



Changes of the Neutron Flux of the Nuclear Reactor Triga Mark III Since the Conversion from High to Low ^{235}U Enrichment

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ABSTRACT

The neutron flux of the Triga Mark III research reactor was studied using nuclear track detectors. The facility of the National Institute for Nuclear Research (ININ), operates with a new core load of 85 LEU 30/20 (Low Enriched Uranium) fuel elements. The reactor provides a neutron flux around 2×10^{12} n cm⁻²s⁻¹ at the irradiation channel. In this channel, CR-39 (allyl diglycol polycarbonate) Landauer® detectors were exposed to neutrons; the detectors were covered with a 3 mm acrylic sheet for (n, p) reaction. Results show a linear response between the reactor power in the range 0.1 – 7 kW, and the average nuclear track density with data reproducibility and relatively low uncertainty ($\pm 5\%$). The method is a simple technique, fast and reliable procedure to monitor the research reactor operating power levels.

1. Introduction

In 2010 an agreement between Canada, USA and Mexico, within the International Global Threat Reduction included the reduced enrichment for research and test reactors program, consisting in modify the nuclear reactors core fuel elements from highly enriched uranium (70%) to a lower one (20%). The fuel modification could be done after extensive international cooperation between Mexico, the International Atomic Energy Agency (Vienna, Austria) and the United States of America. In spite of core modification such as lower fuel enrichment and with fewer elements, it is expected that the ININ research reactor would operate with the same characteristics i.e. neutron density and power as the one before fuel alteration was made. One way to determine the neutron flux is related to passive detectors. Many experimental results demonstrated the methodology soundness in the field of neutron studies. Some groups employed Nuclear Track Detectors (NTD) [1, 2] in neutron beam dosimetry, extending the technique first to neutron field mapping [3, 4], and later for radiography and

radiation protection [5, 6, 7, 8], neutron induced nuclear recoils events by CR-39 polycarbonate and more recently it was applied in fast neutron spectrometry [9]. Based on the referenced information and driven by experience it was considered an important initiative to determine NTD response and limitation to determine characteristic neutron flux of Triga Mark III reactor as a function of the operating power. In Figure 1 a horizontal cut section of the TrigaMark III core before the modification was made is shown. It consisted in a mixed core with 53 standard fuel elements and 25 FLIP (Fuel lifetime improvement program) highly enriched elements with 70 % ^{235}U .

In Figure 2 the new nuclear reactor core with LEU 30/20 (Low enrichment uranium) fuel elements is shown, in operation since 2012.

The reactor core is submerged in an aluminum pool, which is supported by a reinforced concrete structure (it supports earthquakes even to 0.2 G). Dimensions of the pool are: 7.6 m long, 3.0 m wide, and 7.6 m depth, with an estimated volume of 150 m³. Aluminum thickness varies

from 6.3 mm on the top to 19 mm in the wall bottom and in the bottom of the pool (Flores-Callejas, 2011). An image of the reactor is shown in Figure 3.

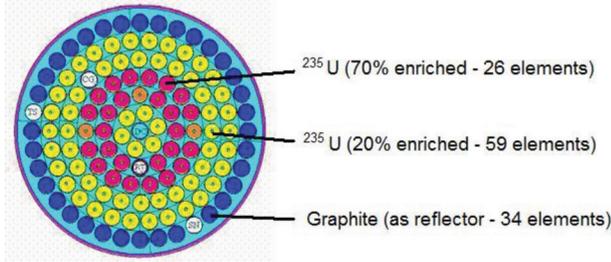


Figure 1: Mixed reactor core in operation 1988-2011. It is composed with standard low fuel elements (yellow) and FLIP high fuel elements, with 70% of U^{235} (red).

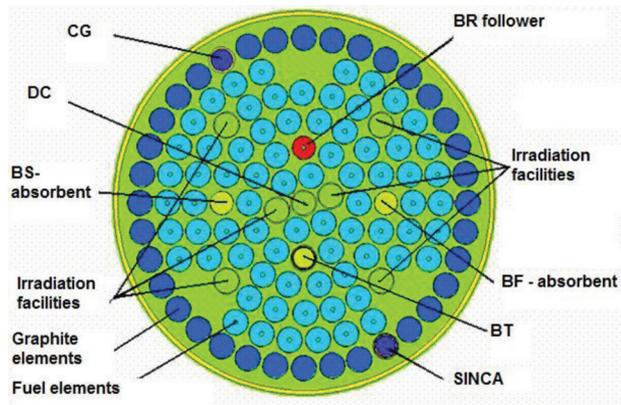


Figure 2: The reactor core in operation since 2012.



Figure 3: Reactor hall and reactor general view.

2. The Nuclear Track Methodology

Nuclear Track Methodology (NTM) is often employed for neutron flux measurements and dosimetry.

CR-39 polymer is employed as detector, which is sensitive to charged particles. Neutrons are detected indirectly, through a nuclear reaction of backscattering of neutrons with a charged particle. In this work the neutron-proton interaction is used. In order to increase the efficiency of the (n, p) reaction, an acrylic plate 3 mm width in contact with the CR-39 detector is employed.

In Figure 4 the neutron flux of the Triga Mark III as a function of the kinetic energy is shown. The NTM is sensitive mainly in the fast neutron region.

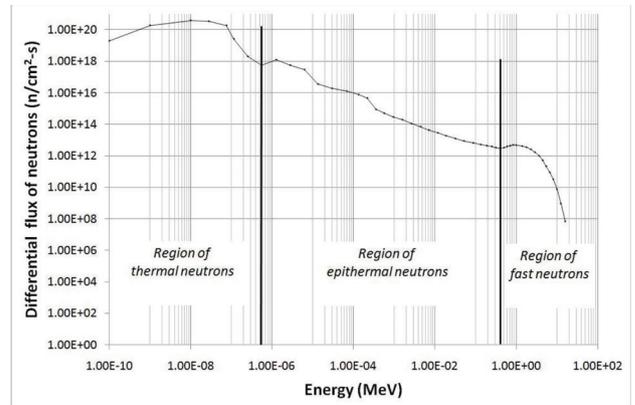


Figure 4: Energy spectrum of the neutron flux of the Triga Mark III.

The detectors schematic views are given in Figure 5. The CR-39 detectors used have a square area of $1 \times 1 \text{ cm}^2$, and $500 \mu\text{m}$ width geometry, in contact with an acrylic plate 3 mm width.

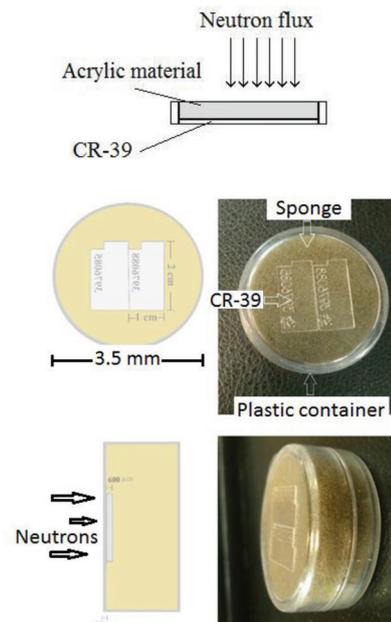


Figure 5: Detectors assembly for neutron irradiation.

A set of two dozen of the assembled detectors, were prepared and later introduced in the reactor access channel to be irradiated by neutrons at different reactor power output.

After exposure to neutron flux, the plastic detectors were chemically etched in 6.25 M KOH solution at $60 \pm 1^\circ\text{C}$ for 6 h in a thermo-regulated water bath. Then they were washed with distilled water and dried with absorbent paper, avoiding any mechanical damage to the detectors surface, following a very well-established protocol [1, 11, 12]. Later on, the detectors were analyzed with an automatically Digital Image Analysis System (DIAS); detailed description is given by Gammage and Espinosa [13].

In order to calculate the efficiency, a group of 15 detectors was irradiated during four hours, corresponding to a neutron fluence of $5.469 \times 10^6 \text{ cm}^{-2}$, and then chemically etched together as a batch. The average track density for the batch was $3357 \pm 70 \text{ cm}^{-2}$ for a calculated efficiency $E = (6.138 \pm 0.18) \times 10^{-4}$ (tracks per neutron). This value for E is comparable with efficiencies reported by other authors.

3. Results

Operating the ININ research reactors at 1MW, expected neutron flux values during irradiation are: for thermal and epithermal neutrons $\Phi_{\text{th}} = 5.5 \times 10^8 \text{ n cm}^{-2} \text{ s}^{-1}$ and $\Phi_{\text{ep}} = 1.25 \times 10^5 \text{ n cm}^{-2} \text{ s}^{-1}$, respectively. However, other experimental conditions were also employed depending on the reactor power output. In Figure 6 examples of etched nuclear tracks are shown, corresponding to different reactor power output. Variation of diameters and track density are observed.

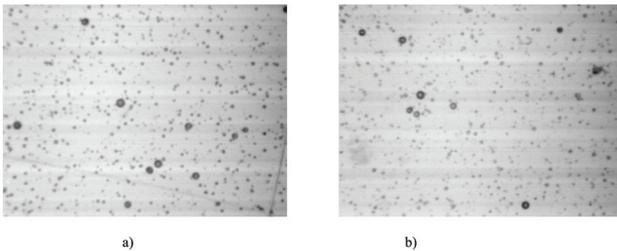


Figure 6: Etched tracks density variation per field for different power values: a) high density and b) low density.

It can be observed that the tracks corresponding to recoil protons are more numerous compared to larger size-tracks. These correspond to charged particle having mass and energy well above the proton ones. Their density decreases as the reactor operational power rises reaching a negligible value closing to 7kW power.

In Figure 7 etched track density as a function of the reactor operating power is reported for two conditions: before (solid triangles) and after (solid circles) the nuclear core modification. The straight lines are the result of least-

squares fitting to a linear function. The upper line labeled A corresponds to the nuclear reactor before the core modification.

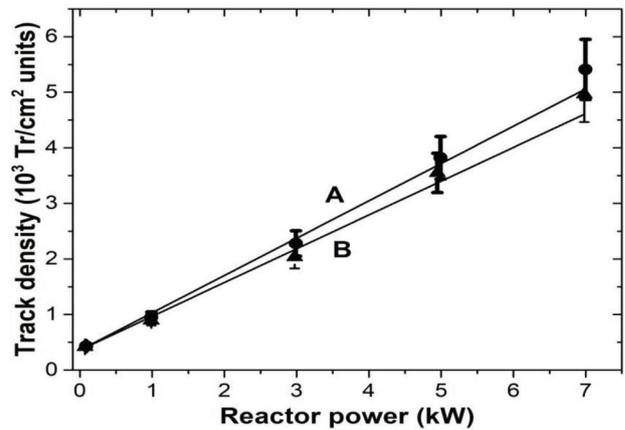


Figure 7: Track density as a function of the ININ research reactor operating power before (A) and after (B) the nuclear core modification.

4. Discussion

We have observed mainly two groups of track sizes corresponding to scattered protons and reaction products. The first one is well defined. The other may correspond to reactions taking place in the detecting material $^{12}\text{C}(n, nx)$, $^{16}\text{O}(n, nx)$ and the air gap $^{14}\text{N}(n, \alpha)$; however the number of this group (track density) is almost negligible since the reaction threshold is well above 5 MeV and in the fast neutrons region ($E_n > 5\text{MeV}$) neutron density is several orders of magnitude lower in comparison to the thermal one. We observe also that these larger tracks have a low dependence on the neutron spectrum shape suggesting that for a higher reactor power a larger number of thermal neutrons are available. In this study we devoted our analysis only on the well-defined proton tracks ($E_n > E_{\text{threshold}} \sim 200 \text{ keV}$) from that the response (R) for the recoil reaction is determined dividing the measured track density (e.g. 5×10^4 at 3 kW) by the neutron fluence (8×10^9 average value from Figure 4). Then it was found to be $R = 6.25 \times 10^{-4} \pm 10\%$. In spite of the approximation (only one type of track) NTD proved to be a good technique to measure the value of the neutron fluence dependence of the reactor power. It is expected that track density should be determined counting all the tracks (protons and reaction products) since we assume that they are produced either by (n, p) or (n, x) reactions (where x is any charged particle different from protons). In our case the following relation holds:

$$\rho_{tr} = K N_{At} \Phi(E_{threshold} - E_n) \sigma(E_n) \quad (1)$$

Thus the nuclear track density ρ_{tr} is proportional through a calibration constant K , to the product of the number of available atoms for detection N_{At} times flux $\Phi(E_{threshold} - E_n)$ times the average cross section $\sigma(E_n)$ reaction.

Conclusions

The study shows several advantages of Nuclear Tracks Methodology such as being a simple, fast and reliable method with the advantage to be a complementary, alternative low-cost procedure to measure operating power (W) of the ININ research reactor after core restructuring. From the results given, several important conclusions can be drawn: the first one is the linearity of proton induced track density $\rho_{tr, average} = 16.2 \pm 7\%W$. The results show a monotonic response for reactor power, from 0.1 to 7 kW range and that the average nuclear tracks density is reproducible having a relatively low uncertainty ($\pm 3\%$). The response of Nuclear Tracks Detectors to reactor operating power is $R = 6.25 \times 10^{-4}$. Further study is required to determine the thermal neutron flux lower component with highly efficient neutron converter material, and it has been already programmed as continuation of this project. As a concluding remark, we suggest as an alternative method the given procedure with Nuclear Track Detectors since includes also the possibility to determine neutron flux density measured at an unknown low reactor power.

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