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In-Pile Qualification of the Fast-Neutron-Detection-System

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***Abstract*— In order to improve measurement techniques for neutron flux assessment, a unique system for online measurement of fast neutron flux has been developed and recently qualified in-pile by the French Alternative Energies and Atomic Energy Commission (CEA) in cooperation with the Belgian Nuclear Research Centre (SCK•CEN). The Fast-Neutron-Detection-System (FNDS) has been designed to monitor accurately high-energy neutrons flux (E > 1 MeV) in typical Material Testing Reactor conditions, where overall neutron flux level can be as high as 10^{15} n.cm^{-2}.s^{-1} and is generally dominated by thermal neutrons. Moreover, the neutron flux is coupled with a high gamma flux of typically a few 10^{15} γ.cm^{-2}.s^{-1}, which can be highly disturbing for the online measurement of neutron fluxes.**

The patented FNDS system is based on two detectors, including a miniature fission chamber with a special fissile material presenting an energy threshold near 1 MeV, which can be ^{242}Pu for MTR conditions. Fission chambers are operated in Campbelling mode for an efficient gamma rejection. FNDS also includes a specific software that processes measurements to compensate online the fissile material depletion and to adjust the sensitivity of the detectors, in order to produce a precise evaluation of both thermal and fast neutron flux even after long term irradiation.

FNDS has been validated through a two-step experimental program. A first set of tests was performed at BR2 reactor operated by SCK•CEN in Belgium. Then a second test was recently completed at ISIS reactor operated by CEA in France. FNDS proved its ability to measure online the fast neutron flux with an overall accuracy better than 5%.

***Index Terms*—Nuclear Measurements, Fission Chamber, Reactor Instrumentation**

I. Introduction

FAST neutron flux (E ≥ 1 MeV) is a key neutron parameter in nuclear reactors. Its measurement is particularly relevant to assess material damage under irradiation. In very low power research reactors, such as ZPRs (Zero Power Reactors), the fast neutron flux is usually measured on-line with specific fission chambers, containing for example ^{238}U coating. In more powerful reactors, such as Material Testing Reactors (MTRs) or nuclear power plants (NPPs), techniques used in ZPRs are not appropriate. This is mainly due to the rapid evolution of the fissile coating under high neutron flux that reduces the sensitivity of the sensor to the 'fast' spectrum domain (cf. II.B). This neutron parameter is therefore not accessible on-line and is generally evaluated afterward by activation dosimetry or by Monte Carlo calculations. However, in the current context of increasing requirements for in-pile measurements, particularly for experiments in MTRs, the on-line measurement of fast neutron flux has become a major objective.

In order to ensure the quality and the relevance of irradiation programs in the future Jules Horowitz Reactor (JHR), the French Alternative Energies and Atomic Energy Commission (CEA) has significantly increased its research and development effort in the field of in-pile instrumentation during the last decade. In this context and in the framework of the Joint Instrumentation Laboratory between the CEA and the Belgian Nuclear Research Centre (SCK•CEN), a measurement system dedicated to on-line measurement of fast neutron flux has been developed.

II. FNDS specifications

On-line measurements of fast neutron flux are based on the use of a fission chamber with a specific fissile coating, presenting an energy threshold near the fast domain (E > 1 MeV). If the use of such fission chamber is not a problem at very low neutron flux, it faces major difficulties under intense mixed neutron and gamma fluxes. First of all, because of the low neutron sensitivity of this type of fission chamber, the high gamma flux of MTRs leads to a high gamma contribution to the signal. Furthermore, neutron captures on the nuclei of the fissile coating create isotopes that have a high cross-section in the thermal spectrum domain. Thus the 'fast' sensitivity of the detector decreases rapidly. Isotopic impurities of the coating must also be taken into account. Figure 1 illustrates this difficulty for the use of ^{242}Pu, which has a suitable response in the fast spectrum domain [1].

We can notice that impurities and isotopes created by neutron captures induce an increasingly high sensitivity to thermal neutrons.

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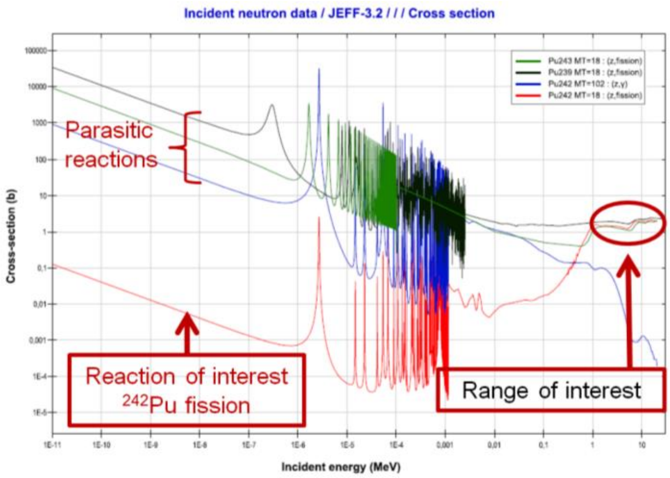

Fig. 1. Fission cross sections of a typical ^{242}Pu fissile coating showing that impurities and isotopes created by capture must be taken into account for fast neutron flux measurements

A. FNDS general description

In order to compensate difficulties mentioned above, FNDS includes an acquisition system allowing measurements with fission chambers in Campbelling mode. This mode allows a very efficient rejection of the gamma contribution [2] while offering a very wide dynamic range. FNDS also integrates signal processing software that firstly calculate in real time the evolution of the fissile coating of the fission chamber using an evolution code DARWIN [3], and that secondly deduce the corresponding evolution of the neutron sensitivity of the fast fission chamber. This software extracts in real-time the value of the fast neutron flux from the signal.

In order to allow a precise evaluation of thermal neutron fluence received by the 'fast' fission chamber, FNDS is equipped with a second detector that is sensitive to thermal neutron flux and positioned near the 'fast' fission chamber. This second detector may be a fission chamber with ^{235}U coating or a Self-Powered Neutron Detector (SPND).

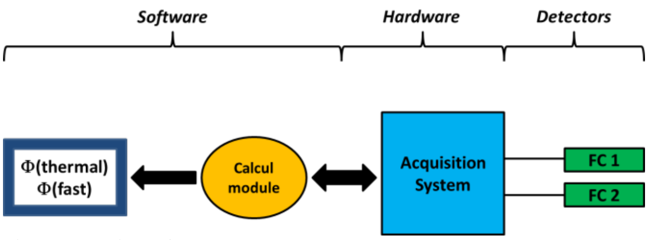

Fig. 2. Overview of FNDS components

FNDS thus consists in 2 detectors for 'fast' and 'thermal' spectrum domains, an acquisition system operating in Campbelling mode and a calculation module for on-line analysis of neutron fluxes (Figure 2). These innovations were patented for the detectors [4] and for the entire measurement system [5].

B. Detectors

An important bibliography study was carried out to establish the state of the art of neutron and photonic measurements in MTRs [6], and led us to select fission chamber sensors. It was shown that the most suitable fissile isotope for the estimation of the fast neutron flux is ^{242}Pu under the typical irradiation conditions of MTRs, such as OSIRIS (CEA Saclay – France), BR2 (Mol – Belgium) and JHR reactors [1, 7]. Figure 3 illustrates the raison why ^{242}Pu coating is the best choice compared to other fissile isotopes; it shows the stability of its fast neutron sensitivity at high fluence.

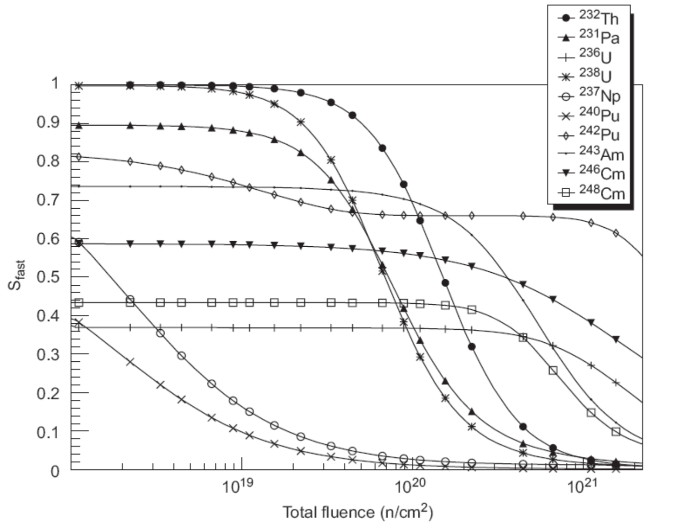

Fig. 3. Sensitivity to fast neutrons for initially pure deposits under typical BR2 neutron spectrum [3]

A typical 'fast' fission chamber selected for MTRs contains 100 µg of ^{242}Pu while the typical associated 'thermal' detector contains 10 µg of ^{235}U. Both sensors have a 3 mm outer diameter body and integrated mineral insulated cable.

These sensors have been developed and manufactured at the Fission Chamber Manufacturing Workshop located in CEA Cadarache.

C. Acquisition system

The acquisition system has 2 channels for the sensor couple. Each channel is equipped with a high-voltage power supply for polarization with adjustable voltage (typically 250 V to reach the saturation plateau of a 3 mm fission chamber). The measured low-level current signals pass through a preamplifier (manufactured by CEA Saclay), amplification stage and then are filtered and digitalized for processing with the measurement interpretation software.

There are typically 3 modes to operate fission chambers: pulse, fluctuation (or Campbelling) and current modes. In MTRs conditions, the advantage of the Campbelling mode is the radical limitation of the gamma contribution on the signal [2] compared to current mode. Indeed, MTR neutron fluxes are too high to operate such fission chambers in pulse mode.

In Campbelling mode, the measurement of the variance of low fission chamber signal with a specific bandwidth has required the development of a dedicated acquisition system. As such a system was not available from Industry; prototypes were specially designed at CEA. Studies are on-going for the industrialization of such acquisition system in a short term [7].

D. Processing software

The FNDS processing software calculates the sensitivity of each fission chamber to the thermal, epithermal and fast neutrons from specific input data (variance measurements, calibration coefficients, mass and isotopic composition of the fissile coatings, nuclear data library, etc.) and then calculates the thermal and fast neutron fluxes versus time.

Processing software includes DARWIN code [3], developed by the CEA, to compute fission cross sections of each isotope present in the fissile coating and to calculate the isotopic evolution of these coatings with fluence and time. The method to combine measurements and estimate fast neutron flux is detailed in [6, 8].

III. In-Pile qualification of FNDS

FNDS has been validated through a two-step experimental program. A first set of tests was performed at BR2 reactor through the FICTIONS-8 experiment. Two FNDS prototypes were operated in-pile during nearly 1000 hours. This experiment exhibited the consistency of the measurement of thermal to fast neutron flux ratio with Monte Carlo calculations, as well as the right compensation of fissile material depletion [9].

A second set of tests was then necessary to qualify the absolute fast neutron flux measurement process. The main requirement was to perform measurements in well-controlled conditions (neutron spectrum, flux gradient, etc.) in order to minimize external sources of uncertainty and bias. In this context, it was decided to carry out the EFICAF (Estimation of Flux in Isis by Fission Chamber) experiment in ISIS reactor (CEA Saclay, France). ISIS reactor allows stable and reproducible irradiation conditions. Its neutron flux level is also sufficient to operate fission chambers in Campbelling mode. Moreover, its flexibility allowed to carry out all the measurements that were necessary for the qualification (on-line measurements and activation dosimetry measurements without external disturbance).

Table 1 and Table 2 summarize the results of respectively thermal and fast neutron fluxes measured by FNDS and compared with values given the TRIPOLI4 Monte-Carlo code and activation dosimetry.

TABLE I
Thermal neutron flux evaluations and deviations between FNDS and TRIPOLI4 calculations and between FNDS and AlCo1% measurements

	CF U235 ($n.cm^{-2}.s^{-1}$)	(TRIPOLI/CF U235)-1	(AlCo 1%/CF U235)-1
1st measurements	9.34E+11	11.0%	7.5%
2nd measurements	9.15E+11	13.3%	9.7%

TABLE II
Fast neutron flux evaluations and deviations between FNDS and TRIPOLI4 calculations and between FNDS and Fe, Ni measurements

	CF Pu242 ($n.cm^{-2}.s^{-1}$)	(TRIPOLI/CF Pu242)-1	(Fe-Ni/CF Pu242)-1
1st measurements	4.39E+11	7.9%	4.4%
2nd measurements	4.40E+11	7.7%	4.1%

These results confirm the good agreement for absolute thermal neutron flux using Campbelling mode operation and the corresponding calibration process [10]. The deviation between FNDS fast neutron flux measurements and dosimetry results is mainly covered by the uncertainties of the activation dosimetry measurements (typically 4% for fast neutron flux evaluation). The results of this experiment confirm the quality of the on-line fast neutron flux measurements at a few 10^{11} $n.cm^{-2}.s^{-1}$ (E > 1 MeV) with this type of miniature fission chambers and therefore confirm FNDS capability to measure in real-time the absolute thermal and fast neutron fluxes with an excellent accuracy.

IV. Conclusion

EFICAF experiment demonstrated the ability of FNDS to measure on-line thermal and fast neutron fluxes. Deviations between fast neutron flux measured by FNDS and activation dosimetry results are below 5%. These results confirm the excellent accuracy of the analysis method using a couple of ^{235}U and ^{242}Pu fissile coatings and special calibration in Campbelling mode.

FNDS is now operational and is assumed to be the first and unique acquisition system able to provide an on-line measurement of the fast neutron flux in MTR conditions. This system will of course be used to perform spectral neutron characterization of JHR channels, but it may also be implemented in future irradiation experiments, for a better and real-time evaluation of the fast neutron flux received by material and fuel samples.

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