Qualification of miniature fission chambers at high temperature in OSU Research Reactor

Grégoire de Izarra[1,*], Loïc Barbot[1], and Kevin Tsai[2]
[1]Instrumentation Sensors and Dosimetry Laboratory, CEA Cadarache, St-Paul-lez-Durance, France
[2]Idaho National Laboratory, Idaho Falls, ID, USA
(*) gregoire.deizarra@cea.fr

***Abstract*—With the renewed interest in Sodium Fast Reactors and Advanced Small modular reactors such as Molted Salt ones, there is a need for high temperature (600 °C) neutron instrumentation. In this context, two types of miniatures fission chambers were identified for testing, a CFUE43 dedicated to high temperature conditions and a CF3, the reference fission chamber for in core measurement at CEA. An irradiation was performed at the Ohio State University Research Reactor, in a high temperature irradiation rig that might reach temperatures up to 1200 °C. The rig was installed against the reactor casing, allowing the experimental load to see a maximum neutron flux of about 10^{12} n/cm²/s at full power.**

During three days, the fission chambers were irradiated at different temperature steps, from 20 °C up to 820 °C. Electronic pulse shape, leakage current and counting mode were monitored in parallel thanks to the libera MONACO 3 measurement system. CFUE 43 cannot be operated in counting or Campbell mode because of the low electromagnetic immunity of its mineral cable. CF3 fission chamber can be operated in counting mode above 600 °C even if its leakage current is high, of the order of 10 µA. Failure of CF3 with temperature was monitored. It can be explained with simple models.

***Keywords* —Enter key words or phrases.**

I. INTRODUCTION

Between the 1970s and the late 1980s, the CEA developed several fission chambers operating at high temperature to instrument French sodium-cooled fast reactors (SFR) such as Phénix and SuperPhénix. These developments, carried out in collaboration with the Photonis company (now Exosens), led to the marketing of ex-core detectors, the CFUC, as well as miniature detectors such as the CFUE. These developments were put on hold in the late 90s before being restarted in the 2010 decade through the ASTRID project [1]. At the end of the ASTRID project, it was decided to pursue the work on high temperature fission chambers to maintain the acquired knowledge and for use in specific research programs such as the SAIGA experiment [2] or future advanced reactors.

As part of a collaboration between CEA and INL through the US Department Of Energy, it was possible to test neutron detectors under irradiation at high temperature in the Ohio State University Research Reactor (OSURR).

It was decided to focus the tests on two type of miniature fission chambers: a modified CFUE43 from Exosens designed for sodium fast reactor conditions, and a CF3, which is the reference detector for in-core neutron flux measurement at CEA. The irradiation campaign was tailored first to assess the performance of these sensors at a temperature of 600 °C and then to monitor their failure and their maximum operating temperature.

In this paper, we describe the irradiation campaign. After a brief description of the detectors and the associated electronic measurement system, the main characteristics of the OSU reactor and high temperature irradiation rig are given. A presentation of the main experimental results and their interpretation is given. At last, several improvements to these fission chambers for high temperature application are envisaged.

II. MATERIAL AND METHODS

A. Fission chambers

Two fission chamber models were tested: one CF3 and two CFUE43. The CF3 is a wide range fission chamber designed and built by the CEA for irradiation in PWR in-core conditions. The CFUE43 were purchased from Exosens. This version of CFUE operate specifically in current mode, which is not in the first place attractive for our application because it is not possible to distinguish the neutron contribution from the gamma-induced and the leakage current. We therefore chose to adapt the filling gas pressure in order to maximize the amplitude of the pulses and to exploit CFUE fluctuation and pulse modes. The characteristics of these chambers are summarised in **Erreur ! Source du renvoi introuvable.**.

TABLE I
CHARACTERISTICS OF THE TESTED FISSION CHAMBERS

	CFUE43 N°200 & 201	CF3 N°2349
Fissile deposit	170 µg of ^{235}U	1 µg of ^{235}U
Sensitive length	15 mm	10 mm
Diameter	7 mm	3 mm
Inter-electrodes gap	0.3 mm	0.25 mm
Filling gas	Ar	Ar+4%N_2
Cable	15m, Thx 1 I I 30 Mg	15m, Thx 1 C CaC 22Si
Measurement mode	Counting, Campbell	Counting

The CFUE43 detector is suitable for high-temperature operation: the mineral insulation used in the cable is MgO powder, while the filling gas is pure argon. Argon/nitrogen mixture used in CF3 increase electron drift speed but it is known to change under high-temperature irradiation (nitriding of detector structures).

B. Measurement system

A Libera MONACO 3 system was used during the whole irradiation to polarize the detectors, record signals and process them in real time [3]. This four channels instrument can operate simultaneously in counting, Campbell and current mode at a maximum sampling rate of 1 kHz. This is valuable for the qualification of fission chambers at high temperature: the evolution of leakage current with temperature is monitored while the counting and Campbell mode give the fission rate.

Automatic discrimination and saturation curve generation are available to check the good condition of the detector at the start of the experiment. At last, an oscilloscope mode is also available to monitor electronic pulses generated by the fission chambers. However, due to the 20 MHz bandwidth of the preamplifier, it is not possible to capture the exact duration and shape of the pulses.

C. Reactor and irradiation rig

The OSURR reactor is a pool-type research reactor built in 1960. Originally fuelled with highly enriched fuel plates, the reactor was converted to low-enriched fuel in the 1980s, then its maximum licensed power was increased from 10 kW up to 500 kW in 1992. The depth of the pool is 6 m (20 feet), while the altitude of the core centre is 1.2 m. The typical height available for sample irradiation is around 60 cm (2 feet).

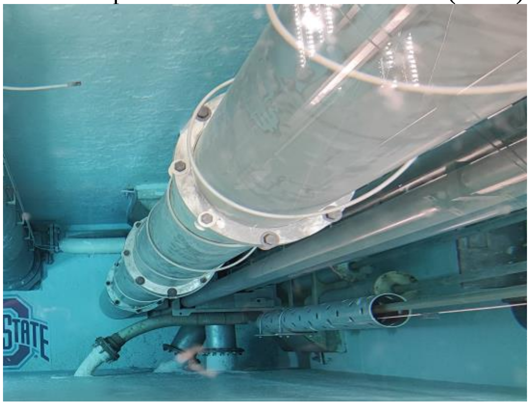

Fig. 1. Picture of the OSU research reactor, with a 23.7 cm diameter dry channel installed against the core casing.

The reactor has removable ex-core dry channels, 16.5 and 23.7 cm in diameter, which are positioned against the core housing to irradiate large elements **Erreur ! Source du renvoi introuvable.**. At the tubes' location, the neutron flux is of the order of 10^{12} n.cm^{-2}.s^{-1}. Furnaces and cryostats have been developed at the NRL (Nuclear Reactor Laboratory - OSU) to equip those ex-core tubes and allow to perform irradiations at temperatures between 4 K and 1500 K [3].

To carry out irradiations at high temperature, the OSURR facility provided us a furnace composed of a cylinder of insulating material buster M35 and a silicon carbide tubular heating element which is positioned at the bottom of the 23.7 cm diameter aluminium dry tube.

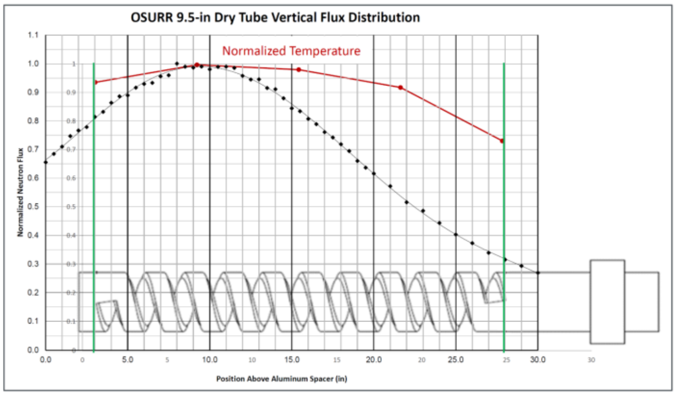

Fig. 2. Temperature and neutron flux as a function of the altitude from the bottom of the SiC Heating element. The twisted SiC element is depicted in the picture for more clarity.

The fission chambers were first encapsulated in closed end steel tubes sealed to prevent leakage in case of failure. They were then inserted into a silica tube with an internal diameter of 50 mm. Fission chambers altitudes were set to have the centre of the sensitive length in the maximum neutron flux (Fig. 2). In order to monitor the temperature at the level of the detectors, three type K thermocouples were positioned in the silica tube at altitudes of 3, 6 and 9 inches from the bottom of the heating elements.

D. Irradiation schedule

The experiment, which took place over three days, allowed the detectors to be irradiated at different temperatures and power levels.

Each day started with the detector at room temperature and the reactor power at 100 W to check the proper operation of the detectors with saturation, discrimination curve and pulse shape analysis. Then measurements were recorded at reactor power of 0.1, 1, 10, 100 and 200 kW to verify the linearity of the measurement modes. Once the nominal operation of the detectors was proven, the furnace was heated up to the target temperature while keeping the reactor power at 1 kW. Few temperatures target were planned for this experimental campaign: 350 °C, 600 °C, 650 °C and 750 °C. After the temperature was stabilized, few reactor power steps were recorded to monitor the measurement modes linearity. Leakage current and mean pulse shape were also recorded.

A part of the third irradiation day was dedicated to the study of the maximum operating temperature and then the failure of the fission chambers. To do so, the reactor power was kept constant at 1 kW and the furnace temperature was raised slowly from 750 °C up to the failure point.

III. EXPERIMENTAL RESULTS

A. Results at room temperature

Before starting the reactor, raw signals were recorded with the FC polarized to evaluate the noise level. As shown in figure 3, the noise level in the CF3 is acceptable, whereas the

CFUE43 pic to pic noise level is larger than the expected pulses amplitude. This might be due to the mineral cable used in the CFUE43 which has a high transfer impedance. As a result, counting and Campbell mode are not usable with CFUE43. Only the current mode is immune to high frequency noise.

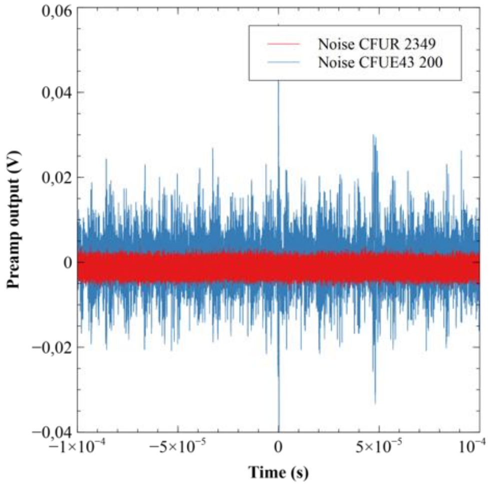

Fig. 3. Noise level recorded with the Libera MONACO 3 system on the CF3 N°2349 and on the CFUE43 N°200. The reactor was shutted down for this measurement.

The reactor was started and stabilized at 100 W to record the CF3 discrimination curve and mean pulse shape (Fig.4). At 1 kW, we noticed CFUE43 current mode seems usable.

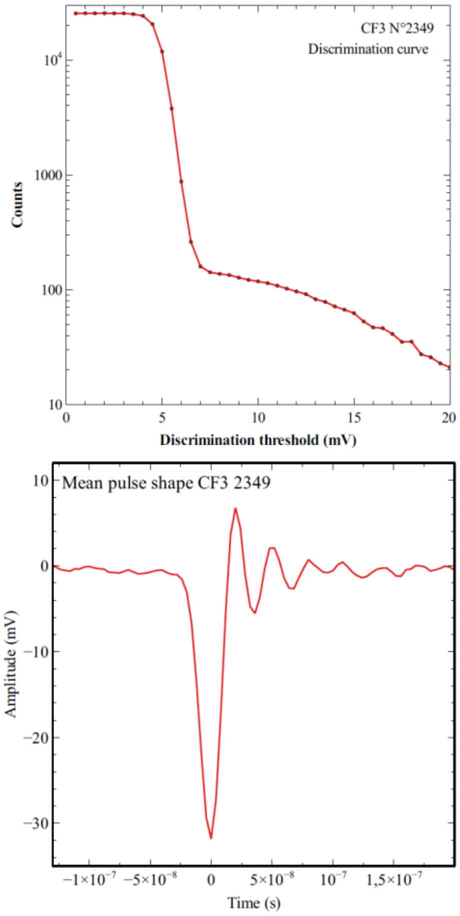

Fig. 4. (up) Discrimination curve of the CF3 N°2349, optimum discrimination level is around 7 mV. (down) CF3 N°2349 mean pulse shape.

Few reactor power steps were performed to monitor the linearity of the fission chambers. The count rate against reactor power recorded with the CF3 is depicted in figure 5.

The maximum count rate of the CF3, 2.78 10^5 cps, is too low to take advantage of the Campbell mode.

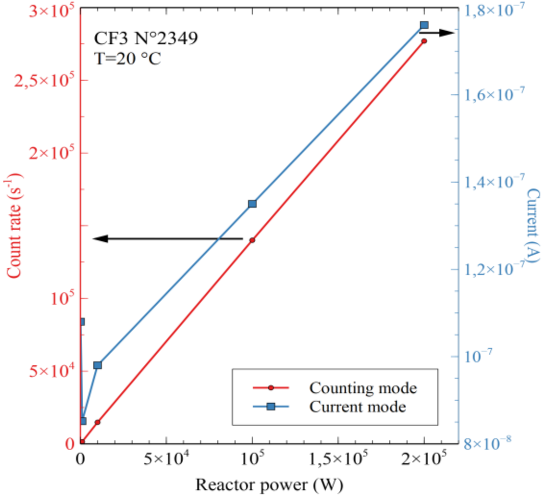

Fig. 5. CF3 N°2349 count rate versus reactor power at room temperature. The mean current measurement is also depicted for comparison with leakage current.

B. *High temperature results*

Because of the SiO_2 mineral cable, the CF3 leakage current is rather high above 600 °C, of the order of 10 µA. Nevertheless, the counting mode is still usable (Fig 6), even if the maximum count rate decreases slightly with the temperature. Between room temperature and 600 °C, the count rate decreased by 4 %.

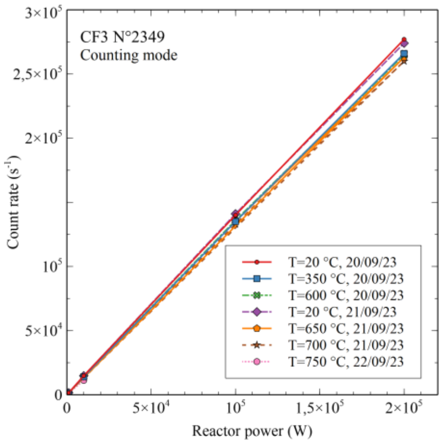

Fig. 6. CF3 N°2349 count rate as a function of reactor power at different furnace temperature. The count rate decreases slightly with the temperature.

During the high temperature power steps, the pulses generated by the CF3 were monitored using the built-in oscilloscope feature of the libera MONACO 3 system. Only one pulse per second is recorded which is not sufficient to extract precise quantitative results from the data. However, it was possible to analyse the FWHM and the amplitude of the recorded pulse to get tendencies. The pulse shape analysis is available in figure 7. Between room temperature and 650 °C, there is no change of the pulse shape. At 750 °C, the pulses start to widen drastically, indicating a change of filling gas transport properties. For the last part of the irradiation, we decided to monitor the failure of the CF3, the temperature was raised slowly while keeping a constant reactor power of 1 kW. At 820 °C, a drastic decrease of pulse duration was noticed along with really narrow pulses. By decreasing the high voltage, the narrow pulses disappeared. To our opinion, the decrease of the pulse duration is due to the failure of the gas thigh feedthrough: A part of the filling gas moved in the mineral cable. This leaded to an increase of reduced electric field and thus to an increase of the electron drift velocity. The really narrow pulses might be due to partial discharge, a well-known phenomenon that appears in fission chambers at high temperature.

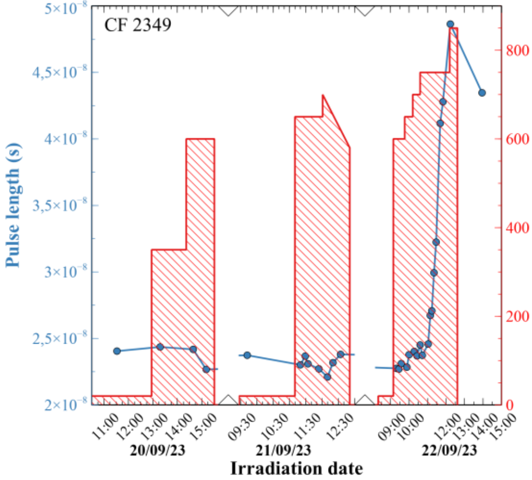

Fig. 7. CF3 N° 2349 pulse full width at half maximum measured during the irradiation campaign.

IV. DATA ANALYSIS

It was shown that performances at high temperature of CF3 fission chambers are slightly different than the one at room temperature. To explain the decrease of count rate and the change of pulse shape with temperature, we developed simple models. The count rate change with temperature might be due to a change of neutron temperature that impact neutron reaction rate. To prove this hypothesis, a furnace model was built with PHITS and JENDL5 [5] library. Using a room temperature thermal neutron source, cross sections at 300 K, 900 K and thermal scattering law for SiC and SiO_2, we were able to compute the neutron spectrum and the fission rate at the centre of the furnace (Fig. 8). With this simple model, a decrease of neutron reaction rate of 4% was computed between 300 K and 900 K, which is in agreement with the experiment.

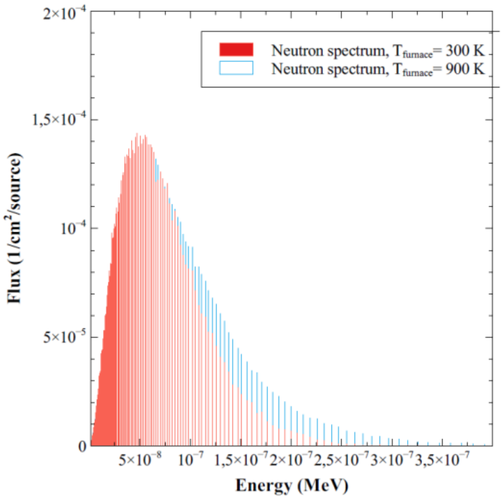

Fig. 8. Computed neutron spectrum inside the furnace, when the irradiation rig is at 300 K (red) and 900 K (blue).

The change of CF3 pulse shape at high temperature might be due to a change in the filling gas composition. Gas mixtures with nitrogen are not used at high temperature since it disappear under the combined action of temperature and radiation in nitriding reaction of the fission chamber's structures. To prove the removal of nitrogen from the filling gases, we computed the electron drift velocity in various argon/nitrogen mixtures [6] (Fig.9). Using the full width at half maximum, and assuming the electronic transfer function has no impact on FWHM differences, the longest pulses recorded at 750 °C correspond to an electron drift velocity of about (10 ± 3) 10^3 m/s. This corresponds to argon with a molar content of nitrogen between 0 and 0.5 % of nitrogen.

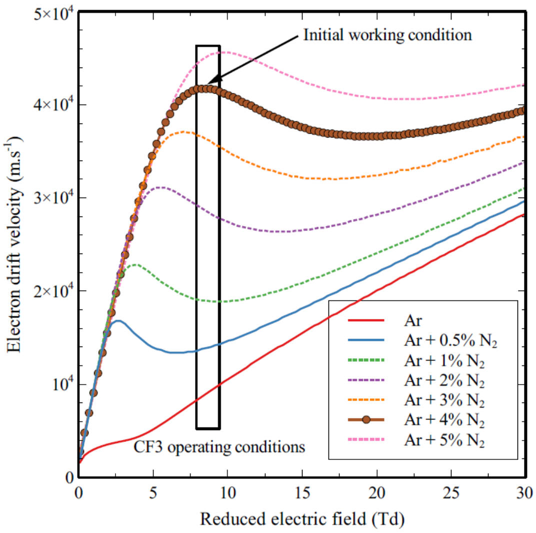

Fig. 9. Electron drift velocity in various argon/nitrogen mixture.

V. CONCLUSIONS

During the irradiation, it was not possible to test CFUE43 fission chamber in pulse and Campbell mode. This is probably due to the high transfer impedance of the 3 mm mineral cable.

The mineral cable should be upgraded to a high immunity one with an outer copper layer to improve the electromagnetic noise immunity of the detector. Even if the CF3 detector was not designed for high temperature operation, the experiment proved that pulse mode worked properly up to 750 °C. Above 750 °C temperature, the combined effect of radiation and temperature remove the nitrogen from the filling gas through nitriding reaction with the metallic structure of the detector. The Campbell mode was not tested because of the low fissile mass and the filling gas composition. By increasing the fissile mass deposit and filling the detector with pure argon, it should be possible to test the Campbell mode in the OSU research reactor.

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