TRIGA-SSR THERMAL COLUMN NEUTRON CHARACTERIZATION BY FOIL ACTIVATION METHOD

MARIUS NEHOIANU [1], *ANDREEA ŞERBĂNESCU* [2],
ŞERBAN CONSTANTIN VALECA [1], *LAURENTIU AIOANEI* [2]
[1] University of Piteşti, Romania
[2] Institute for Nuclear Research (RATEN ICN) Piteşti, Romania
e-mail: andreea.serbanescu@nuclear.ro

Abstract

Knowledge of neutron flux densities is needed both for the reactor control and for the use of neutron fields or neutron beams. This paper is dedicated to the neutron field characterization of an irradiation site created into the graphite thermal column of the TRIGA steady state reactor operated by RATEN ICN Pitesti. Neutron flux and spectrum have been measured by using multiple foil activation method followed by spectrum unfolding. The measured flux densities are reported to the Self-Powered Neutron Detector (SPND) Silver monitor placed into the Beryllium reflector, near to the thermal column. Foil activation detectors, bare and Cadmium covered, dedicated for thermal neutron spectra, were used. Experimental corrections for neutron self-shielding as well as for gamma activity measurements have been applied. The irradiation site is placed relatively near to the reactor core. This is why the fast neutron contribution evaluation has been also an important issue. The unfolding results, reported to 10 MW reactor operation power, showed a thermal neutron flux density of 2 1011 n/cm2s with a fast neutron contribution less than 1%. The Cadmium ratio for the Gold reaction, as an indicator of the neutron spectrum thermalization, was measured at the value of 52.

Keywords: *Thermal neutron flux, Multiple foil activation, Spectrum unfolding*

Introduction

The 14 MW SSR TRIGA core is operated by RATEN ICN Pitesti since 1980. In-core and out of core irradiation facilities have been developed for the most efficient use of the neutron fields generated by the core [1-3]. A modular thermal column has been installed into the reactor pool, linked to the beryllium reflector region of the core [4]. The thermal column is composed by 96 rectangular aluminium cladded graphite blocks placed on a support fixed into the reactor pool. By replacing individual graphite blocks with suitable irradiation devices, experimental locations can be created, thus developing thermal flux irradiation facilities. The knowledge of neutron field characteristics for such particular irradiation locations is an essential requirement.

The development of neutron reference spectra irradiation facilities requires, beside the execution of the experimental arrangements, sustained computational and experimental efforts to ensure that the neutron field characteristics are well known, with an acceptable uncertainty, and to certify that these parameters are well controlled and may be reproduced. As major requirement, the warranty of reproducibility represents the interest values (neutron flux densities) reporting to the local monitoring system.

Neutrons detection methods are based on their interaction with the environment. Being non-charged particles, they do not produce directly measurable electrical effects.

Neutron detection is based on the secondary particle detection. Virtually, any neutron detector involves a combination of target conversion material and a conventional ionizing radiation detector. Two detection methods can be distinguished, as follows: active detection (the secondary radiation is detected simultaneously with its emission) and passive detection (the effect of primary interaction is measured in a later stage), respectively.

The activation method is a passive one, the induced activity being measured after the exposure process. The induced activity is obtained by primary interactions of the neutrons in the target material.

The present work aims to contribute to the neutron characterization of the TRIGA SSR thermal column by using the multi-foil activation method followed by the neutron flux and spectrum determination by unfolding. It is a complex procedure leading to the determination of neutron flux density and energy distribution based on the absolute measurement of a few reaction rates.

Multifoil Activation Method. Neutron Flux and Spectrum determination

Activation reactions include both radiation capture and transmutation reactions leading to a radioactive isotope. There are three stages in the experimental procedure: activation, cooling and foil detector measurement.

A relation can be established between the induced activity represented by the photopeak area and the reaction rate per target nucleus, so called ″saturation activity″.

$$RR = \frac{A}{\varepsilon b} \frac{\lambda exp(\lambda \tau)}{(1-exp(-\lambda T))(1-exp(-\lambda t))} \frac{a}{mpN} \quad (1)$$

where: RR = reaction rate per target nucleus; A = photopeak area; λ = decay constant; τ = cooling time; t = irradiation time; T = measurement time; b = branching ratio; ε = detector efficiency; a = atomic mass; m = sample mass; N = Avogadro's number; p = interest isotope weight.

The reaction rate or saturation activity can be written as:

$$RR = \int_0^{\infty} \sigma(E)\Phi(E)dE \quad (2)$$

By using the multi-group description of spectrum and cross sections:

$$\phi_i = \int_{E_i}^{E_{i+1}} \Phi(E)dE \quad (3)$$

and:

$$\sigma_{ij} = \frac{\int_{E_i}^{E_{i+1}} \sigma_j(E)\Phi(E)dE}{\int_{E_i}^{E_{i+1}} \Phi(E)dE} \quad (4)$$

The sample saturation activity for the j reaction can be written now as:

$$RR_j = \sum_{i=1}^{n} \sigma_{ij}\Phi_i \Delta E_i \quad (5)$$

were j=1, m represents the number of foil reactions and i=1, n represents the number of energy groups. Usually, $m << n$, and the above equation system does not have a unique solution.

The unfolding procedure leads to the most suitable solution for the measured reaction rates.

On using the iterative procedures, we start from a guess spectrum which is adjusted step by step until the standard deviation of the measured activities from the computed ones becomes less than a specified value. Such procedures are implemented in unfolding codes, like SAND-II code [5] which has been used in our work.

Experiments for thermal neutron flux and spectrum measurements in the TRIGA-SSR thermal column

The neutron flux and spectrum measurements in the TRIGA-SSR thermal column have been performed in the H4 location (see Fig. 1). This location is relatively close to the reactor core and therefore the thermal neutrons weight is expected to be lower.

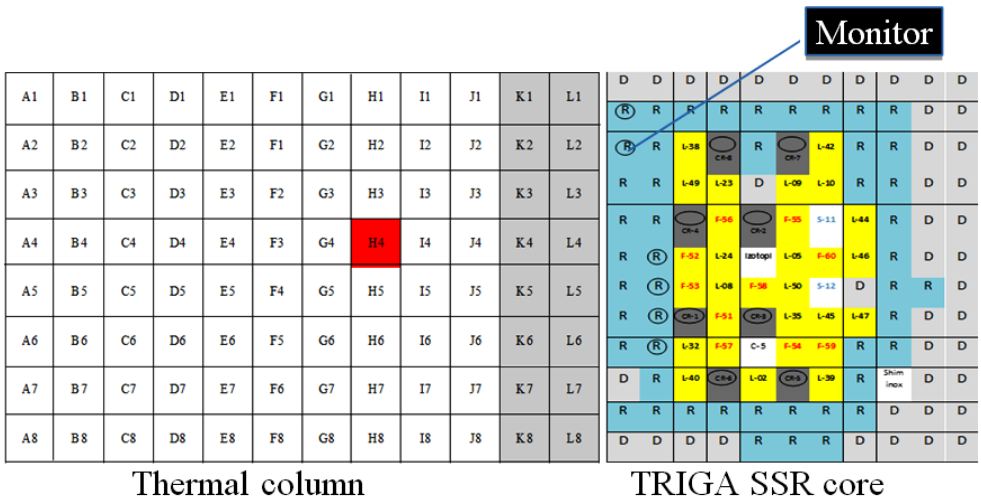


Fig. 1. TRIGA-SSR core with the thermal column

The foil irradiations have been performed by using a pneumatic rabbit system placed in the thermal column. The pneumatic system has a storage capacity for cooling. The foil detectors are placed in small aluminum capsules, minimizing the neutron field perturbation. For monitoring purposes, a Self Powered Neutron Detector placed in the core margin (see Fig. 1) has been used. The voltage collected on a 10 kΩ resistor has been recorded by using a fast data acquisition system.

The foil detector characteristics, the duration of the irradiation, and the monitoring data are shown in Table 1. The monitoring records for each foil irradiation are presented in Fig. 2. The reactor thermal power has been also recorded during the foil irradiations. The mean values, corresponding to each irradiation day are also presented in Table 1. The scaling factors presented in the last column are aimed to scale all reaction rates to the 10 MW (thermal) reference power by multiplying each measured reaction rate.

Table 1. Foil detector characteristics. Monitoring data and scaling factors

Detector	Foil diameter (mm)	Foil mass (mg)	Exposure duration (min)	$\bar{U}(mV)$	$\bar{U}(mV)$	P_{th} (MW)	Scaling factor (to 10 MWth reference power)
Mn 1%	6	0.077	7	1.882	1.916	11.39	0.893824
Au 5%	6	0.44	5.5	1.919			0.876591
Lu 10%	6	0.832	10	1.923			0.874767
Au 5% Cd	6	0.4333	34.5	1.924			0.874313
Al	12	251.9	58.2	2.013	2.013	11.60	0.835656
Ni	12.7	221.5					

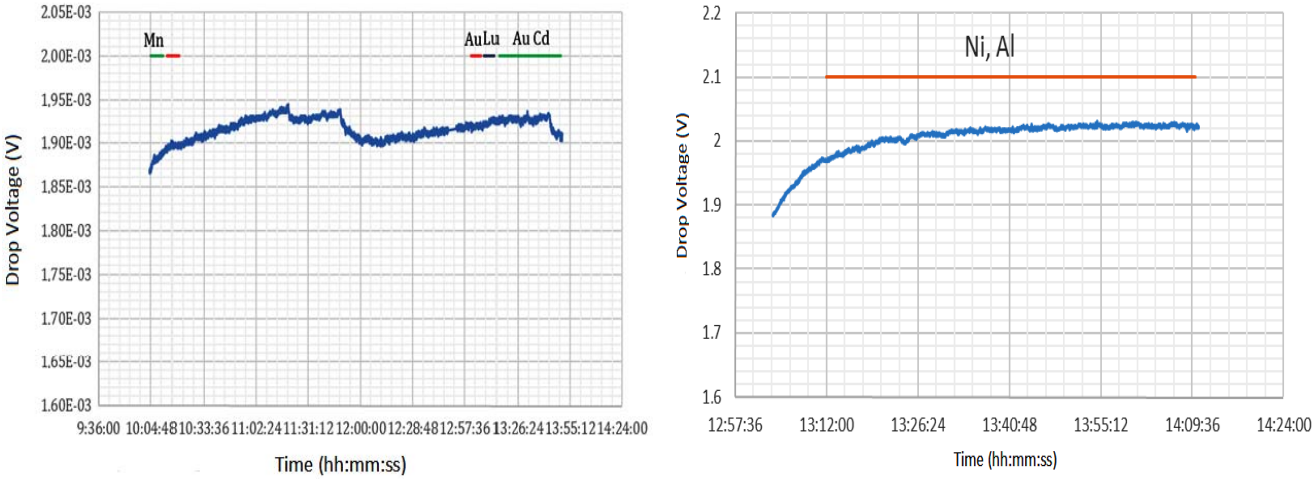


Fig. 2. Monitoring results

For the induced activity absolute measurements, the gamma detector efficiency needs to be known. This has been experimentally determined by using ^{152}Eu and ^{133}Ba gamma standard sources. Calibration sources have been placed at the same distances as the one used for foil activity measurements.

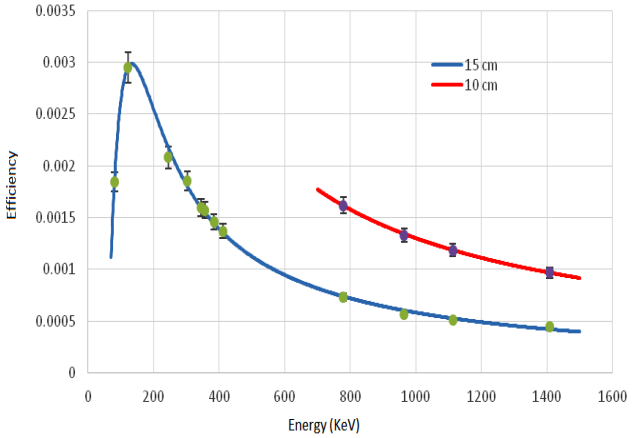


Fig. 3. Gamma detector efficiency calibration

Fig. 3 shows the efficiency calibration as obtained by fitting the experimental data with the function

$$\varepsilon = p_1\left[E^{p_2} + p_3\, exp\left(p_4 E\right)\right]$$

by using the SAMPO code [6].

Data processing for neutron flux and spectrum determination

The reaction rates per target nucleus (saturation activities) have been determined from the measured induced activities. Table 2 shows an example of saturation activity computation by using repeated activity measurements.

The neutron self-shielding correction, important in thermal flux irradiations, has been applied by using self-protected cross sections. They have been generated, except Ni and Al, by using the SELFS-3 code [7].

Table 2 Reaction rates computation

Foil: Au 5% **Reaction: Au197(n,g)Au198**

Foil mas(g): 4.400E-04		T1/2(min): 3882.24	Lambda (min-1): 1.785E-04	Irradiation(min): 5.5
Irradiation date/time	1/30/2020 13:06	p = 1	b = 0.95	Saturation factor = 0.000981505

Nr. crt.	Measurement date/time		Time (sec) Live	Time (sec) Real	Fotopeak area 411.8 keV	Eff(d,E)	Cooling time (min)	Reaction rate (ips/nucleu)
1	1/31/2020 9:44	15 cm (PC)	499	503	14141	1.351E-03	1238	2.087E-11
2	2/3/2020 10:24	15 cm (PC)	634	639	8161	1.351E-03	5598	2.065E-11
3	2/4/2020 10:58	15 cm (PC)	2209	2224	22303	1.351E-03	7072	2.112E-11
4	2/5/2020 11:22	15 cm (PC)	1365	1374	10505	1.351E-03	8536	2.089E-11
						Mean value(ips/nucleus): 2.088E-11		
						Standard deviation (%): 0.92		

For unfolding, two guess spectra have been chosen. The first one is a MCNP computation performed for the former thermal column configuration [8]. The second guess spectrum has been generated as recommended by Westcott [9] for graphite, by using the cadmium ratio for gold reaction as obtained by reaction rate measurements. Both guess spectra are presented in Fig. 4.

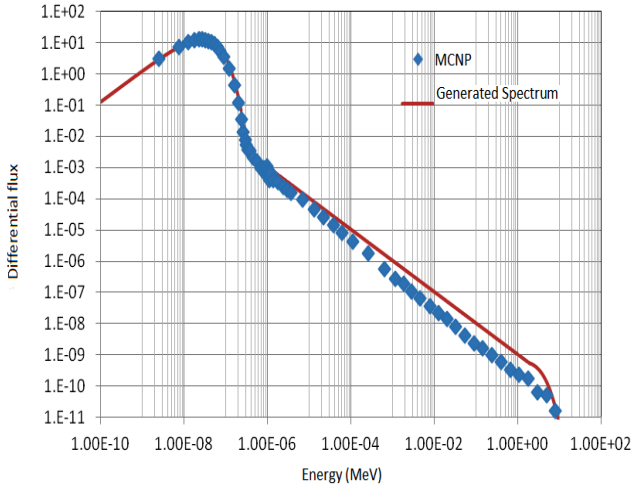


Fig.4. Guess spectra

Both guess spectra lead to the final solution after a small number of iterations (two and four iterations, respectively) with a standard deviation of measured reaction rates from the computed ones less than 5%.

A comparison between the computed and the measured reaction rates for the generated guess spectrum is presented in Table 3.

Fig. 5 shows the flux spectra, in units of energy, after two and four iteration, using the neutron spectrum unfolding code SAND II.

The fast neutron detectors (Ni and Al) were not included in the reaction rate set used for this work. By including them, no differences in the solution spectrum or flux density can be observed. For this reason, the fast neutron reaction rates have been separately used to estimate the presence of a fast neutron component. As guess spectrum a fission spectrum has been used. That was the only way to estimate a fast neutron component representing 0.6% from the thermal flux density.

The unfolding results are summarized in Table 4.

Table 3. Reaction Rates Comparison

Reaction	**Saturation activity**		**Energy limits**		**Deviation (%)**
	Measured (cps)	**Computed (cps)**	**E_{inf} (MeV)**	**E_{sup} (MeV)**	
$Au^{197}(n,\gamma)$	1.830E-11	1.957E-11	5.250E-09	4.750E-06	-6.48
$Au^{197}(n,\gamma)$ Cd	3.500E-13	3.481E-13	4.500E-06	3.400E-04	0.55
$Lu^{176}(n,\gamma)$	7.440E-10	7.078E-10	1.000E-08	1.500E-07	5.11
$Mn^{55}(n,\gamma)$	2.490E-12	2.470E-12	5.000E-09	1.150E-07	0.82
Standard deviation: 4.80 %					

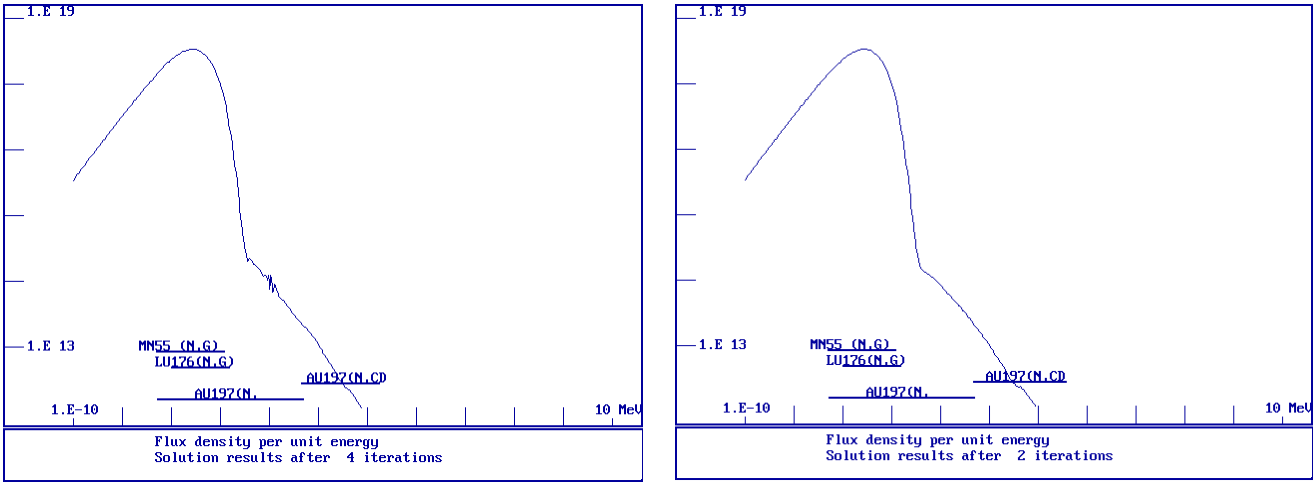


Fig. 5. Thermal column solution spectra

Table 4. Unfolding results - summary

Guess spectrum	Reaction rates	Flux density (n/cm^{2}s)
MCNP computation	thermal	2.270 x 10^{11}
	thermal+fast	2.277 x 10^{11}
Generated	thermal	2.325 x 10^{11}
	thermal+fast	2.311 x 10^{11}
Fission	fast	1.408 x 10^{9}

The measured Cadmium ratio for $Au^{197}(n,\gamma)Cd$ reaction is 52.28, indicating presence of an epithermal component.

The neutron flux density measured in the H4 position from TRIGA-SSR thermal column is about 2.3 x 10^{11} n/cm^{2}s reported to 10 MW (thermal) reactor's operating power. Both spectra used as guess lead to identical solutions.

It is noteworthy that the existence of a fast neutron component representing 0.6% has been proven.

Conclusions

The aim of this paper was to perform the neutron field characterisation for an irradiation location from the graphite thermal column of the TRIGA steady state reactor operated by RATEN ICN Pitesti.

Neutron flux and spectrum have been measured by using multiple foil activation method followed by neutron flux and spectrum determination by unfolding.

Both bare and Cadmium covered foil activation detectors (dedicated for thermal neutron spectra) were used. The flux densities measurements were reported to the SPND silver monitor placed near the thermal column, in the reactor core margin (into the Be reflector). Experimental corrections for neutron self-shielding as well as for gamma activity measurements have been applied.

For unfolding, two guess spectra were chosen, namely: a MCNP computation performed for the former thermal column configuration, and a spectrum for graphite generated by using the Cadmium ratio measured for the Gold reaction, respectively.

Due to the position of the irradiation location nearby the reactor core, the fast neutron contribution evaluation was taken into consideration. The studied irradiation location in the thermal column showed high neutron flux density values, being located nearby the reactor core, but the final results were not affected by the presence of the fast neutron foil detectors (Ni and Al).

The unfolding results, reported to 10 MWth reactor operation power, showed a thermal neutron flux density of $2x10^{11}$n/cm^{2}s, with a fast neutron contribution less than 1%, that is not affecting the final results.

The Cadmium ratio for the Gold reaction, as indicator for the neutron spectrum thermalization, has a measured value of 52, indicating the presence of an epithermal component.

The solution was obtained after a small number of iterations due to the reduced number of reaction rates, on one hand, and because the experimental spectrum approach to the guess spectrum, the iterative process requiring no major changes in the spectral shape, on the other hand.

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