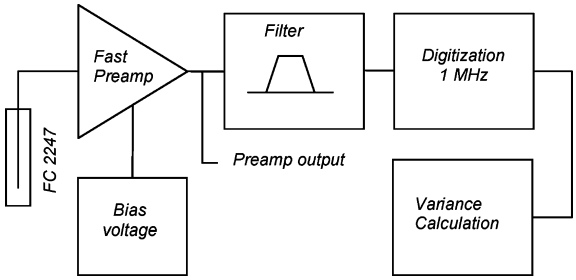

Fig. 2. Measurement setup in Campbelling mode using FNDS. The high immunity coaxial cable that links the detector to the preamplifier is about 25 m long.

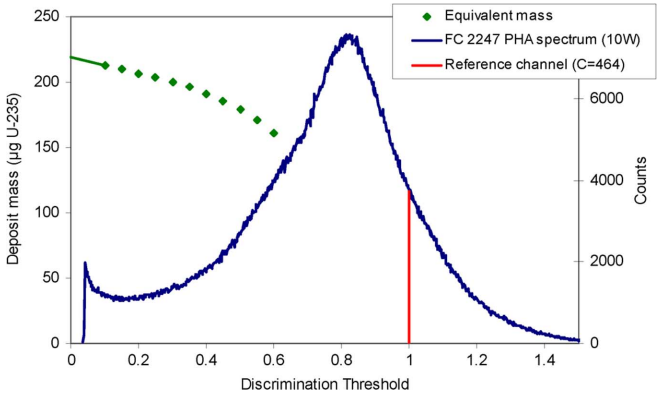

Fig. 3. FC 2247 PHA spectrum at 10 W. Reference channel C is determined based on the spectrum maximum. An extrapolation of the spectrum below 0.1 C allows us to estimate the active mass of the fissile deposit.

V. Major Results and Discussion

A. Calibration Via Pulse Rate

Our test detector signal was compared to that of a calibrated fission chamber (FC 2232, same geometry, 25 μg U-235). The measurement was made in irradiation channel n°2 at a reactor power of 10 W. Our calibrated detector yielded a fission rate of $R_{/\mathrm{at}} = 27.9$ c/s/μg. The measurement is made using a standard Pulse Height Analysis chain (using Canberra spectroscopy electronic modules).

The FC 2247 PHA spectrum gives us a counting rate depending on the discrimination threshold (expressed as a fraction of a reference channel C, which is defined as half the spectrum maximum, see Fig. 3). The "equivalent uranium mass" is defined as the mass that corresponds to a fission rate equal to the counting rate. Thus, the equivalent mass depends on the discrimination threshold (see the dotted curve on Fig. 3).

At low threshold, the noise level introduces a bias in the estimation of the counting rate (as we can see on Fig. 3, the counts start to increase below 0.1 C). To circumvent this issue, we performed an extrapolation of the equivalent mass down to a zero threshold. The obtained active uranium mass for FC 2247 is 219 μg. There is a 12% deviation between this mass and the total mass coated on the electrode (around 250 μg). This deviation can be partly explained by the self-absorption effect that accounts for a few percent (cf. [12]). There is also an impact of the uncertainty on the reference measurement (detector positioning, statistical and calibration uncertainties).

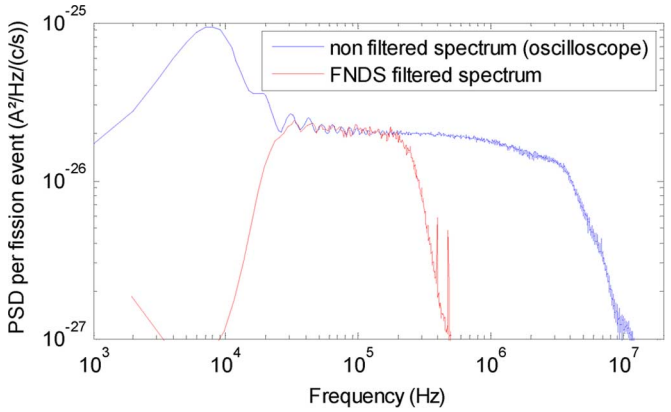

Fig. 4. FC 2247 spectra acquired with a broadband oscilloscope and with FNDS (frequency range 20 kHz to 300 kHz).

By multiplying the active mass by the fission rate per atom, the total event rate inside the detector can be obtained. Based on this measurement, we will subsequently use an empirical pulse calibration factor to convert a counting rate obtained for a specific threshold into the total event rate. This factor is equal to 1.1 for a typical threshold of 0.3 C.

B. Detector Linearity With Reactor Power

One of the main goals of this measurement campaign was to test the linearity of the detector by measuring the Campbelling mode signal at various reactor power levels. We tested 5 power levels from 1 W to 80 W. The detector was installed in the irradiation channel n°2 at core mid-plane and polarized at 300 V.

At high power (80 W) a broadband spectrum of the signal at FNDS preamplifier output was acquired on-line using an oscilloscope (LeCroy WaveRunner, 500 MHz bandwidth, maximum sampling of 5 GS/s). FNDS signal spectrum was also calculated afterwards using samples of acquired signals. Both spectra are compared in Fig. 4.

The plot of the FNDS spectrum clearly shows the effect of the pass-band filter that eliminates the ionic signal part (below 20 kHz). The frequency domain is nearly flat, which is in favor of the measurement steadiness.

FNDS variance measurements (in V^2) were converted into power spectrum densities by using the electronics calibration factor $K_e = 10^{15}\ \Omega^2$. Hz. At each power level, a counting rate measurement was performed and converted into a total event rate by using the pulse calibration factor.

Fig. 5 shows that the detector linearity is very satisfactory over nearly two decades. The first measurement points are close to FNDS noise background (about $10^{-7}\ \mathrm{V}^2$) and it was necessary to subtract noise from the signal.

The linear fit gives an empirical estimation of the calibration coefficient of $1.8\ 10^{-26}\ \mathrm{A}^2$/Hz/(c/s). The uncertainty of this result is difficult to assess since it depends mostly on the pulse calibration factor. We estimate that it amounts to approximately 10% (68% confidence interval).

C. Calibration Via Pulse Measurements

Detector signals were acquired at the FNDS preamplifier output in order to access statistical properties of delivered

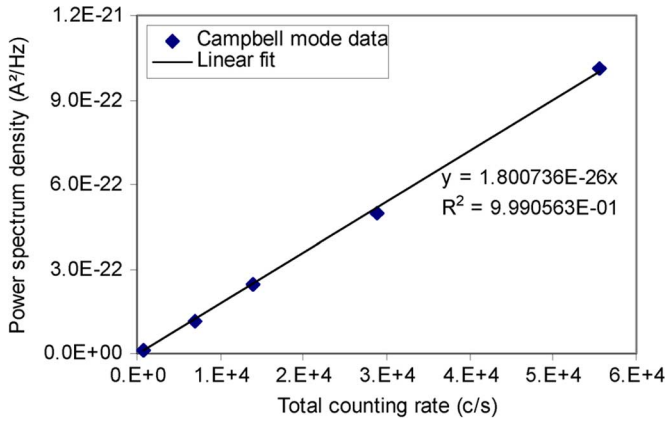

Fig. 5. Campbelling mode signal acquired by FNDS versus total event rate in the FC 2247. The linear fit slope gives us an estimation of Campbelling mode calibration factor K_d.

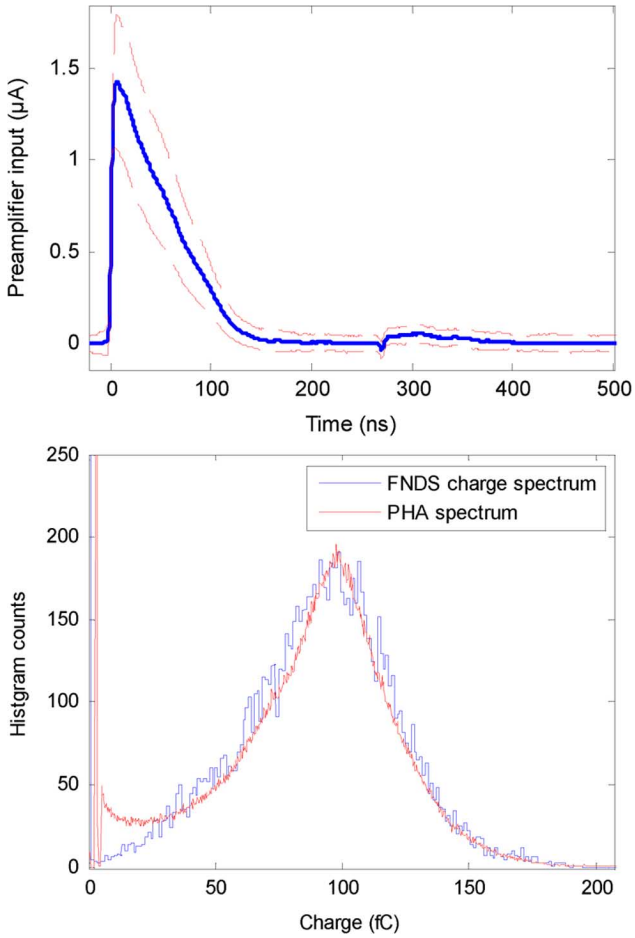

Fig. 6. Average pulse acquired at FNDS preamplifier output (upper plot). Charge spectrum (lower plot) based on individual pulses analysis (blue) and measured using a standard PHA channel (red).

pulses (collected charge, pulse width, pulse shape). Our objective here is to estimate all parameters needed to apply (2).

Individual pulses were acquired at low power (10 W) using our oscilloscope. The event rate in the detector is lower than 10^4 pulses per second. Fig. 6 shows the detector average pulse as well as the pulse shape standard deviation (upper plot). Scarce pulses overlapping have been dealt with during data post-processing. The charge spectrum was calculated offline (lower plot). It was found to be is very consistent with the one obtained by a standard PHA measurement.

TABLE I
FC 2247 PULSE PARAMETERS

Parameter	Electronic component	Ionic component
Width	150 ns	40 µs
Amplitude	1.4 µA	7.2 nA
Charge	91 fC	132 fC

The main estimated parameters of the average pulse are summarized in Table I. As it can be seen, the average charge coming from the pulses' electronic component is not equal to the charge collected from the ionic part. This is due to the charges not being uniformly created in the electrode gap. On the contrary, charges are mostly created close to the fissile deposit, so the electrons' path in the gas is on average smaller than the ions' path.

The sum of electronic and ionic charges gives the total charge $\bar{Q}$ deposited by an average fission product in the detector. This quantity is often expressed in terms of number of electrons. In our case, we have on average 1.4 10^6 electrons per fission product. Charge standard deviation σ_Q was found to be 33% of the average charge.

Using the parameters in Table I and by numerically computing the Fourier transform of the pulse shape, we were able to calculate the calibration coefficient using (2).

With $\Delta T = 1$ ms, $F_2 - F_1 = 280$ kHz and a mean PSD value of 2.2 10^3 Hz^{-1} over this frequency range, our calculation yielded a K_d equal to 2.05 10^{-26} A^2/Hz/(c/s). This value is consistent with the empirical value of 1.8 10^{-26} A^2/Hz/(c/s). The deviation of 14 % between the two values can most likely be attributed to the imperfections of our estimation of the detector total counting rate. It can also be attributed to the assumptions that support the detector model, in particular the fact that the second moment of the pulse shape has been neglected. Another source of uncertainty is the poor signal to noise ratio (around 10) that we endured when acquiring pulses at the FNDS preamplifier output.

VI. CONCLUSION

In this paper a method is detailed to calibrate fission chambers in Campbelling mode. It is based on characterizing detector pulses and calculating detector response using a detailed expression of Campbell's second theorem.

Results obtained at the MINERVE facility using a CEA-made miniature fission chamber with a 250 μg uranium deposit demonstrated the feasibility of the method. The calibration coefficient obtained is 2.05 10^{-26} A^2/Hz. A 14% deviation was observed between this value and the reference one based on a calibration of the detector in pulse mode.

In a subsequent work, we plan to further test the robustness of the method and apply it to other miniature fission chambers of varying construction (gas mixture, pressure and fissile deposit).

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