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Experimental study of columnar recombination in fission chambers

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ABSTRACT

In this paper, we present experimental saturation curves of a small gap miniature fission chamber obtained in the MINERVE reactor. The chamber is filled with argon at various pressures, and the fissile material can be coated on the anode, cathode, or both. For analyzing the recombination regime, we consider a model of columnar recombination and discuss its applicability to our chamber. By applying this model to the data, it is possible to estimate the ratio between the recombination coefficient k and an effective column radius b, appearing in the model, to be $k/b=(2.5\pm0.9)\times10^{-6}$ m^2/s for argon. From these results, a routine measurement of the recombination regime is proposed in order to detect gas leakage. This online diagnosis would be beneficial in terms of lifetime and reliability of the neutron instrumentation of nuclear reactors.

1. Introduction

Fission chambers (FC) [1–4] are nuclear detectors that are widely used to deliver online neutron flux measurements for mock-up reactors and material testing reactors. When used for safety purposes, the FC must continuously and quickly deliver measurements that are reliable and easy to interpret, for several reactor cycles. A failure of the detector can be easily confused with a detection of a genuine abnormal situation: it is therefore customary to operate several identical detectors that back each other up. However, an online diagnosis of FC failures would be beneficial in terms of maintenance [5,6].

An effective diagnosis procedure is to be built on a physical modelling of the detector that picks out the observable quantities correlated to the detector specifications. For instance, a gas leakage can be detected by a variation of the mean collected charge or current with respect to the applied bias voltage, i.e. the so-called saturation curve. This curve features three domains, namely the recombination, the saturation and the avalanche domains in order of increasing voltage. For gas pressures of a few bars and low fission rate, the recombination is mainly columnar, i.e. involves electrons and ions coming from the same ionizing fission product. Following the pioneering works of Jaffé [7] and Boag [8], the empirical modelling of the columnar recombination has been recently improved and justified by Chabod [9,10]. Incidently, the problem has recently received attention in an other field than nuclear instrumentation, the search for dark matter in the Universe [11].

However, the involved parameters of this model (namely the recombination coefficient k and the effective column radius b) have been little studied experimentally. Only scarce data are found outside the field of nuclear instrumentation (e.g. [12–14]), yielding $b\sim10^{-5}$ m and $k\sim10^{-11}$ m^3/s for pressures about 1 bar. In this paper, we present new experimental data obtained with a newly developed FC with a diameter of 8 mm (named CF8Rgr in this paper) at several gas pressures in the MINERVE reactor [15] at the Cadarache center of the CEA (namely French Alternative Energies and Atomic Energy Commission). The data is analyzed within the framework of the columnar recombination model, to derive the relevant parameter combinations that can be eventually used for a diagnosis procedure. This paper belongs to our long lasting effort in joining theoretical, modelling and experimental studies to improve design, signal analysis and diagnosis of FC in mock-up, industrial and material testing reactors, e.g. [16–25].

The paper is organized as follows: the experimental data are described (Section 2); the columnar recombination model is presented and its applicability of the model to the data is discussed (Section 3); the method to fit the physical parameters to the data is devised (Section 4); the results are given and discussed (Section 5) with a special focus on a possible use in online diagnosis (Section 6); then we conclude (Section 7).

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2. Experimental data

2.1. Description of the CF8Rgr

The CF8Rgr is a small gap miniature fission chamber. Its design allows easily for changing the detector fill gas, thanks to a dismountable sealing system. This makes it possible to investigate the impact of gas mixture and pressure on signal quality, all other parameters being constant. Three CF8Rgr test detectors were used for these experiments. In the first one (referred to as 2280A), a 1 mg high purity U238 deposit was coated on the anode. In the second one (referred to as 2280C), a deposit with identical material and mass was coated on the cathode. After experiments, these two detectors were dismantled to get their fissile deposit back. A two-deposit detector (referred to as 2280) was constructed by making use of these previous coated anode and cathode. The theoretical sensitivity of this detector is thus the sum of 2280A and 2280C sensitivities. This specific operation was performed in the prospect of various studies such the one here detailed, and others to be presented elsewhere.

The relevant quantities used in this paper are given in Table 1.

2.2. The experimental campaign

Experiments were conducted with all detectors successively filled with pure argon at various pressures: 4 bars, 8 bars, 12 bars and approximately 15 bars (maximum pressure available). Note that because of the filling process, there is an uncertainty about 0.5 bar on the pressure. The fabrication process is assumed to be efficient enough so that gas contamination with nitrogen or oxygen is negligible. For each pressure and detector, experiments consisted in measuring charge distributions of fission products at various bias voltage using a standard gamma spectrometry chain: Canberra 2006 pre-amplifier, 2024 amplifier, MPII digitizer and Genie-2000 acquisition software. From each experimental PHA (Pulse Height Analysis) spectrum, the mean fission product charge Q_0 is calculated in arbitrary units and plotted versus bias voltage, yielding the saturation curve (Section 2.3).

The experimental campaign was held in February and March 2014 in the MINERVE reactor, which is a pool type bi-zone low power reactor operated by CEA Cadarache [15]. The core is made of two parts: a driver zone made of highly enriched MTR fuel elements coupled to a central experimental zone made of 3% U235 enriched UO2 fuel pins. At the center of the MAESTRO [28,29] experimental zone, the neutron spectrum is a mixed energy spectrum representative of an UOx PWR at nominal operating conditions.

For the experiments, test detectors were connected to a low noise coaxial cable of about 10 m. The detection setup was installed at the center of MINERVE experimental zone so that the fissile deposit was at mid fuel elevation. The reactor was operated at 50 W, which corresponded to a detector count rate of around 200 c/s. All measurements were performed in PHA mode (pulse height analysis) so as to gather a satisfactory statistics of more

Table 1
Relevant quantities of the CF8Rgr: anode and cathode radii r_1 and r_2, electrode length ℓ, electron and ion mobility μ_e and μ_a, number X_0 of electron–ion pairs created by the fission products per unit of its track length, normalized to the pressure P. μ_a comes from [26]. μ_e and X_0 comes from [27] confirmed by computations made with the tools of [21].

m			$m^2\,s^{-1}\,V^{-1}$ bar		$m^{-1}\,bar^{-1}$
r_1	r_2	ℓ	$\mu_e P$	$\mu_a P$	X_0/P
$2.75\cdot10^{-3}$	$3.25\cdot10^{-3}$	$21\cdot10^{-3}$	$3.5\cdot10^{-2}$	$4.4\cdot10^{-5}$	$1.8\cdot10^{8}$

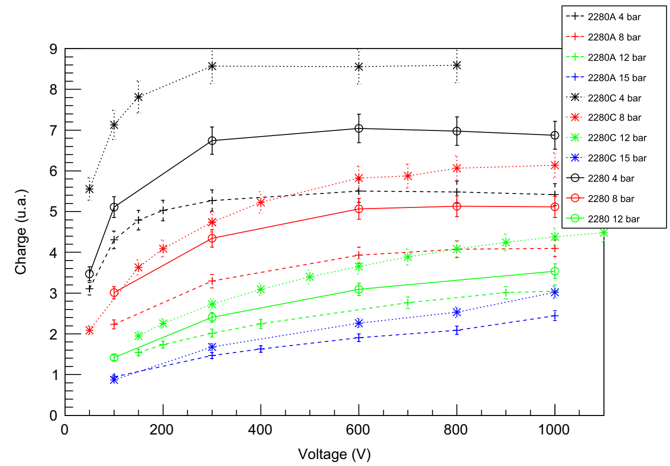

Fig. 1. Experimental saturation curves for the CF8Rgr, at various pressure, the coating being on the anode (2280A) and on the cathode (2280C) or both (2280). On the y-axis, the collected charge (in arbitrary units) is divided by the pressure for plotting purpose.

than 10^5 counts. Measurements were monitored using another miniature fission chamber in pulse mode set in a dedicated experimental channel. Due to cable capacitance (around 200 nF), a significant amount of signal is lost in the cable and thus not measured by our acquisition chain: the observed mean fission product charge is nearly one half of the real charge deposited in the detector. Note that this proportion is constant and, in particular, does not depend on the applied bias voltage. The following experimental results are used in relative, so it was not required to precisely account for this phenomenon.

2.3. The saturation curves

The saturation curves (in arbitrary units of charges) are shown in Fig. 1. No inflexion point, betraying an avalanche regime, can be noticed, except for 4 bar above 1000 V. The curves are concave, with a monotonic growth, typical of a recombination regime. The relative uncertainty is conservatively estimated to 5% from the measuring procedure. It is worth noticing that the so-called saturation plateau is never reached for 12 and 15 bar, making it impossible to assess without extrapolation the mean charge Q_0 that is created in the filling gas. Note that in the case of the chamber with coating on both electrodes (2280), the mean collected charge is found to be the average of the cases with coating on the anode (2280A) and cathode (2280C), as it was expected.

3. Columnar recombination

In an ionization chamber, an ionizing particle ionizes the gas filling the space between two electrodes. The applied voltage separates the electrons and ions, which drift towards the anode and the cathode respectively along the electric field in the absence of magnetic field. The fact that a fraction of the electrons is captured by the ions is coined by the term recombination. Three stages are usually considered:

(1) geminate recombination, where the electron is captured by its parent ion;
(2) columnar recombination, where the electron is captured by an ion coming from the same ionizing particle; because the path of the latter is almost a straight line, and its time of flight is much shorter than the collection time of the charges, the