

Evaluation of the Axial Absolute Power Profile Measurements at the JSI Triga Mark II Reactor

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ABSTRACT

Within the bilateral collaboration between the Commissariat à l’Energie Atomique (CEA) and the Jožef Stefan Institute (JSI) a set of experiments was performed to improve the power calibration process of the JSI TRIGA Mark II reactor. Measurements of the distribution of absolute fission rates at various locations in the reactor core were performed using absolutely calibrated CEA developed fission chambers. A series of calculations, based on the use of advanced Monte Carlo transport codes, such as MCNP, were performed to support the reactor axial fission density distribution measurements and to verify and validate the computational model of the TRIGA Mark II reactor. The same model is then used for the evaluation of experimental and calculational uncertainties, such as geometry, experimental materials, masses etc.

1 INTRODUCTION

Precise knowledge of the reactor core power and power density distribution is of critical importance for safe reactor operation. In addition, it enables experiment optimization and result estimation, in-core flux and fission rate calculations and determination of reactor material isotopic changes.

The TRIGA Mark II reactor at Jožef Stefan Institute uses ex-core neutron detectors to monitor the power and power distribution within the core. Due to the high significance of the detector accurate output, regular calibrations have to be performed. The main method used at the TRIGA reactor is the calorimetric calibration method, which is burdened by considerable uncertainty that consequently results in absolute power determination errors [5]. In order to improve the reliability of the measurements, absolute fission rates at different radial and axial positions in the core can be measured using absolutely calibrated fission chambers (FCs). Supported by computer calculations, the FC reaction rate results enable a better understanding of the local reactor core power distribution dynamics and with it the possibility of calibration correction factors determination.

In October 2011 measurements with the absolutely calibrated FCs were performed at the TRIGA Mark II reactor as a part of the collaboration between Jožef Stefan Institute (JSI) and Commissariat à l’Energie Atomique (CEA)[3]. In the experiment a ²³⁵U fission chamber was used. Measurements of the fission rates were made at 9 different measuring positions (MPs) in

the reactor core for 3 different control rod settings. The result of the irradiation campaign was a set of detailed axial fission rate profiles distributed uniformly over the whole of the reactor core.

The measurement campaign was supported by computer neutron transport calculations, using an advanced Monte Carlo transport code, MCNP [8]. For the purpose of experiment safety and engineering aspect analysis and post-experimental result evaluation, an already verified detailed model of the TRIGA Mark II reactor was further developed and used for these calculations.

A comparison between the FC measured and computer calculated fission rates was made and shows relatively good agreement - the average differences being below 5 %. The specific axial profile of the fission rates at different measuring positions in the core of the reactor was successfully reproduced, which indicates the sufficient accuracy of the computer model. Due to the possibility of considering the fission rate measurements as an experimental reaction rate benchmark, extensive investigations were made into all possible sources of experimental and calculational uncertainties together with their evaluation.

In the paper the comparison of the absolute fission reaction rate measurements and calculations is presented together with evaluated uncertainties.

2 EXPERIMENT

The fission reaction rate measurements were performed using a fission chamber containing $8.88 \mu\text{g} \pm 0.18 \mu\text{g}$ g of 98.49 % enriched ^{235}U . The sensitive area of the FC was cylindrically shaped, 4 mm in height and 3 mm in diameter (nominal dimensions). The reaction rates were measured in 9 different MPs (MP 14, 15, 16, 17, 20, 21, 22, 23, 25) in the reactor core as shown in Fig. 1.

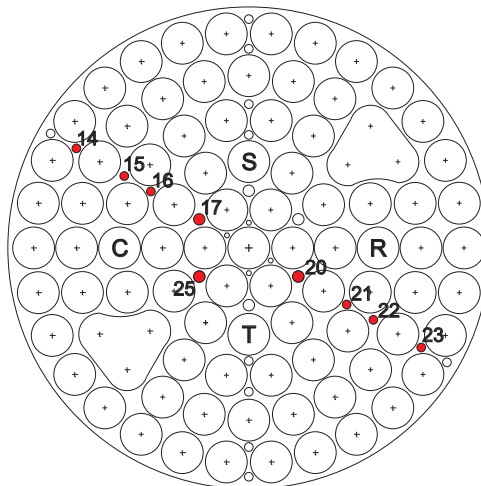


Figure 1: Top view of the reactor upper supporting grid with labeled measuring positions and control rods (S - safety, C - compensating, R - regulating, T - transient) [6].

Fission rates were measured at 24 axial positions in each of the MPs. In order to ensure the FC radial position uncertainty to be as low as possible, the FCs were inserted into the reactor core using a specially designed FC positioning system consisting of a drive mechanism, which was connected to the fission chamber by an integrated cable, and aluminium guide tubes positioned in the MPs. The FC detector axial position was measured relative to the lower end of the aluminium guide tube with an uncertainty ~ 0.2 mm. The uncertainty of the FC response for the calibrated FCs is estimated to be below 3 %, including the 2 % uranium mass uncertainty.

The reactor power was constant throughout the whole irradiation campaign at a nominal value of 100 W to ensure the linear response in the FC count rate versus the reactor power relationship.

3 MONTE CARLO CALCULATIONS

The fission rate calculations were performed with an advanced Monte Carlo neutron transport code. A computational model of the TRIGA Mark II reactor, which had already been verified for criticality and reaction rate distributions [2], was used to calculate the reaction rates. Several modifications of the model were made in the effort of recreating the actual experimental design and circumstances in as much detail as possible. The process included modelling of the fission chambers, aluminium guide tubes and other minor experimental accessories [1]. The calculations were made with the MCNP 5.1.60 programme using the ENDF/B-VII.0 nuclear data library.

In order to normalize the calculated reaction rates to the actual reactor power, a scaling factor has to be applied [1]:

$$C_{MC} = \frac{P \bar{\nu}}{w_f k_{eff}} \left[\frac{\text{neutron}}{s} \right], \quad (1)$$

where P (W) is the reactor power, $\bar{\nu}$ (neutron/fission) is the average number of neutrons created per fission, w_f (MeV/fission) is the effective energy released per fission event and k_{eff} represents the effective multiplication factor of the TRIGA reactor computational model. The reading of the reactor power P at steady state operation is obtained from one of the ex-core neutron detectors, i.e. linear channel [4]. Due to the high sensitivity of their response to the control rod position, a correction factor C_{CR} has to be applied to the original value of P to compensate for the asymmetric flux distribution in the core [4]. For the $\bar{\nu}$ value the theoretical prediction 2.439 is used, which is also confirmed by MCNP calculations. The value of w_f is slightly dependent on the type of the reactor and its core composition but is typically of the order of 198 MeV/fission [7]. The multiplication factor k_{eff} also changes with the control rod position variation and is therefore calculated in the Monte Carlo calculations.

4 RESULT COMPARISON

The aim of the absolute power calibration with absolute fission chambers is to compare the measured and calculated axial profile of the absolute fission rates at different locations in the reactor core and derive the scaling factor. In addition the fission rate profiles are used to verify control rod correction factor calculations.

The calculated fission rates were normalized according to the equation $C = C_{MC} \cdot C_{CR} \cdot N$, where N represents the number of uranium atoms in the FC. With the control rod correction factor taken into account the reactor power was 103.5 W. The values of the remaining parameters of the scaling factor were $\bar{\nu} = 2.439$ neutron/fission, $w_f = 198$ MeV/fission, $k_{eff} = 1.04545$ and $m(^{235}\text{U}) = 8.88 \mu\text{g}$. The resulting value of the scaling factor was: $C = 1.73\text{E}+5 \text{ s}^{-1}$.

In the next step the calculated reaction rates were normalized by a factor obtained by the least square method, the best-fit normalization factor being $C = 1.81\text{E}+5 \text{ s}^{-1}$. The relative difference between the factors is $\sim 4.6 \%$. The extensive presentation of the measured and calculated axial distributions was presented in a recent PHYSOR conference paper [1]. In this paper only the comparison for MP16 is shown.

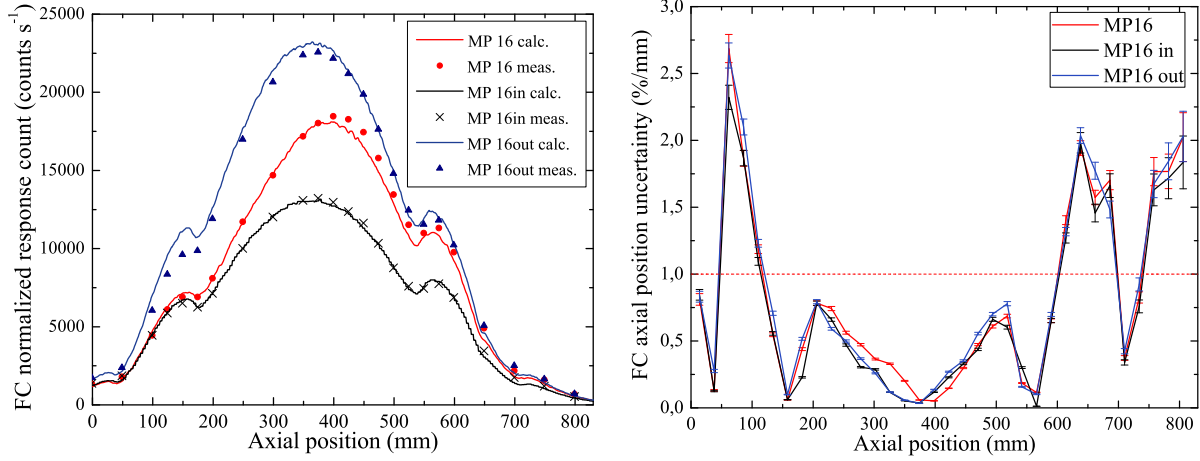


Figure 2: **Left:** Comparison of the measured (symbol) and calculated (line) axial fission rate distributions for three control rod positions. **Right:** Reaction rate axial gradient profiles in the measuring position MP 16 for three different control rod positions.

To investigate the effect of control rod position variation on the power distribution in the core of the reactor, two additional measurements of fission rates at the MP 16 were made for two different control rod settings. First the compensating rod was fully inserted and the regulating rod was extracted (MP 16in), next the compensating rod was fully extracted and the regulating rod inserted (MP 16out). The difference in rod insertion causes an asymmetric power distribution throughout the core. The calculation of the scaling factor according to Eq. 1 and the least square method gave similar results as the comparison with the equal rod positioning. The discrepancies between the measured and calculated reaction rates were well under 5 %, which again validates the calculational model and the control rod correction factor calculations. The results are shown in Fig. 2 (left).

5 UNCERTAINTY EVALUATION

In order to verify the preliminary uncertainty estimates, a special effort was made to thoroughly research all the possible uncertainties and present their evaluation. The comparison between the calculated and experimental values (Fig. 2 left) shows discrepancies between the fission rates as well as a slight offset in the axial positions. Both were studied in the evaluation of the possible uncertainty sources.

In this section each of the uncertainty origins is separately discussed evaluated.

5.1 Fission chamber axial position uncertainty

The reaction rate distribution changes along the height of the reactor core are significant. With the nominal precision of the fission chamber positioning system approximately 0.1 mm and the reproducibility of the positioning within 0.3 mm, the 1 sigma contribution to the axial position uncertainty can be estimated to around ± 0.2 mm. The effect of the FC axial position uncertainty on the FC signal value however was evaluated by calculating the axial ²³⁵U reaction rate gradient (% per mm) in the core. Its values were computed with the gradient equation:

$$\frac{1}{R_i} \left| \frac{dR_i}{dz} \right| = \frac{1}{R_i} \left| \frac{R_{i+1} - R_{i-1}}{z_{i+1} - z_{i-1}} \right|, \quad (2)$$

where R_i is the reaction rate value on the i -th position of the axial profile. The results of the gradient calculation are shown in Fig. 2 (right). The gradient was averaged over a 25 mm interval to exclude any possible statistical distortion. The core active fuel axial interval is located from the axial position at 140 mm to 570 mm.

As can be observed, the gradient in the central area is on the order of $0.5 \text{ \%}/\text{mm} \sim 1 \text{ \%}/\text{mm}$. The greatest fission rate gradient of approximately $2.5 \text{ \%}/\text{mm}$ can be seen at axial positions around 100 mm and 600 mm, where the graphite plugs and metal cladding replace the uranium fuel in the fuel element.

The uncertainty of the FC axial position, by the average fission rate gradient being $\sim 1 \text{ \%}/\text{mm}$, is approximately 0.3 %.

5.2 Fission chamber radial position uncertainty

Due to the relatively high heterogeneity of the reactor core in the radial direction, the radial reaction rate gradient is expected to be greater than the axial gradient. Therefore it is important to take into account the uncertainties in the FC radial position. The fission chambers measuring 3 mm in diameter were inserted into the reactor core using aluminium guide tubes, their inner diameter measuring 4 mm, which means an upper limit radial position error of 0.5 mm. To accurately estimate the plausible uncertainties, the radial gradient ($\%$ per mm) of fission reaction rates was calculated. Its values were computed using the reaction rate distribution over a mid-height core plane and the two-dimensional gradient equation:

$$\left| \frac{dR}{dr} \right|_{i,j} = (x_i^2 + y_j^2)^{-\frac{1}{2}} \left(x_i \left| \frac{R_{i+1,j} - R_{i-1,j}}{x_{i+1} - x_{i-1}} \right| + y_j \left| \frac{R_{i,j+1} - R_{i,j-1}}{y_{i+1} - y_{j-1}} \right| \right). \quad (3)$$

In Fig. 3 (left) the result of the radial gradient calculation, obtained by using the Monte Carlo method is shown. The measuring positions, where the FC reaction rates were measured, are indicated with black rings. The calculations show that the contribution of the radial position uncertainty to the uncertainty in the FC signal is significant.

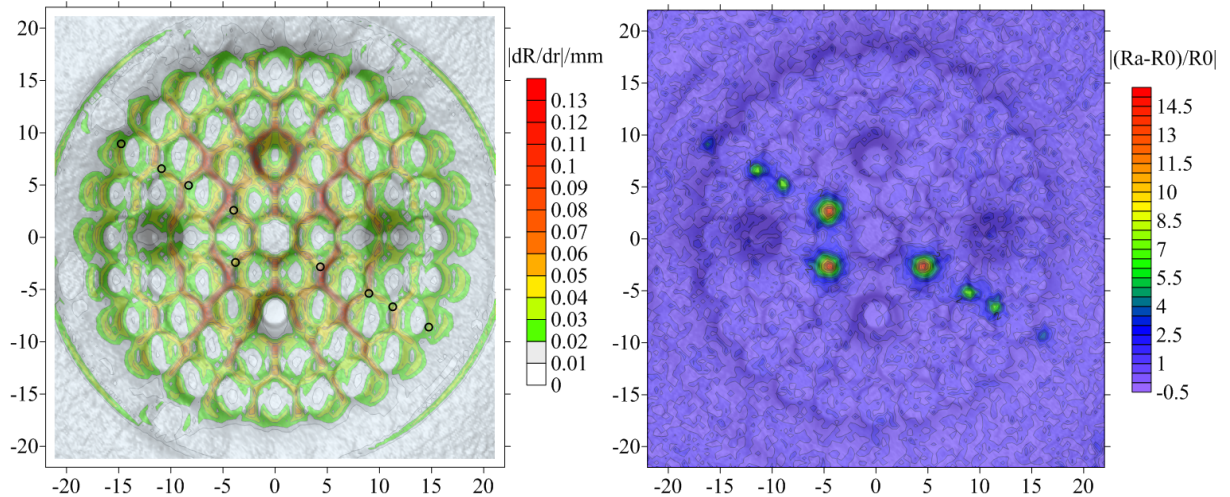


Figure 3: **Left:** Reaction rate radial gradient profile at the mid-height of the reactor core. The black rings in the picture represent the measuring positions of the experiment. **Right:** The absolute value of relative difference between the reaction rate with inserted aluminium guide tubes and without them at mid-height in the reactor core.

Inspection of Fig. 3 (left) allows rough estimates of the gradient values. The radial gradient is increasing with the decreasing of distance to the centre of the core, hence we can expect the lowest uncertainties on the outer edge of the core. Fig. 3 (left) shows a 2 %/mm \sim 3 %/mm (shades of green) reaction rate gradient at the measuring locations most distant from the centre, that are MP 14 and 23. Closer to the reactor core are MP 15, 16, 22 and 21 which are all positioned on the area labeling a 4 %/mm \sim 5 %/mm (light green and yellow) gradient. Closest to the core centre are MP 17, 20 and 25, where the dynamics of the reaction rate is the highest. The gradient values vary from 5 %/mm up to 7 %/mm.

The contribution of the FC radial position uncertainty to the FC measured reaction rate uncertainty for the marginal measuring positions (MP 14, 23) is within the calibrational uncertainty of the FC. The radial gradient of other MPs of the range 4 %/mm \sim 7 %/mm however is significant and exceeds the acceptable value limit. With the maximum possible uncertainty of the FC radial position 0.5 mm, it is crucial to take this evaluation under special consideration.

5.3 Fuel element axial position uncertainty

During a regular fuel inspection campaign a few side view photographs of the fuel elements and the upper reactor grid were taken. In contradiction with the previous knowledge of their position - the fuel element triangular spacer and the upper grid were thought to be aligned - the fuel element axial position was discovered to randomly vary in order of several millimeters. The discrepancy was roughly estimated to be around ± 3.5 mm. A side view photograph of the TRIGA Mark II reactor core can be seen in Fig. 4.

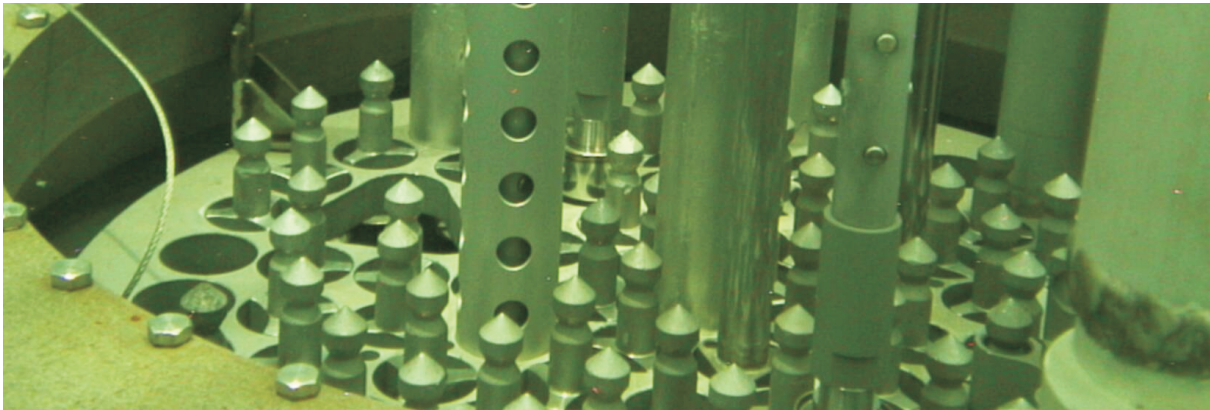


Figure 4: Side view photograph of the TRIGA Mark II reactor core taken during the regular fuel inspection campaign.

The effect of the fuel element axial position shift was modeled and its effect on the FC measurement axial position uncertainty studied. The altered axial position of the fuel element had no noticeable effect on the values of the reaction rate in the core, however it caused the axial shift of the entire distribution. The ± 3.5 mm height variation of the fuel elements resulted in a ± 3 mm ± 1 mm uncertainty of the FC measurement axial position, which, compared to the ~ 1 mm uncertainty of the fission chamber axial position, is significant.

5.4 Aluminium guide tube effect

The effect of the experimental equipment on the FC measurements has also been studied. We focused on the alteration of the FC reaction rate response due to the aluminium guide tubes.

Although aluminium is neither a good absorber nor a good moderator of neutron, it displaces water, which significantly affects the neutron spectrum. Therefore a smaller portion of thermal neutrons and a higher share of fast neutrons is expected inside the insertion tube. To evaluate the difference in reaction rates the aluminium tubes were removed from the reactor calculational model and then the results were compared, which can be seen in Fig. 3 (right).

The relative difference was calculated by $\left| \frac{R_{Al}-R_0}{R_0} \right|$, where R_{Al} represents the reaction rate with inserted aluminium tubes and R_0 the reaction rate without them. The calculations show a large effect on the reaction rate response inside the MPs. Again the difference between the measuring positions located near the edge and close-centre ones can be observed. The three MPs closest to the centre experience a minimum of 10 % decrease in fission rate response while the other MPs experience a decrease of around 1 % near the edge and approximately 4 % ~ 6 % downfall closer to the core centre. Fig. 3 (right) presents calculations made for a mid-height core plane, whereas mesh computations for other axial positions had also been made and show similar results.

The relatively high effect on the measured reaction rates inside the MPs due to aluminium tube insertion can be taken into account when calculating with the computer model. The relative error of the aluminium depression relation is a consequence of Monte Carlo calculation statistical error and is of the order 10 %.

5.5 Control rod position uncertainty effect

The control rod position scale in TRIGA Mark II reactor is divided into 900 steps - 0 being totally extracted and 900 fully inserted - the absolute uncertainty in the position being 3 steps [6]. In the experiment only two rods were used to control the reactor, the compensating and the regulating control rod. It has already been shown [4], that control rods significantly affect the neutron flux profile in the reactor. The effect of the uncertainty in the rod positions on the uncertainty of the FC measurements was studied.

Calculations were made with the regulating and compensating rod in the calculational model were alternately lowered and inserted by 5, 10 and 50 steps. The relative difference between the fission rates of the original and altered rod positions was then calculated. The results for 5 and 10 step offset showed an average of around 0.5 % ~ 1 % difference, but were burdened by a large statistical error. Therefore the control rod position was also tested for a 50 step deviation, the results showing an average of approximately 2 % relative difference, burdened by ~ 50 % statistical error.

Despite the relatively large computational error, the contribution of a maximum of 3 step control rod position uncertainty to the fission chamber measurement uncertainty was found to be negligible.

6 CONCLUSION

The evaluations show that most of the identified sources do not represent a significant contribution to the total fission chamber measurement error. However concern arises over the high level of uncertainty due to FC radial positioning and the effect of aluminium tubes for the measuring positions closest to the centre of the reactor core (MP 17, 20, 25). In Table 1 the experimental and calculational uncertainties burdening either FC reaction rate value or axial profile position are presented. Because of the paper space limit only the general sources of uncertainty were presented. With work still in progress, additional evaluations of uncertainties

such as temperature, fuel burn-up, cross-section libraries etc. will be presented in future papers. In the future an effort will also be made to study the compensation of these discrepancies with correction factors calculated by the validated computational model of the TRIGA reactor. If the evaluated uncertainties are acceptable the experiment will be proposed for inclusion in the International Handbook of Evaluated Reactor Physics Benchmark Experiments.

Table 1: Evaluations of experimental and calculational uncertainties.

Uncertainty source	Uncertainty	Fission response error	Axial profile position error
FC ^{235}U mass	2 %	2 %	/
FC calibration	1.66 %	1.66 %	/
FC axial position	0.3 mm	0.3 %	0.3 mm
FC radial position	0.5 mm	2 % ~ 3.5 %	/
Fuel element position	~3.5 mm	/	~3 mm
Control rod position	3 steps	≤ 0.5 %	/

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