Dependability of the fission chambers for the neutron flux monitoring system of the French GEN-IV SFR

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Abstract. The neutron flux monitoring system of the French sodium-cooled fast reactor will rely on fission chambers that permit both reactivity control and power level monitoring from startup to full power. They are installed inside the reactor vessel, putting severe constraints on the detector design to ensure its dependability. In this paper, we present the Photonis high-temperature fission chambers (HTFC) featuring wide-range flux monitoring capability and justify their specifications with the use of simulation and experimental results. We show that the HTFC dependability is enhanced thanks to a robust physical design. In order to satisfy the requirement of wide-range capability, we propose to estimate the count rate of a HTFC using the third-order cumulant of its signal. The use of this cumulant can be seen as an extension of the so-called Campbelling mode, based on the variance, hence the name high order Campbelling method (HOC).

Key Words: Instrumentation, Neutron flux monitoring, Fission chamber

1. Introduction

Sodium-cooled fast reactors (SFR) have been selected by the Generation IV International Forum, thanks to their capability of reducing nuclear waste and saving nuclear energy resources by burning actinides [1]. With reactors such as RAPSODIE, PHENIX and SUPER PHENIX, France gained a 50 year experience in designing, building and operating SFR [2]: since 2006 the CEA leads the development of an innovative GEN-IV nuclear-fission power demonstrator. As a part of it, the neutron flux monitoring system must, in any situation, permit both reactivity control and power level monitoring from startup to full power. It also has to monitor possible changes in neutron flux distribution within the core region in order to prevent any local melting accident.

The neutron detectors will have to be installed inside the reactor vessel because locations outside the vessel will suffer from severe disadvantages; (i) The installation of neutron detectors under the vessel is not feasible due to the presence of a core-catcher that prevents from inserting neutron guides in this region; (ii) The lateral and upper neutron shields, the role of which is to limit the damage and radiological impact of the neutrons outside the core, will also dramatically decrease the neutron flux amplitude, making thus difficult any neutron detection outside the vessel itself above or by the sides of the vessel. However, an installation inside the reactor vessel puts severe constraints on the detector design to ensure its dependability, that is, both its reliability and maintainability.

In this paper, we show that the architecture of the neutron flux monitoring (NFM) system will rely on in-vessel high-temperature fission chambers (HTFC) featuring wide-range flux monitoring capability based on the higher order Campbelling method.

2. HTFC Development

In this section, we present our endeavor to enhance the HTFC reliability through a comprehensive modelling of the detector itself, a more robust physical design and the study of the mineral insulation behavior at high temperature above 400°C.

2.1.HTFC Modelling

For more than a decade, our team has undertaken theoretical, modelling and experimental studies to improve the design and the signal analysis of fission chambers in order to enhance their overall performance and dependability. This work is beneficial in defining HTFC with respect to their technical requirements, and in preparing experimental tests for their validation and qualification as items important to nuclear safety.

Constraints due to thermal expansion have been numerically shown to be negligible. However, the decrease of the resistivity of the insulators with temperature and irradiation can be an issue as far as partial discharges are concerned [3].

The development of tools based on the suite DARWIN [4] makes it possible to assess, for a given HTFC and its location within the vessel, the expected fission rate, its evolution with irradiation time, its sensitivity to energetic domains of interest (e.g. fast neutrons) [5], [6]. It has been shown that U235 is the isotope of choice to deliver a suitable fission rate for signal processing, and stable enough with time, provided the HTFC is not placed within the core or at reflector level [3]. It was also shown [7] that the surface mass of the coating has to be below 1 mg/cm^2 in order to keep the self-absorption (i.e. the rate of fissile products emitted towards the gas gap, but not reaching it due to absorption in the coating) below 5%: a constraint that leads to large diameter (48 mm), multi-electrode designs. Finally, the activation of the coating and the structures of the HTFC can be computed to anticipate on post-use handling.

The saturation curves are computed with tools derived from the theoretical considerations of [8]. An experimental validation is presently undertaken at MINERVE reactor of CEA that would put some constraints on physical parameters involved in the so-called recombination regime [9]. Fig. 1 shows saturation curves at various pressures and fission rates.

A comprehensive tool [10], [11] has been developed that simulates the ionization of the gas by the fission products, the transportation of the charges, the induced current. Observable quantities such as the mean pulse, the charge spectrum, the mean current (hence the sensitivity in current mode) the spectral density (hence the sensitivity in Campbelling mode), can be computed, their dependence to the design parameters (geometrical specifications, gas composition, bias voltage) can be studied. For instance, increasing the gas mass crossed by the fission product (either by increasing the gas pressure or increasing the gap between the electrodes) increases the pulse height, as long as the fission product is not stopped in the gas itself, but also increases the pulse length. Using gas mixtures with molecular gases to shorten the pulse length is not advised in SFR, as the molecules would dissociate under the gamma radiation. This tool has received a partial experimental validation [12]. Also, it is possible to estimate the fraction of the signal due to gamma interactions with the HTFC structures in current or Campbelling mode [13]. It is thus possible, for a given region in the reactor, to choose a set of design parameters that is a good compromise for monitoring the flux over ten orders of magnitude up to nominal power.

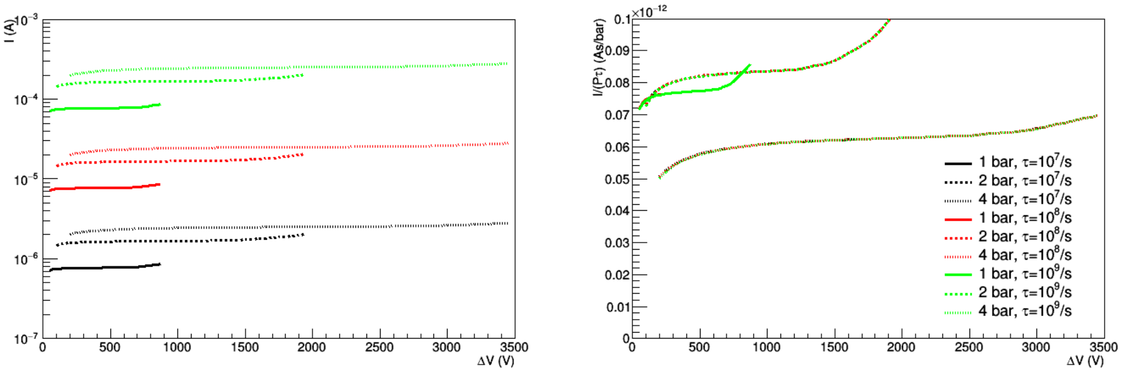

Fig. 1. HTFC saturation curves for various argon pressure and fission rates of the fissile layer. The electrode spacing is 1.5 mm. The fission chamber signal is expressed in current (left) and current normalized to fission rate and pressure (right). Note that as as long space charges are not taken into account, there is a perfect scaling in fission rate.

2.2.Physical Design

During the last decades of the 20th century, CEA and Photonis jointly developed high temperature fission chambers for the PHENIX and SUPER PHENIX fast reactor [14] [15]. Two types of detectors were hence developed:

- CFUC06 for PHENIX, which was filled with pure argon.
- CFUC07 for SUPER PHENIX, which was filled with Ar + 4% N_2 gas mixture, in order to get larger flux dynamic.

The physical architectures of CFUC06 and CFUC07 were based on a guard ring structure (Fig. 2), which allows us to increase the insulation between High Voltage (HV) and Signal electrodes, especially at high temperature of about 550°C. This is due to the fact that no ceramic insulator is placed between the two electrodes, and that two cables are used, one for HV and one for Signal, with no connection of the electrodes to the ground reference.

This experience benefited to Photonis' know-how on the HTFC manufacturing process. More specially, the experience feedback shows that alumina exhibits satisfactory insulating properties, and after testing different metal materials that Inconel 600 allows the manufacturing of a reliable fission chambers. Our improvements in modelling (Sect. 2.1) and analyzing the fission chamber signal (see further in Sect. 2.3 and 3) made it possible to change the internal structure of HTFC to a one-cable structure (Fig. 2): in this configuration the same cable is used for both HV and Signal, and the cathode is connected to the ground. Thus, this change allows simplifying the design of HFTC by decreasing the quantity of piece parts and making it more robust by increasing the piece part size. Photonis is currently manufacturing prototypes that must be tested with CEA at high temperature.

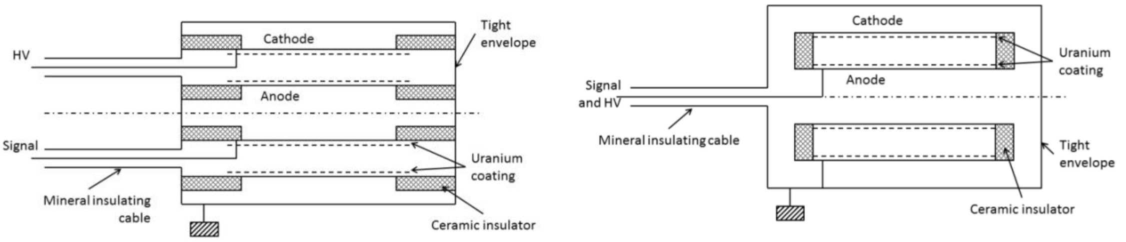

Fig. 2. Sketch of guard ring (left) and a one-cable structure (right) of a fission chamber from an electric point of view.

Fig. 3. Axial cross section of the new HTFC structure.

Fig. 3 shows the new structure of this HTFC, which is designed to take into account the difference between each material thermal expansion coefficient in the three dimensions. The main characteristics of these prototypes are:

- Electrodes and detector body in Inconel 600.
- Three electrodes, two cathodes and one anode, the detector envelope being one cathode.
- An outer diameter of 48 mm.
- A gap between the electrode of 1.5 mm.
- A sensitive length of 210 mm.
- Pure argon filling gas, to avoid nitrogen disappearing at high temperature.
- A uranium thickness of 1 mg/cm^2.
- The same high immunity parasitic and mineral insulated cable as the one qualified for CFUC06 and CFUC07, manufactured by Thermocoax Company.

2.3.Impact of partial discharges

The HTFC is subject to partial discharges at high temperature when the electric field between the electrodes is greater than 200 V/mm. These discharges give rise to pulses similar to the desired neutron pulses generated by the fission chamber itself, which may bias the HTFC count rate at start-up only.

The exact mechanism leading to these electrical discharges is unclear. Gas pressure on the order of several bar and gap distances on the order of mm means that these discharges are occurring under conditions significantly inferior to the Paschen limit. Extrapolation of the

Paschen curve for Argon to high pressure suggests that discharges should not be observed for electric fields below a value of about 10kV/mm.

Current work is focused on modelling and experimentation to identify the location in the HTFC where the discharges may occur. Initial calculations showed that the maximum field attained in a faultless HTFC should be well below the 10kV/mm threshold, and so consideration has been given to triple points and possible defaults in the fissile layer or HTFC structure where electrical field enhancement may occur.

In addition, the effect of temperature seems to be critical for the formation of these discharges, as they are not observed at low temperature. Future effort shall be made to determine how the higher temperature may either lead to defaults or cause other conditions to arise which are responsible for the discharges. Ideally the goal is to eliminate these discharges by the change of design after understanding the exact mechanism of their creation.

If this proves not to be practical, we have also worked on a signal analysis method able to discriminate the desired neutron signal from the signal created by the discharges. As displayed in Fig. 4, we have experimentally verified the feasibility of this method. The histogram showed in this figure is the result of analysis of 10^4 neutron pulses and as many pulses due to partial discharges. Fig. 4 gives the distribution of the width (at the half maximum) of the collected pulses. The distribution has two well separated peaks. The peak related to the longer width can be identified with the neutron pulses (since the results match the data provided by Photonis). It was assumed that pulses with shorter width are created by the partial discharges. This was verified through measurements without neutron flux.

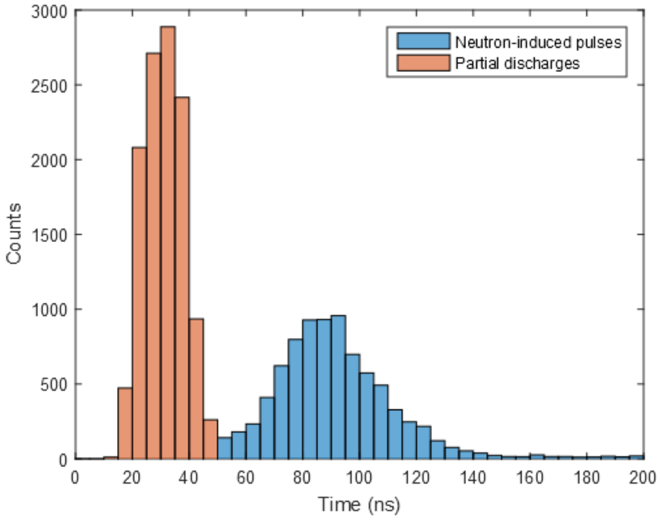

Fig. 4. Experimental discrimination (with a CFUE chamber similar to the HTFC) of neutron pulses from partial discharges.

Despite the apparent similarity between the two types of pulses, we have shown that we are able to discriminate these partial discharge pulses of those produced by the fission products in the HTFC using the half-height width of the measured pulses.

3. Signal Processing Development

The fission chambers are traditionally operated in three different modes (namely the pulse, the Campbelling and the current mode for low, middle-high and high count rates respectively). These operational modes require different electronic systems hence resulting in a deficiency of robustness. Also, the overlap of these modes is not necessarily guaranteed. For the newly developed NFM a unified mode is proposed via the higher order Campbelling methods.

3.1.High order Campbelling method (HOC)

The fission chamber signal is described by a filtered Poisson process. One recalls that the Campbelling mode of such signal is based on the signal variance, which is the second-order cumulant as well. The generalization of this method gives proportionality between the higher order cumulants of the signal and its count rate s_0:

$$\kappa_n^{(st)} = s_0 \langle x^n \rangle \int_{-\infty}^{+\infty} f(t)^n dt \tag{1}$$

where the proportionality is given by a coefficient including the raw moments of the amplitude distribution w(x) and the integral of the pulse shape f(t). Hence the application of High order Campbelling method (HOC) essentially means the measurement of the higher order cumulants κ_n. [16], [17].

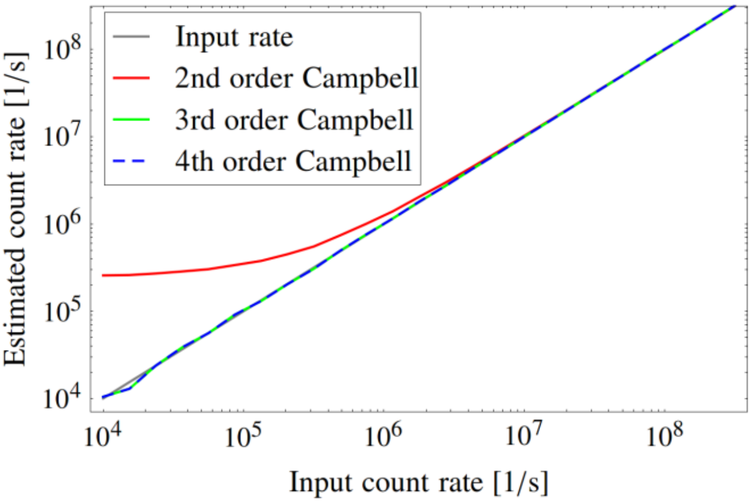

Fig. 5. Noise rejection and linearity of HOC methods (in presence of Gaussian white noise)

It was shown through numerical simulations that the application of the third order Campbelling mode is reliable and can guarantee linear estimation over a wide count rate. It can also sufficiently reject the impact of electronic noise and suppress the impact of pulses not originating from neutron events (Fig. 5).

Due to the relatively fast convergence of the third order cumulant estimation the monitoring of transient events with HOC modes is also reliable.

Campbelling mode based on the third-order cumulant will permit to ensure the HTFC response linearity over the entire neutron flux range using a signal processing technique that is simple enough to satisfy design constraints on electric devices important for nuclear safety.

3.2.Experimental calibration

An experimental campaign devoted to the required calibration process of HOC method was also carried out at the MINERVE facility. The calibration implies the determination of the proportionality coefficient, therefore the determination of the pulse shape and the pulse amplitude distribution in Eq. (1).

Our experimental setup consisted of a current-sensitive CFUL01 fission chamber placed in the reflector zone of the MINERVE reactor. The CFUL01 is a representation of the HTFC that is fair enough to demonstrate the feasibility and the reliability of the HOC method. The fission chamber was connected to a wide range pre-amplifier. Then, the output signal was digitized at high sampling frequency during a large time span with an advanced digital oscilloscope.

At low reactor power levels pulses were collected separately. Even at low power there is a small possibility to measure pileup events, hence during the post processing of the results the pileup events were found and these events were not taken into account during the determination of the calibration coefficient. These results provided information about the amplitude distribution of the pulses hence the raw moments of this distribution. Based on the collected pulses the mean pulse shape was also defined. This information enabled us to determine the calibration coefficients.

At medium and high power levels longer signals were collected. At medium levels the pulses moderately overlap.

As a result, counting them separately is still possible to estimate the count rate of the signal. This provides an opportunity to estimate the count rate with simple pulse mode and compare with the estimation coming from the calibrated HOC mode.

As one can see in Fig. 6, the Campbelling results show a good agreement with the simple pulse counting estimation at low count rates. It is also shown that the HOC technique provides a linear estimation of the count rates at higher power levels as well. Hence the application of the HOC methods is reliable.

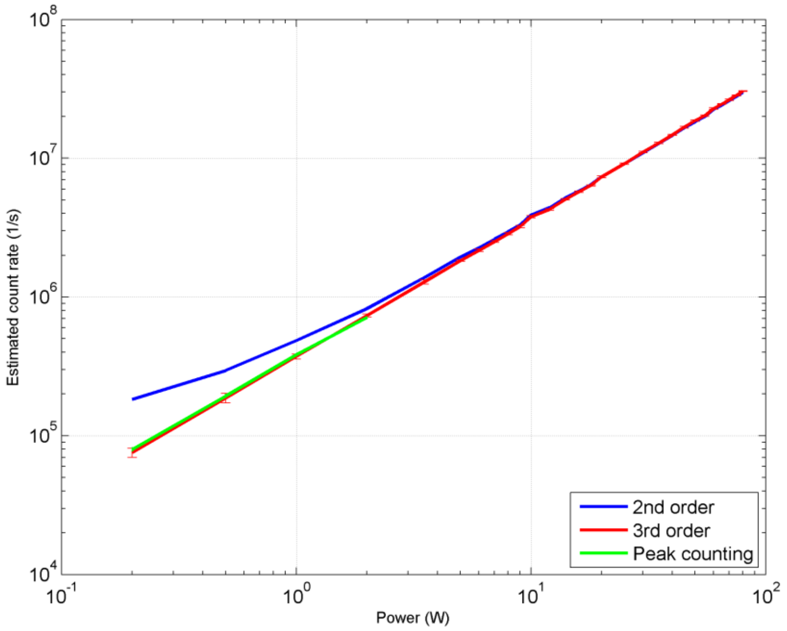

Fig. 6. Experimental validation of HOC technique linearity.

3.3.Electronic implementation

The electronic system design must meet a variety of requirements such as temperature stability, electromagnetic compatibility, response time, neutron flux estimation accuracy.

The electronic system contains an analog part and a digital part. The analog part is essentially made by the low noise fast current neutron flux preamplifier which is a key element in the electronic system. The low noise fast current neutron flux preamplifier converts the current signal from the HTFC to voltage signal with an input impedance of 50 ohms to match the fission chamber cable. The input matching impedance enables a long connection (150 to 300 m) between the detector and its associated electronic system. The detector can therefore be exposed to hard radiations conditions without damage for the electronics.

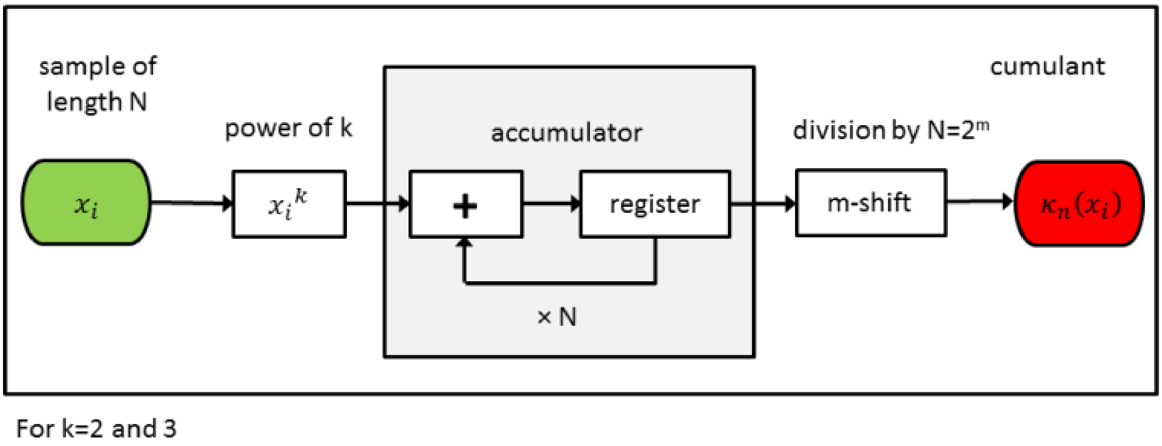

Fig. 7. Functional flow-block diagram of HOC method to be implemented in a FPGA circuit. The digitized input signal of length N is processed in order to estimate κ2 and κ3 cumulants. Each operation is executed within one clock cycle: exponentiation, summation and division. The summation is done with the use of an accumulator that consists of an adder and a register. The division by N=2m is carried out by a shift operator.

Then, an analog-to-digital converter digitalizes the voltage signal which is injected into a FPGA (Field Programmable Gate Array) circuit. Fig. 7 shows the functional architecture of the HOC method to be implemented in a FPGA (see also [18]). Here, the input signal is supposed to be centered, that is zero-mean-valued. The digitized input signal of length N is processed in order to estimate κ_2 and κ_3 cumulants. Given that the signal is centered, the processing is similar to computing the estimators of the two moments, which are actually two power series:

$$\hat{\kappa}_n = \frac{1}{N}\sum_{i=1}^{N} x_i^k,\ \ k = 2 \text{ or } 3 \tag{2}$$

4. Conclusion

We have presented the Photonis high-temperature fission chamber, developed for an installation within the core vessel of foreseen French sodium-cooled fast reactor. We have justified its main specification with the use of simulation and experimental results. Thanks to its robust physical design, the HTFC is expected to meet the requirements in terms of reliability and maintainability. The estimation of the count rate over a wide dynamics is made possible by using the third-order cumulant of its signal with a properly designed electronic system.

In order to qualify the HTFC, we are now involved in the preparation of functional and stress tests in the JOYO facility in Japan, in tight collaboration with the Japanese Atomic Energy Agency (JAEA).

References

[1] L. Buiron, B. Fontaine, L. Andriolo, Transmutation abilities of the SFR low void effect core concept CFV 3600 MWth, in: Proceedings of ICAPP 12—International Congress on Advances in Nuclear Power Plants. No. 12029, Chicago, USA.

[2] D. Tenchine, Nucl. Eng. and Design vol. 240, p.1195 (2012)

[3] P. Filliatre, C. C. Jammes, B. Geslot, and L. Buiron, Ann. Nucl. Energy, vol. 37, p. 1435, 2010.

[4] A. Tsilanizara and C. M. Diop, J. Nucl. Sci. Technol., vol. 37, p. 845, 2000.

[5] P. Filliatre, L. Oriol, C. Jammes, and L. Vermeeren, Nucl. Instr. and Meth. A, vol. 593, p. 510, 2008.

[6] P. Filliatre, L. Oriol, C. Jammes, and L. Vermeeren, Nucl. Instr. and Meth. A, vol. 603, p. 415, 2009.

[7] C. Jammes, P. Filliatre, P. Loiseau, and B. Geslot, Nucl. Instr. and Meth. A, vol. 681, p. 101, 2012.

[8] S. Chabod, Nucl. Instr. and Meth. A, vol. 598, p. 578, 2009.

[9] P. Filliatre, B. Geslot, C. Jammes, and V. Lamirand, Nucl. Instr. and Meth. A, vol. 817, p.1, 2016.

[10] P. Filliatre, C. Jammes, B. Geslot, and R. R. Veenhof, Nucl. Instr. and Meth. A, vol. 678, p. 139, 2012.

[11] C. Jammes et al., IEEE Trans. Nuc. Sci., vol. 57, p. 3678, 2010.

[12] B. Geslot et al., Rev. Sci. Instr., vol. 82, p. 033504, 2011.

[13] P. Filliatre, L. Vermeeren, C. Jammes, B. Geslot, and D. Fourmentel, Nucl. Instr. and Meth. A, vol. 648, p. 228, 2011.

[14] J-P. Trapp, S. Haan, L. Martin, J. Perrin, and M. Tixie, "High temperature fission chambers: State-of-the-art," in Proc. Specialists' Meeting, In-Core Instrumentation and Core Assessment, Mito-shi, Japan, 1996.

[15] C. Jammes, P. Filliatre, B. Geslot, T. Domenech, and S. Normand, IEEE Trans. Nucl. Sci., vol. 59, p. 1351, 2012.

[16] L. Pál, I. Pázsit, and Zs. Elter, Nucl. Instrum. and Meth. A, vol. 763, p. 44, 2014.

[17] Zs. Elter, C. Jammes, I. Pázsit, L. Pál, and P. Filliatre, Nucl. Intrum. and Meth. A, vol. 774, p. 60, 2015.

[18] G. de Izarra, Zs. Elter, C. Jammes, Nucl. Instr. and Meth. A, vol. 839, p. 12, 2016.