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MEASUREMENTS OF NEUTRON FLUX DISTRIBUTION AND ENERGY SPECTRUM IN THE HORIZONTAL BEAM TUBE AT THE TRIGA MARK II REACTOR VIENNA

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ABSTRACT

The core of the TRIGA Mark II research reactor at the Vienna University of Technology/Atominstitut has been recently fully refurbished with new fuel, slightly irradiated. Given this new core configuration, irradiation facilities need to be properly characterized in order to support future research activities. Aims of this work is to present the result of the measurements of neutron flux distribution and energy spectrum performed in one of the reactor horizontal tubes, applying a method based on a de-convolution technique of activated foils coupled with Monte Carlo code simulations (MCNP6). This method is very flexible and can be applied to characterize nuclear reactors that present a wide variability of core geometries, structural materials' compositions, fuel composition and neutron energy spectra. The method allows measuring both slow and fast neutron components proving as result a neutron spectrum in 620 energy groups. In the case of the measurements presented in this work, the absolute neutron flux was evaluated within accuracy within ±10%.

1. Introduction

The core of the TRIGA Mark II research reactor at the Atominstitut (ATI) of the Vienna University of Technology has been recently fully refurbished with new fuel elements, slightly irradiated. In this new core configuration, irradiation facilities need to be properly characterized in to order to support future research activities.

The characterization of the reactor is part of a PhD research project that will focus on the determination of both neutron fluxes distribution and energy spectrum by means of Monte Carlo calculations and direct measurements.

Aims of this work is to present the measurement of the neutron flux distribution and its energy spectrum performed in one horizontal beam tube (Beam Tube B) applying a method based on a de-convolution technique of activated foils coupled with Monte Carlo code simulation (MCNP6).

2. The TRIGA Mark II reactor

The TRIGA (Training Research and Isotope production General Atomics) MARK II reactor [2] is a pool-type research reactor moderated and cooled by light water.

The TRIGA Mark II at the Atominstitut is licensed for 250 kW steady state and up to 250 MW pulse operation. Recently the reactor was converted from a highly heterogeneous core which included HEU fuel elements to a full LEU core. As a result, the current core load consists out of 76 stainless steel clad zirconium-hydride fuel elements (8.5%-wt enriched 19.95%-wt in 235U), in a cylindrical geometry.

The TRIGA Mark II of ATI is equipped with various irradiation facilities inside and outside the reactor core. It incorporates facilities for neutron and gamma irradiation studies as well as for isotopes production, samples activation and students training.

The horizontal section of the reactor is shown in Figure 1[3] where the reactor core, the graphite reflector, the four horizontal beam tubes, the thermal column, the thermalizing column (that incorporate the neutron collimator), the reactor tank and the biological shield in concrete are displayed.

The four beam tubes (i.e. A, B, C and D) penetrate the biological shield and the aluminium tank reaching reactor reflector. These tubes provide both irradiation facilities for large specimen (up to 15 cm) in a region close to the core; and neutron beams and gamma radiation for experiments installed externally to the biological shielding.

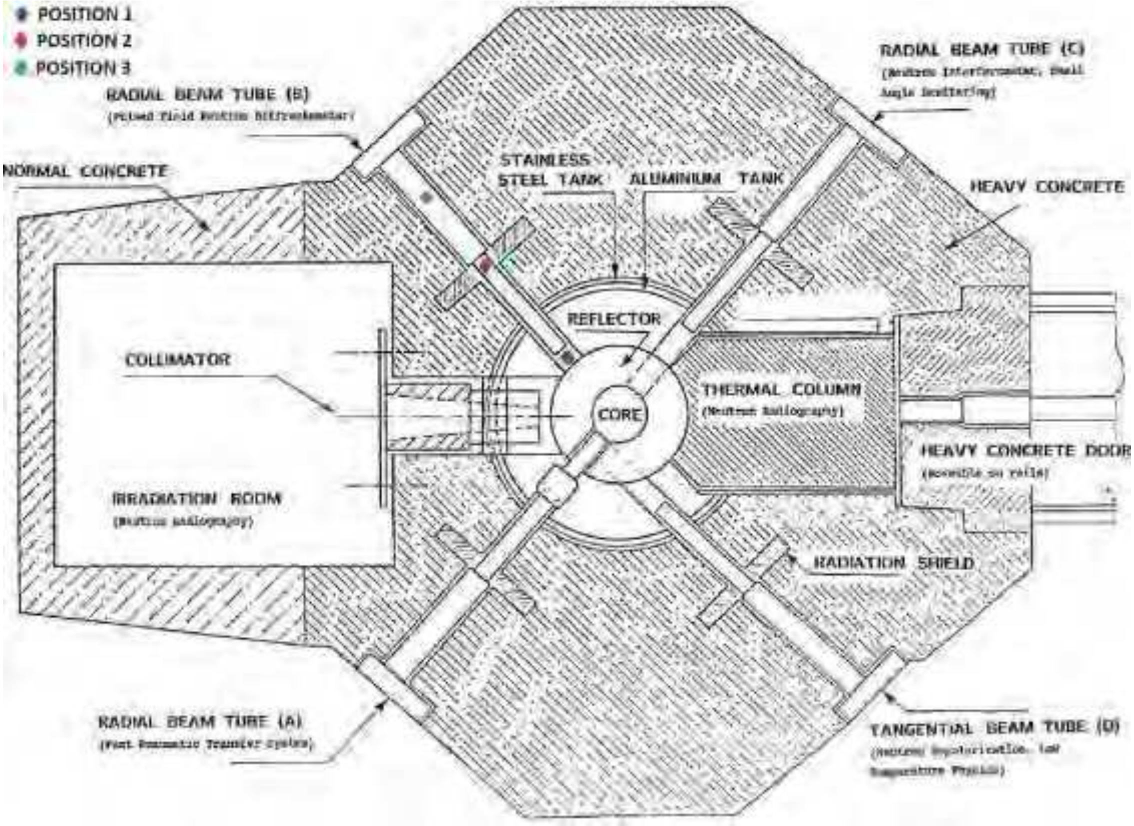

Figure 1: Horizontal section of TRIGA reactor at ATI

3. Experiment setting

At the TRIGA reactor at Atominstitut the horizontal beam tubes are all utilized for ongoing experiments. For this reason, the decision to start the reactor characterization from the Beam Tube B was due to the opportunity to perform foils irradiations during a special inspection of the beam tube. In this occasion, the Beam Tube B was opened and the collimator that normally lies inside, was extracted for inspection and verification.

It has to be pointed out that the setting of this experiment was strongly influenced by the limited time available for the irradiation of the foils and radiation protection constraints; i.e. few days of reactor availability in the described conditions and limitation of reactor power level. Due to these constrains it became necessary to schedule irradiations in only 3 positions along the beam tube and, for each position, all target foils had to be irradiated at the same time.

Accordingly, the irradiations time and the reactor power were set in order to optimize the measurement of the irradiated foils (activity, cooling-down time, counting time).

The irradiation positions were defined as in Table 1; the distances are taken from the graphite reflector and the location of the irradiation positions is shown by the markers in Figure 1.

The Figure 2 shows the irradiation device and its positioning inside the beam tube.

Irradiation position	Distance from reflector (cm)
Position 1	5
Position 2	125
Position 3	185

Table 1: irradiation positions for flux determination in Beam Tube B

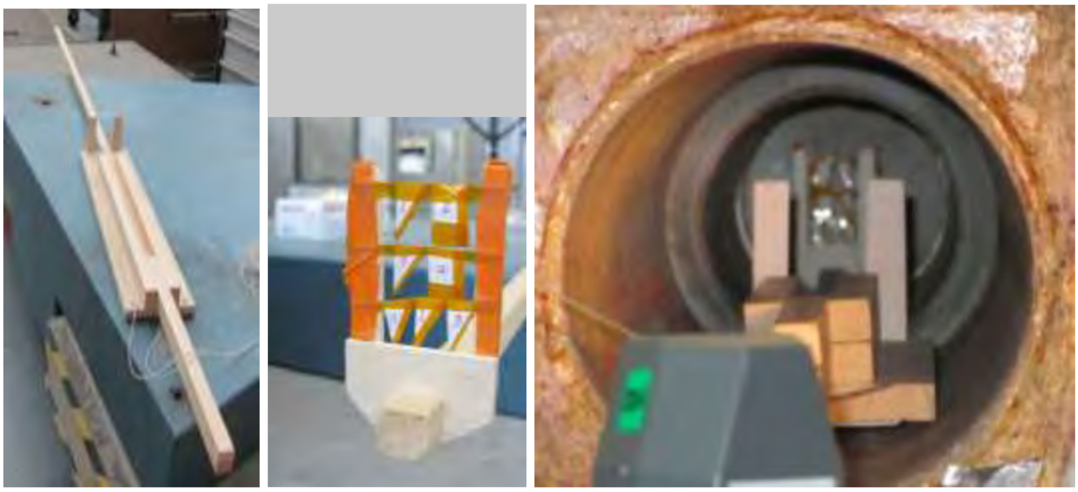

Figure 2: irradiation device used for foils irradiation in Beam Tube B and the positioning of the device inside the beam tube

3. Material Foils Selection and Irradiation

3.1 The SAND II code

The code SAND II [4] (Spectrum Analysis by Neutrons Detectors II) determines, applying a de-convolution method, the energy spectrum distribution and the absolute intensity of a neutron flux using as inputs the measured activities of infinitely diluted irradiated foils.

The calculation algorithm identifies a solution that meets some predefined criteria (e.g. maximum error or maximum number of iterations) through successive iterations starting from a *guess flux distribution* provided as “first approximation” input.

After a certain number of iterations, the solution is provided either in the form of differential flux, and in that of integral flux. As results are given in tabular form at 620 discrete energy intervals in the range between 10^{-10} and 18 MeV, the problem is essentially to solve for 621 unknowns in a system of *n* linear activity equations, where *n* is the number of foils used.

Since SAND II best approximated solution depends on the choice of the first approximation spectral form (guess flux), in this experiment the input guess flux utilized was calculated by means of a simulation of the TRIGA reactor performed using the Monte Carlo code MCNP6[1]. It is worthy to notice that SAND II best approximated solution is significantly dependent from the guess flux form (i.e. energy distribution) but almost independent from its absolute value.

3.2 Material Foils selection

In this work, to detect the thermal, epithermal and fast neutron spectrum components, a proper set of (n,γ), (n,α), (n, p) and (n, n^{l}) reactions with different activation thresholds have been selected for irradiations in the Beam Tube B, as shown in Table 2.

It should be pointed out that the selection of reaction presenting different thresholds values is also of primary importance in order to allow the SAND II code to reach a more reliable solution of the 621 equation system. This is because very different cross-sections contribute to reduce the indeterminacy of the system.

Element	**(T-I)**	**θ% T-I**	**Reaction**	**E^{act}_{eff} (MeV)**	**σ_0 (barn)**	**$T_{1/2}$**	**Λ (sec^{-1})**
Au	^{197}Au	100	$^{197}Au\ (n,\gamma)\ ^{198}Au$	--	98.8	2.7 d	$2.97 \bullet 10^{-6}$
Cu	^{63}Cu	69.1	$^{63}Cu\ (n,\gamma)\ ^{64}Cu$	--	4.5	12.7 h	$1.51 \bullet 10^{-5}$
Fe	^{54}Fe	5.84	$^{54}Fe\ (n,p)\ ^{54}Mn$	3.75	0.4	312.7 d	$2.56 \bullet 10^{-8}$
Ni	^{58}Ni	68.08	$^{58}Ni\ (n,p)\ ^{58}Co$	2.5	0.6	70.78 d	$1.13 \bullet 10^{-7}$
In	^{115}In	95.71	$^{115}In\ (n,n')\ ^{115}In^*$	1.65	0.35	4.36 h	$4.42 \bullet 10^{-5}$
Al	^{27}Al	100	$^{27}Al\ (n,p)\ ^{27}Mg$	5.30	$8 \bullet 10^{-2}$	9.46 min	$1.22 \bullet 10^{-3}$

Table 2: set of elements, isotopes and reactions used to perform the measurements in Beam Tube B.

4. Results

4.1 Activation results

Following the irradiations, for each foil the activity was measured by means of a coaxial closed-ended HPGe n-type (series C5020, CANBERRA) with 52.8% relative efficiency, 1.81 keV energy resolution at 1.33 MeV and Peak/Compton edge ratio equal to 73.6. The efficiency calibration of the detector was performed by means of a certified solid multi gamma calibration source (Type QCRB1186, Eckert&Ziegler) with dimension and geometry similar to the activated foils.

The values of measured specific activities per atom at the end of irradiation and extrapolated to saturation are listed in Table 3 for each material foil in the three irradiation positions.

Position 1		**Position 2**		**Position 3**	
Foil	**Activities (Bq/atom)**	**Foil**	**Activities (Bq/atom)**	**Foil**	**Activities (Bq/atom)**
AU	$(6.14 \pm 0.30) \bullet 10^{-11}$	AU	$(2.70 \pm 0.13) \bullet 10^{-13}$	AU	$(8.43 \pm 0.42) \bullet 10^{-14}$
AU +CADMIUM	$(4.52 \pm 0.23) \bullet 10^{-11}$	AU +CADMIUM	$(1.68 \pm 0.08) \bullet 10^{-13}$	AU +CADMIUM	$(5.78 \pm 0.29) \bullet 10^{-14}$
CU	$(1.22 \pm 0.06) \bullet 10^{-12}$	CU	$(5.04 \pm 0.25) \bullet 10^{-15}$	CU	$(1.18 \pm 0.06) \bullet 10^{-15}$
AL	$(2.06 \pm 0.10) \bullet 10^{-16}$	AL	$(6.11 \pm 0.30) \bullet 10^{-18}$		
NI	$(6.20 \pm 0.31) \bullet 10^{-15}$	NI	$(1.67 \pm 0.08) \bullet 10^{-16}$		
FE	$(3.34 \pm 0.17) \bullet 10^{-15}$	IN +CADMIUM	$(1.98 \pm 0.10) \bullet 10^{-16}$		
IN +CADMIUM	$(8.09 \pm 0.40) \bullet 10^{-15}$				

Table 3: measured specific activities per atom extrapolated to saturation for foils irradiated in Beam Tube B (Position 1, Position 2 and Position 3)

As SAND II code requires activities adjusted to infinite dilution of target nuclide, all input activities should be corrected for self-shielding effect. In this case, considering the specific reactions cross sections and the characteristic of the target foils, the only measurements that needed to be corrected for self-shielding were those related to Au foils activation and the correction was done according to the Westcott [5][6] theory.

Considering the optimization of cooling-down and counting time of the foils, statistical uncertainties of the measurements were evaluated for less than 3%. To investigate the systematic error several repeated measurements of an irradiated foil of gold were performed, every time repositioning the foil on the detector. The error was evaluated to less than 2% giving a total uncertainty of the gamma spectrometry measurements of about ± 5%.

4.2 Neutron energy spectrum results

The measured specific activities extrapolated to saturation have been used as input for the SAND II code in order to evaluate the neutron energy spectrum.

As from original data and drawings of the reactor was not clear if the Beam Tube B faces the graphite or a void in correspondence of the reflector, one of the purposes of this work was also to clarify this issue. For this reason, the SAND II code was run alternatively using two different input guess fluxes both generated by MCNP calculation: one guess flux was calculated considering the configuration facing graphite inside the reflector, the other facing a void volume inside the reflector. The considerable difference in the two Guess fluxes obtained by MCNP, did not affect the final results obtained by SAND II calculation; this result is considered a confirmation of the capability of SAND II code to build up the measured energy spectrum regardless of the absolute value and, partially, of the energy distribution of guess flux.

As results, the SAND II code provided the differential fluxes distributed over 621 energy values in the range between 10^{-10} and 18 MeV: Figure 3 and Figure 4 show respectively the Differential and Integral Flux in each of the 3 irradiation positions as provided by SAND II code.

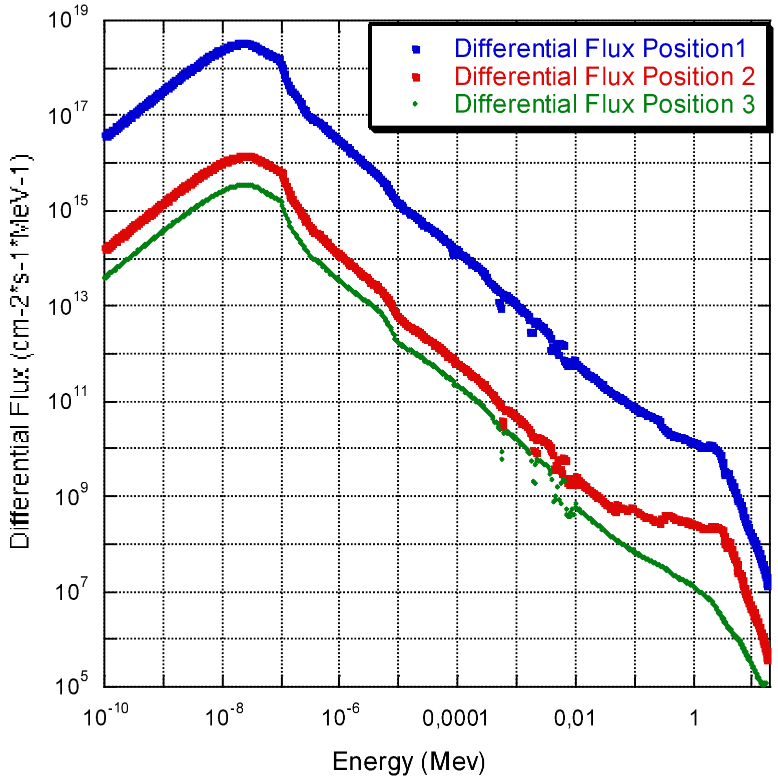

Figure 3: Measured Differential Flux in Beam Tube B (Position 1,2,3)

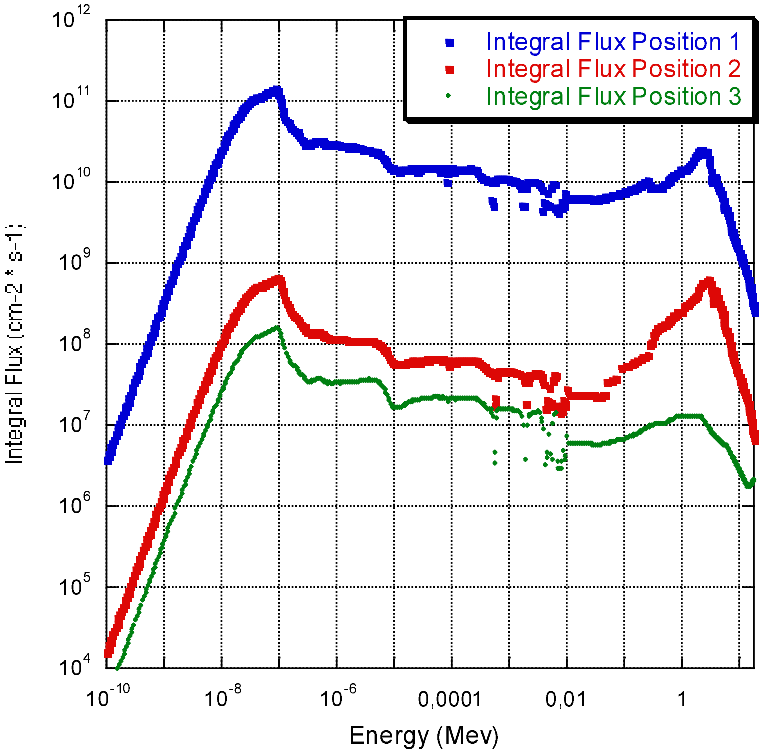

Figure 4: Measured Integral Flux in Beam Tube B (Position 1,2,3)

As the results are given by SAND in the form of very detailed differential energy spectrum, it is simple to calculate integral flux values over desired energy intervals. Thus, the Thermal (E<0.55 eV), Epithermal (0.55 eV < E < 100 keV) and Fast (E>100 keV) neutron flux is reported in Table 4.

	Total Flux (cm-2 *s-1)	**Thermal flux (<0.55eV)** (cm-2 *s-1)	**Epithermal Flux (0.55eV-100keV)** (cm-2 *s-1)	**Fast Flux (100KeV-18MeV)** (cm-2 *s-1)
Position 1	$(5.73\pm0.50)\bullet10^{11}$	$(3.28\pm0.30)\bullet10^{11}$	$(1.73\pm0.15)\bullet10^{11}$	$(7.28\pm0.70)\bullet10^{10}$
Position 2	$(3.13\pm0.30)\bullet10^{9}$	$(1.40\pm0.10)\bullet10^{9}$	$(7.11\pm0.70)\bullet10^{8}$	$(1.02\pm0.10)\bullet10^{9}$
Position 3	$(6.04\pm0.60)\bullet10^{8}$	$(3.39\pm0.30)\bullet10^{8}$	$(2.22\pm0.20)\bullet10^{8}$	$(4.43\pm0.40)\bullet10^{7}$

Table 4: Thermal (E<0.55 eV), Epithermal (0.55 eV < E < 100 keV) and Fast (E>100 keV) neutron flux in Beam Tube B

Considering the values obtained for the total Integral Flux in the 3 position, it was possible to build the best fit for the integral flux values along the Beam Tube B (Figure 5) and accordingly evaluate the integral flux in correspondence of various distances, such as (by extrapolation) at the beam port.

The estimated value of the total integral flux in correspondence of the beam port of Beam Tube B was of 1.76 • 10^8 s-1 • cm-2: this result, compared with historical data from other similar TRIGA reactors, indicates that, most likely, the Beam Tube B at TRIGA Vienna reactor faces the graphite in the reflector.

The uncertainties of the differential and integral neutron fluxes were evaluated taking into account the propagation of the uncertainties of the foils measurements in the SAND II de-convolution process; the uncertainties related to the determination of the weight of the foils (less than 1%); the thermal power calibration of the reactor performed according to specific procedure using certified instrumentation (about ± 3%). The uncertainties of the flux values resulted to be within ± 10%.

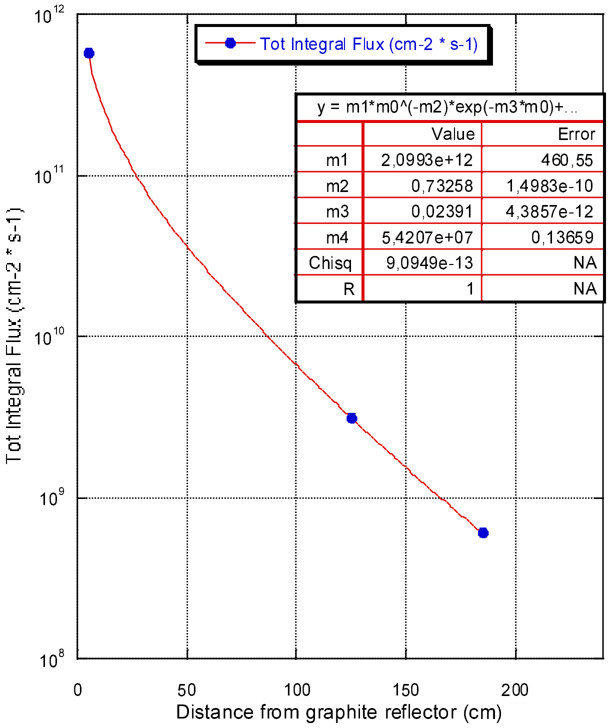

Figure 5: total integral flux behaviour along Beam Tube B

5. Conclusions

This work, through activity measurements of activated foils and consequent application of a de-convolution technique coupled with Monte Carlo calculations, allowed to determine the neutron flux distribution and the energy spectrum in one of the horizontal beam tubes (Beam Tube B) at the TRIGA reactor Vienna. The results are provided in the form of a very detailed energy spectrum (621 energetic intervals in the range between 10^{-10} and 18 MeV) and therefore it is possible to evaluate flux values for all desired energy intervals.

Moreover, the evaluation of flux distribution along the Beam Tube B, led to the indication that the Beam Tube B at TRIGA reactor Vienna presents the configuration design which faces the graphite in the reflector and not a void volume.

Finally, as this method is very flexible, in the near future it will be applied to characterize the reactor in different in-core and in tank irradiation position at the TRIGA reactor Vienna.

6. References

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