Study on the response of IFMIF fission chambers to mixed neutron-gamma fields: PH-2 experimental tests

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A B S T R A C T

The engineering design of fission chambers as on-line radiation detectors for IFMIF is being performed in the framework of the IFMIF-EVEDA works. In this paper the results of the experiments performed in the BR2 reactor during the phase-2 of the foreseen validation activities are addressed. Two detectors have been tested in a mixed neutron-gamma field with high neutron fluence and gamma absorbed dose rates, comparable with the expected values in the HFTM in IFMIF. Since the neutron spectra in all BR2 channels are dominated by the thermal neutron component, the detectors have been surrounded by a cylindrical gadolinium screen to cut the thermal neutron component, in order to get a more representative test for IFMIF conditions. The integrated gamma absorbed dose was about 4×10^{10} Gy and the fast neutron fluence ($E > 0.1$ MeV) 4×10^{20} n/cm^2. The fission chambers were calibrated in three BR2 channels with different neutron-to-gamma ratio, and the long-term evolution of the signals was studied and compared with theoretical calculations.

1. Introduction

In the framework of the IFMIF-EVEDA tasks, CIEMAT is working on the engineering design of fission chambers as on-line radiation detectors for IFMIF. As part of the BA agreement, SCK·CEN has been also involved in this work.

Fission chambers are widely used in nuclear power plants; however, a great difference between the neutron energy spectra in fission reactors and in IFMIF exists. Therefore the technical characteristics of the chambers must be adjusted in order to reach the appropriate sensitivity value according to the IFMIF neutron spectrum (see Ref. [1]). In addition to that, the good performance and the robustness of the detectors under IFMIF irradiation conditions must be checked through a validation process where the viability of the technical characteristics of the IFMIF fission chamber should be demonstrated under a high radiation environment.

As part of the CIEMAT work, a study on the detectors' specifications as well as on the feasibility of this diagnostic to monitor the spatial profile of the neutron fluence rate in the IFMIF Test Cell was carried out [2]. As a result, a detector with a diameter of 3 mm and ^{238}U as fissile deposit was found to be the most adequate for working in the IFMIF high flux test module. For completing the study, validation experiments had to be performed with the objective of testing the behavior of some prototypes under conditions as close as possible to the IFMIF ones. These experimental activities have been divided into three different phases: the phase-1 (PH-1), for studying the detectors behavior under an environment free of neutrons, was completed satisfactorily: the chambers showed the expected behavior under gamma irradiation, the calculated values being in good agreement with measured ones [3]; the phase-2 (PH-2) for monitoring fast neutrons; and the phase-3 (PH-3) for testing the robustness of the detectors in an environment representative for IFMIF. The present work shows the results achieved during the PH-2.

2. Experimental procedure for PH-2

The main objectives of the PH-2 have been to test the sensitivity of two detectors (one fission chamber, model CFUR43/C5B-U8, and one ionization chamber, model CRGR10/C5B, both from PHOTONIS) under a combined neutron-gamma field. These detectors have the same technical characteristics as the proposed ones for IFMIF [2]. The experiments were performed during the BR2 cycle 03/2009 ("1st cycle", from April 16 till May 8, 2009) and the cycle 04/2009 ("2nd cycle", from July 20 till August 19, 2009).

Table 1
Thermal and fast neutron fluence and gamma heating rates for the selected irradiation channels.

Channel	Φ_{th} (n/cm^2/s)	$\Phi_{E>0.1\,MeV}$ (n/cm^2/s)	GHR (kGy/s)
L120 (1stcycle)	1.0×10^{14}	0.12×10^{14}	1.7
G60 (1st cycle)	1.9×10^{14}	0.6×10^{14}	3.0
F46 (2nd cycle)	2.3×10^{14}	0.8×10^{14}	3.6

The linearity of the chambers signal with the neutron flux has been studied, and theoretical calculations for estimating the fission chamber response and the evolution of the fissile deposit were performed. The ionization chamber measured the contribution to the signal due to gamma rays. To get the pure neutron induced signal (given by the fission chamber), the usual procedure is to subtract the currents from each other.

The fission chamber, which operates in current mode, has a diameter of 3 mm and 300 μg of ^{238}U as fissile deposit, with Ar at 5 bar as filling gas. The working voltage specified by the manufacturer is 150 V. The ionization chamber has the same characteristics but without fissile material. Details on the detectors characteristics can be found in Ref. [2]. Both detectors were mounted on an experimental rig for irradiation in several BR2 channels equipped with thimble tubes. During the irradiation the chambers were immersed in demineralized water at an absolute pressure of 2 bar and a temperature of 80 °C. Typical thermal and fast neutron flux and gamma heating rate (GHR) conditions for the selected BR2 irradiation channels can be found in Table 1. These values are valid at reactor midplane level; the axial profile follows in first approximation a cosine profile, with an effective full-width at half maximum of about 600 mm.

On the same rig, baptized as FICTIONS-8, various reference detectors (gamma thermometer, Rh-SPND) were mounted. Two activation dosimeter needles were prepared for short-time irradiation inside the central tube of the rig; from the measured activation rates of Ni, Fe and Nb samples, information on the average fast neutron flux could be obtained. The rig could be positioned in a reproducible way at various vertical levels and orientations. In this way the circumferential and axial flux gradients could be assessed. The knowledge of the flux gradients in each channel was crucial for correlating the signals from each chamber with the reference signals from other detectors, since they were placed at different locations inside the rig.

The neutron spectra in all BR2 thimble tubes are dominated by the thermal component. However, in IFMIF the fission chambers will be exposed to neutrons with energies up to 55 MeV, 80% of them having energies above 1 MeV (see [1]). In order to get a more representative test for IFMIF conditions (low ratio thermal/fast neutrons), during the experiment the fission and ionization chambers were surrounded by a gadolinium (Gd) screen to cut the thermal neutron component. Gd foils (0.6 mm thickness) were folded into a double-wall stainless steel tube, leading to a cylindrical screen with a radius of 2.4–3.0 mm and a height of 50 mm. Fig. 1 shows the typical calculated spectra at the position of the sensitive part of the fission chamber with and without Gd screen. As can be seen in the figure, the thermal neutron part is completely cut by the Gd, but the epithermal one (in the range 1 eV–100 keV) is almost unaffected. The efficiency of a Gd screen remains unchanged until the end of its lifetime, since it is determined by the complete burn-up of the ^{155}Gd and ^{157}Gd isotopes; and calculations showed that these isotopes would be completely consumed at a thermal neutron fluence of 2×10^{21} n/cm^2 (largely sufficient for the planned irradiation time). The absorption of the neutrons leads to additional local nuclear heating, but with negligible effect on the fission chamber temperature. However, the gamma rays emitted after neutron

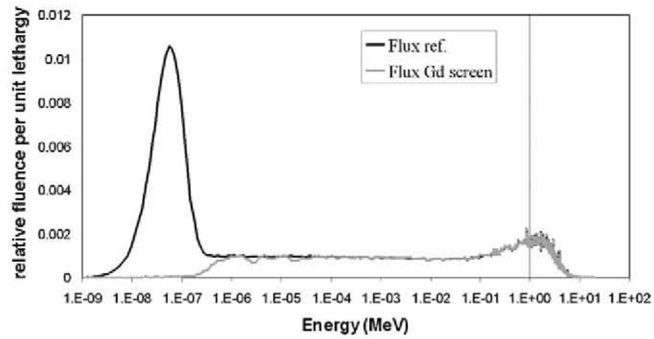

Fig. 1. Calculated neutron spectra with (black line) and without Gd screen (gray line).

capture generate a significant additional signal component in the detectors.

The chambers were equipped with 20 m long, 1 mm diameter MI cables, transmitting the signals to a connector plate outside the reactor pool and from there to the Novelec amplifiers (type 8208HT) that were used to polarize the chambers and amplify the output currents. The output currents were sequentially measured and stored once per minute.

3. Experimental results

3.1. Long term behavior

Both detectors were irradiated during two BR2 reactor cycles (about 50 days). The integrated gamma absorbed dose was about 4×10^{10} Gy and the fast neutron fluence ($E>0.1$ MeV) 4×10^{20} n/cm^2. Both detectors kept on functioning well until the end of the irradiation campaign. Raw data stored during the two cycles can be observed in Fig. 2, where black diamonds correspond to the fission chamber signal and gray squares to the ionization chamber one. As can be seen, an evolution on the detectors signal can be observed, this point will be discussed in the next section. The small difference between the signals of both detectors is partly due to the neutron induced component in the signal of the chamber with fissile deposit, but is also affected by flux gradients between both detector positions.

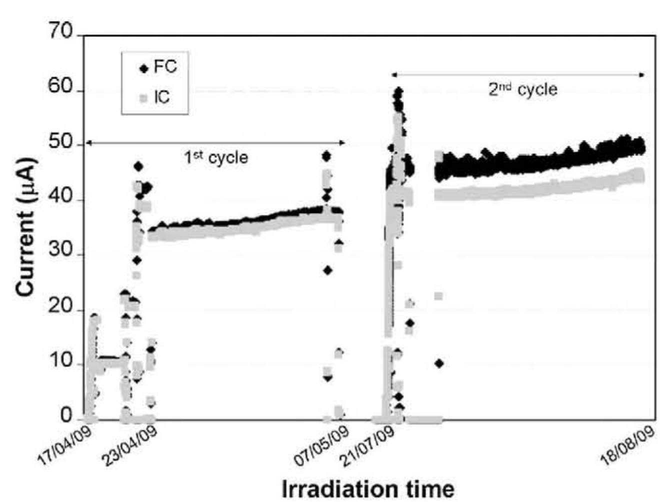

Fig. 2. Long term evolution of the chambers signals. Only the data with a polarization voltage within the saturation plateau (see Section 3.2) are presented.

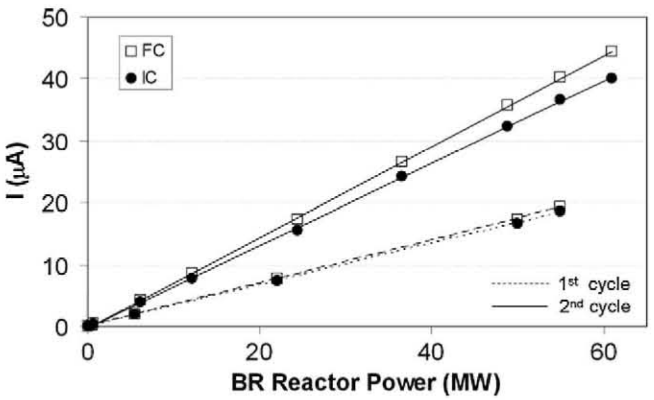

Fig. 3. Observed currents of the FC and the IC (within the saturation plateau) during the startup of the two reactor cycles. Linear fits are added to guide the eye.

3.2. *Linearity of the response and saturation curves*

In Fig. 3 data taken during the stepwise reactor start-up (in both irradiation campaigns) are presented, proving the linearity of the response of both detectors. The differences in the slopes correspond to the two reactor cycles, where the chambers were located in different channels and, consequently, the neutron spectra and flux levels were also different.

The current-to-voltage characteristics of the sensors were recorded for different neutron fluence and fluence rate values. They showed the normal behavior: after a fast increase of the current with voltage, the current levels off and reaches the desired voltage-independent value (beyond 50–100 V). The beginning of this saturation regime depends on the flux: higher voltage needed for high fluxes. Fig. 4 shows the results obtained with the fission chamber for both cycles, the ionization chamber showing a nearly identical behavior (not plotted for simplifying the drawing).

At the end of the irradiation tests (18/08/2009), the voltage supplied to the chambers was increased to 400 V to investigate the behavior up to the breakdown voltage. Up to 250 V, the signals stayed constant. Beyond that value, the signals were affected by secondary ionization in the gas of the chambers, leading to a slight increase in the currents. Around 340 V, breakdown occurred for both detectors. This test proves that there is a large margin in operational voltage.

The insulation resistance (R_{is}) of a fission chamber (and its associated cable) is a crucial parameter, since it determines the leak current: for a typical polarization voltage of 100 V, a R_{is} of 0.1 GΩ would lead to a leak current of 1 μA, which might not be negligible in some circumstances. R_{is} values measured at various stages of the assembly of the rig were always higher than 1000 GΩ. Under

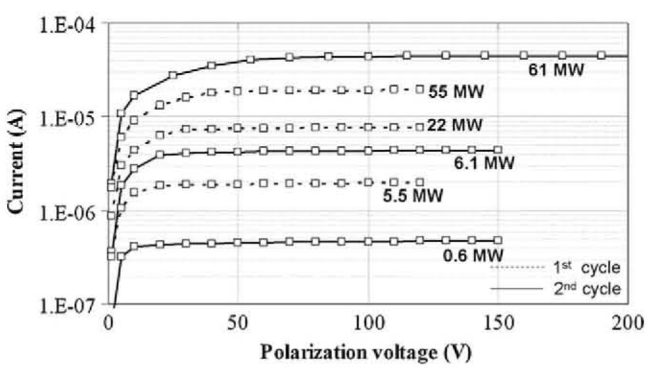

Fig. 4. Examples of $I(V)$ curves at various BR2 power (labeled) for the FC.

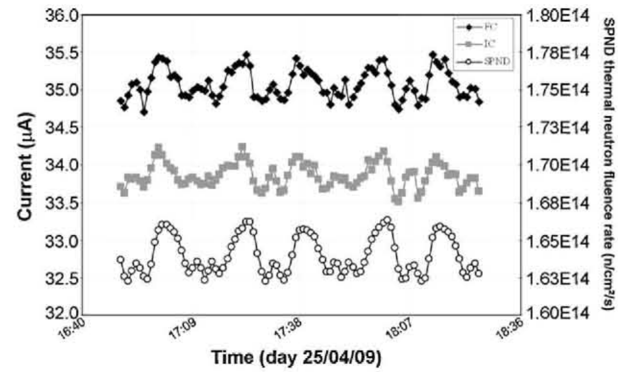

Fig. 5. Example of FC, IC and SPND data obtained in channel G60 with the reactor at 55 MW, following small periodic flux fluctuations in a nicely correlated way.

irradiation in BR2 the R_{is} values dropped significantly to values depending on the radiation field seen by the detector cables. Still, in the reference detector position with BR2 at full power, the R_{is} were higher than 0.3 GΩ, leading to a relative leak current contribution to the detector signal of <2%.

Fig. 5 shows the response of the sensors and of one of the SPNDs to the periodic flux variations (period in the order of 20 min, amplitude of about 1%) due to the movements of the silicon irradiation device in the reactor core. All detectors consistently follow these variations. The relative noise on the chambers currents was found to be of the order of 0.2% for an absolute current of 35 μA.

4. Evolution of the neutron sensitivity of the CFUR43

Due to the special irradiation characteristics of IFMIF (high neutron and gamma fluence rate values, presence of fast neutrons), at present fission chambers cannot be tested in a similar installation. Therefore the use of numerical codes to predict the behavior of the detectors during IFMIF operation is necessary, being an important tool to extrapolate the experimental results to the IFMIF conditions. In this line, a comparison between experimental and theoretical data was done, with the main objective of validating the codes.

Based on the calculated average neutron spectra for each of the three irradiation channels (inside the Gd screens), the evolution of the fissile deposit during the irradiation was calculated with the ACAB code [4]. ACAB provides information about the instantaneous fission rate and the isotopic composition, therefore a comparison between the expected neutron induced signal of the fission chamber with the experimental data can be per-

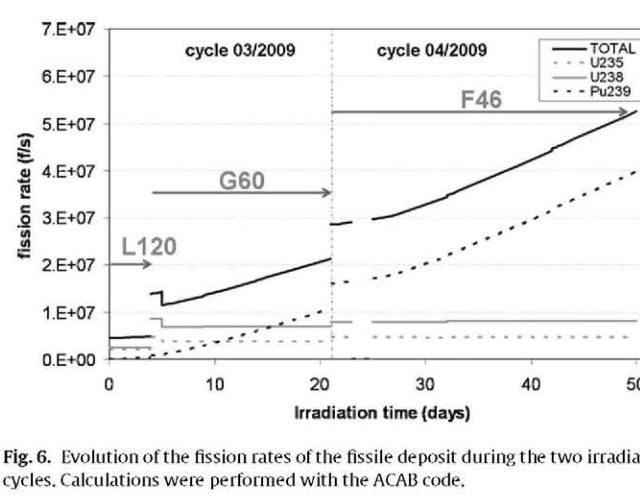

Fig. 6. Evolution of the fission rates of the fissile deposit during the two irradiation cycles. Calculations were performed with the ACAB code.

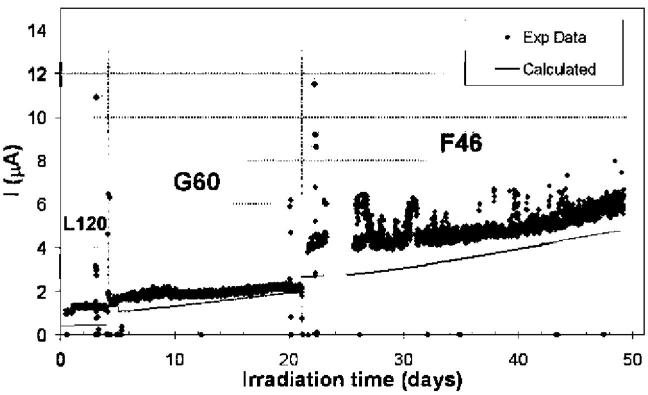

Fig. 7. Purely neutron-induced signal of the FC after gradient corrections and gamma subtraction (black diamonds) and comparison with theoretical calculation (solid line).

formed. Fission rates have been calculated starting from the initial isotopic composition of the fissile deposit (total mass of 300 μg):

$$^{238}\mathrm{U} : 299.39\,\mu\mathrm{g}/^{235}\mathrm{U} : 0.60\,\mu\mathrm{g}/^{234}\mathrm{U} : 0.01\,\mu\mathrm{g}$$

It is well known that under a thermal neutron flux, ^{238}U efficiently transmutes into ^{239}Pu, which easily fissions under thermal neutron irradiation. In these irradiation tests, the thermal neutron flux component is removed by the Gd screen, but the epithermal component is still present (see Fig. 1). This neutron component also leads to some extent to the gradual formation of ^{239}Pu and therefore to a growing fission rate.

Fig. 6 shows the evolution of the fission rate for ^{238}U, ^{235}U and ^{239}Pu calculated with ACAB. The complete irradiation history was taken into account for calculations. The contribution of ^{239}Pu increased gradually during the irradiation in G60 (first cycle) and became dominant when the chambers were introduced in the channel F46 (second cycle of irradiation). The contribution of the uranium remained approximately constant (when rescaled to the neutron flux) during the complete irradiation period.

Fig. 7 shows a comparison between calculated values of the saturation current and experimental data. The numerical procedure presented in Ref. [2] was used to calculate the saturation current (that within the saturation plateau) in the chambers. The fission rates presented before, as well as the technical characteristics of the detectors, were used as inputs for the code. The experimental purely neutron signal have been obtained by subtracting the current due to gammas ($I_{FC} - I_{IC}$). Before subtracting the currents from each other, it was necessary to correct the effect of the flux gradient. It should be pointed out that the results are very sensitive to slight changes in the flux gradient, due to the small difference between the signals from the fission and the ionization chambers, as seen in Fig. 2. The lack of data between the irradiation days 24 and 25 is explained because the rig was out of the thimble channel (zero flux). This point was also taken into account for the calculations (see Fig. 6).

The trends of the experimental data and the calculated curve are very similar, as can be seen in Fig. 7, considering the uncertainties in the evolution of the irradiation conditions as well as in the gradients when calculating both the evolution of the fissile deposit and the experimental values. Moreover, calculated absolute values of the saturation current are in reasonable agreement (discrepancies <30% on average) with the measured ones. It is important to notice the influence of the cross section uncertainties in the predicted value. Calculations performed for a ^{238}U deposit showed that, in BR2 conditions, it could lead to 14% relative error in sensitivity to fast neutrons [5].

5. Conclusions

Test of PHOTONIS CFUR43 fission (^{238}U) and CRGR10 ionization chambers in three different channels of the BR2 reactor have been performed, proving the reliability and adequate functioning of these detectors. In order to get a more representative test for IFMIF conditions, the chambers were surrounded by a Gd screen to cut the thermal part of the neutron spectrum.

The irradiation period lasted 50 BR2 full power days, with an integrated gamma absorbed dose of 4×10^{10} Gy and fast neutron fluence ($E > 0.1$ MeV) of 4×10^{20} n/cm^2. The linearity of the chambers response was very satisfactory and the saturation (I/V) curves presented the normal behavior. The signals remained stable till the end of the experiments, and a slight evolution of the neutron sensitivity due to transmutation of ^{238}U into ^{239}Pu was found. Within experimental uncertainties, the experimental data are consistent with theoretical calculations.

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References

[1] M. Martone (Ed.), IFMIF – Conceptual Design Activity Final Report, IFMIF-CDA-Team, 1996, ENEA-RT/ERG/FUS/9611-Report, December.
[2] D. Rapisarda, A. García, O. Cabellos, F. Mota, et al., Fusion Eng. Des. 84 (2009) 1570–1574.
[3] D. Rapisarda, Á. García, et al., 9th International Symposium on Fusion Nuclear Technology, Dalian, China, October 11–16, 2009, PO3-118.
[4] J. Sanz, O. Cabellos, N. García-Herranz, ACAB-2008, ACtivation ABacus Code V2008, NEA Data Bank (NEA-1839), 2009.
[5] O. Cabellos, et al., Nucl. Instr. Methods A 618 (2010) 248–259.