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Performance investigation of the pulse and Campbelling modes of a fission chamber using a Poisson pulse train simulation code

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ABSTRACT

The detectors of the neutron flux monitoring system of the foreseen French GEN-IV sodium-cooled fast reactor (SFR) will be high temperature fission chambers placed in the reactor vessel in the vicinity of the core. The operation of a fission chamber over a wide-range neutron flux will be feasible provided that the overlap of the applicability of its pulse and Campbelling operational modes is ensured. This paper addresses the question of the linearity of these two modes and it also presents our recent efforts to develop a specific code for the simulation of fission chamber pulse trains. Our developed simulation code is described and its overall verification is shown.

An extensive quantitative investigation was performed to explore the applicability limits of these two standard modes. It was found that for short pulses the overlap between the pulse and Campbelling modes can be guaranteed if the standard deviation of the background noise is not higher than 5% of the pulse amplitude. It was also shown that the Campbelling mode is sensitive to parasitic noise, while the performance of the pulse mode is affected by the stochastic amplitude distributions.

1. Introduction

Sodium-cooled fast reactors (SFRs) are among the advanced reactors selected by the Generation IV International Forum. In order to meet needs of CO_2-zero-emission energy supply beyond 2030, the French government asked, in the year 2006, CEA, namely the French Alternative Energies and Atomic Energy Commission, to lead the development of an innovative GEN-IV nuclear-fission power demonstrator. The major objective is to improve the safety, reliability and availability of an SFR. The foreseen GEN-IV SFR is thus an innovative pool-type SFR featuring a negative sodium-void reactivity coefficient [1]. In addition, the instrumentation and more particularly the monitoring and online diagnostics will be enhanced.

The design of the neutron flux monitoring (NFM) system of the French GEN-IV SFR was discussed in Ref. [2]. As in any reactor, the NFM's main objectives are not only reactivity control and power level monitoring, but also the monitoring of flux distribution within the core regions in order to prevent any local melting accident. Given that the neutron shield of a pool-type SFR is contained in the reactor vessel, the neutron instrumentation is planned to be installed in the vessel in order to monitor the neutron flux over a wide range, that is from startup to the full power of 1500 MW. High temperature fission chambers (HTFCs) were proved to be the most appropriate for this purpose [3,4]. An HTFC has to operate in an extreme environment. All the three prospective locations are in the vicinity of the core with a temperature from 400 °C to 550 °C at full power [4]. Although the development of the HTFCs had already been carried out at CEA from the early 1980s to the late 1990s, there is room for enhancing their robustness and capability [5,4]. All these activities are part of our research program in support of the French GEN-IV SFR nuclear instrumentation and take advantage of our past and recent experience in that domain.

The wide-range capability of a fission chamber requires a sufficient overlap of the signal processing modes in the so-called pulse and Campbelling regime [6] in order to ensure the linearity of the neutron flux measurement [4]. As will be described in more detail later, the processing of the detector signal is different for low and high detector event intensities, i.e. when the signal has the shape of individual "spikes" or consists of overlapping pulses that become a continuous signal for high event rates. The goal is in both cases to determine the detection event rate, which is proportional to the neutron flux. For low event rate the individual pulses are counted by a threshold counting technique (pulse mode) while for overlapping and

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continuous signals, i.e. high event intensity, the intensity is extracted by calculating the higher moments of the digitized detector signal (Campbelling technique). These two modes use different electronics and data processing. The term “linearity” or “mode overlapping” means that there is a region of intermediate event intensity when both methods work and supply the same result.

It has been claimed that the mode overlap could be achieved by lowering the electron collection time and hence the width of the individual fission pulses. A well-known solution to decrease the charge collection time is to add a few percents of polyatomic gas such as nitrogen [7,8]. However, it was observed that nitrogen molecules disappear under irradiation at high temperature of an SFR. In order to circumvent this loss, it was proposed to saturate all the chamber parts with nitrogen [4]. Given that the industrial qualification of this treatment is still uncertain, an alternative solution for the wide-range HTFC operation is sought.

In theory, the Campbelling technique could be used for both low and high detector event intensities, and the Campbelling techniques can be treated theoretically [9]. Therefore it might appear as if there is no need either for ensuring the linearity of the modes or for numerical simulations. However, in reality, electronic and other parasitic noise make the measurement inaccurate, and for low event rates application of the Campbelling technique becomes impractical and indeed impossible. Hence the existence of the mode linearity is not at all granted. Its validity cannot be investigated with pure theoretical methods either; concrete results for the moments of the signal can be obtained in a closed form only for certain signal shapes [9]. Even for these cases, the influence of parasitic noise cannot be assessed analytically, thus an analytical sensitivity and uncertainty analysis is not possible.

Hence, in order to address the question of the linearity of the pulse and Campbelling modes, a specific code was developed for the simulation of fission chamber pulse trains. The code can handle arbitrary signal shapes, amplitude distributions and the presence of added noise. With the help of the code, a quantitative analysis of the mode linearity was made. On the long run, this code aims at improving the signal processing of the future NFM system of the French GEN-IV SFR.

In this paper the principles of the code, its verification, and the results of the quantitative analysis of the mode linearity are described. First, a brief overview of the typical instrumentation based on a fission chamber is given. Second, the filtered Poisson process that permits to describe a conditioned signal of a fission chamber is discussed. Third, our developed simulation code is described and its overall verification is shown. Finally, the performances of the pulse and Campbelling modes are investigated.

2. Neutron monitoring instrumentation

2.1. Fission chamber

Fission chambers are nuclear detectors that are widely used to deliver online neutron flux measurements [6,5,10,11]. This type of detector is an ionization chamber containing fissile material in order to detect neutrons. The most common design consists of one or more coaxial electrode pairs, at least one electrode of which is coated with a fissile layer from a few micrograms to a few grams. The spacing between each anode and electrode goes from tens of microns to few millimeters. The chamber itself is filled with an argon-based gas pressurized at a few bars. When a neutron reaches the fissile coating, it is likely to induce a fission that generates two heavily charged ions, the fission products emitted in two nearly opposite directions. The one emitted out of the fissile layer ionizes the filling gas along its trajectory. Given that a DC-voltage of a few hundred volts is applied between the electrodes, the electrons and positive ions drift across the filling gas in opposite direction, and generate a current signal. That DC-voltage must be high enough to collect all the charges, and low enough to prevent the production of secondary ionization pairs. If both conditions are fulfilled, the fission chamber operates in the so-called saturation regime [6,5], for which the neutron-induced current signal is proportional to the fission rate and nearly insensitive to the DC-voltage. In addition, one can note that the gamma particles that directly ionize the filling gas also generate a signal.

The proper operation of a fission chamber as well as its output signal chiefly depend on the following characteristics: (i) high voltage bias, (ii) inter-electrode distance, (iii) filling gas pressure and composition and (iv) nature and amount of fissile material.

2.2. Electronics

The conditioning electronics of a typical neutron flux-monitoring system consists of the detector itself, a high electromagnetic immunity cable and a current-sensitive pre-amplifier that converts the current flowing through the detector into a measurable voltage [12]. Such a pre-amplifier has to feature a very low input impedance compared to that of the fission chamber. As it will be hereafter described, a fission chamber can operate in three different modes: (i) pulse mode, (ii) Campbelling mode or (iii) current mode. Only the pulse and Campbelling modes, which allow for the neutron–gamma discrimination, will be addressed in this paper. In case of pulse mode, the acquisition system consists of a discriminator directly connected to a counter. The discriminator generates a logic signal if its analog input signal becomes larger than a predefined threshold. In case of Campbelling mode, the acquisition nowadays consists of a frequency band-pass filter, an analog-to-digital converter and a processing unit for variance calculation. The corresponding electronics is summarized in Fig. 1.

The signal was simulated as it arrives from the pre-amplifier. Since in the count rate range considered here the band-pass filter does not have an impact, it was not included into the simulation.

3. Signal modeling and processing

3.1. Filtered Poisson process

According to the previously described facts, the fission chamber signal can be idealized as a Poisson pulse train, or shot noise. In the literature the mathematical model behind these processes is often called a filtered Poisson process [13]. In such a stochastic process the time interval between each pair of consecutive events has an exponential distribution with an intensity parameter s_0 [14]. In the present case the intensity or the count rate is determined by the environment of the detector (e.g. reactor core) and is proportional to the neutron flux level. The consecutive events are pulses, hence the total signal is a superposition of pulses of the form:

$$\varphi(x,t) = x \cdot f(t). \tag{1}$$

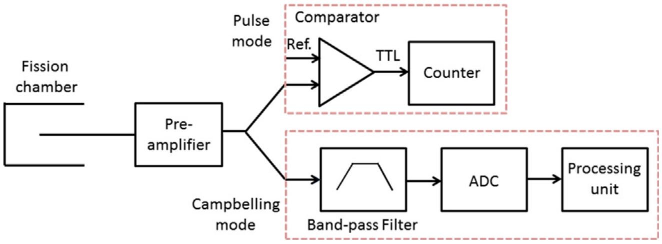

Fig. 1. Overall layout of a neutron monitoring system.