



## Neutronics Analysis of the TRIGA Vienna Mixed Core

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### ABSTRACT

The 250 kW TRIGA Mark II research reactor, Vienna, operates since 7<sup>th</sup> March 1962. The initial criticality was achieved with the first core loading of 57 fuel elements (FE) of same type (Aluminium clad fuel with 20% enrichment). Later on due to fuel consumption SST clad 20% enriched FE (s) have been added to compensate the reactor core burn-up. In 1975 high enriched (HEU) TRIGA fuel (FLIP fuel = Fuel Lifetime Improvement Program) was introduced into the core. The addition of this FLIP fuel resulted in the current completely mixed core. Therefore the current core of the TRIGA reactor Vienna is operating with a completely mixed core using three different types of fuels with two categories of enrichments. This makes the reactor physics calculations very complicated. To calculate the current core, a Monte Carlo based radiation transport computer code MCNP5 was employed to develop the current core of the TRIGA reactor. The present work presents the MCNP model of the current core and its validation through two experiments performed on the reactor. The experimental results of criticality and reactivity distribution experiments confirm the current core model.

As the basis of this paper is based on the long-term cooperation with our colleague Dr. Matjaz Ravnik we therefore devote this paper in his memory.

### 1 INTRODUCTION

The TRIGA Mark II research reactor is the only nuclear operating research facility in Austria satisfying its educational and research objectives. The Atominstitute (ATI) of the Vienna University of Technology (VUT) has been operating this research reactor since March 1962 with a maximum thermal power of 250 kW and maximum thermal flux of  $1 \times 10^{13}$  n/(cm<sup>2</sup>.sec) in the centre of the core. The reactor with a cylindrical core lattice achieved its first criticality on 7<sup>th</sup> March 1962. According to first criticality experiment from the reactor log book, the initial core was employed with the same type of fuel that is 20% enriched aluminium clad fuel or also called 102 type fuel. To keep the reactor into operation for its research and training purposes, some additional but different types of FE(s) were added to the core over its operational history. This makes the current core as completely mixed core of three different types of fuels which are 20% enriched aluminium (Al) clad (102 type), 20% enriched Stainless Steel (SST) clad (104 type) and 70% enriched SST clad FLIP (110 type) fuels. Starting with an uniform core of 57 (102-type) FE(s), the current core has total 83 FE(s) including 53 FE(s) of the 102 type, 9 of the FLIP type and 21 of the 104 type [1]. All these FE (s) are arranged in an annular lattice. Both the first and the current core configurations are been given in Figure 1 where the FE identification numbers starting with digit “2 and 3” denote 102-type fuel, starting with digit “7” present FLIP and the remaining digits indicate the 104-type FE [2].

The TRIGA fuel is a metallic alloy of Uranium and ZrH (U-ZrH) with different Hydrogen to Zirconium (H/Zr) ratios depending on the fuel type [3, 4]. The TRIGA fuel has cylindrical geometry. Generally, the components of a TRIGA FE are enriched U-ZrH fuel meat, two axial graphite reflectors, burnable poisons [3, 4]. The 102-type fuel has upper and lower Samarium disks, 104-type has lower Molybdenum disk while Erbium is homogeneously mixed Erbium in the FLIP fuel.

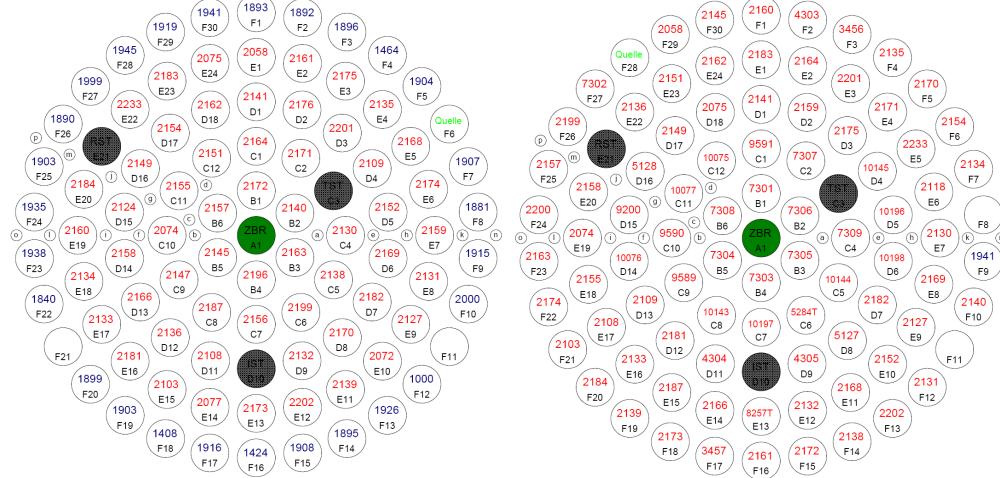


Figure 1: Initial core configuration (left) and current core configuration (right).

The overall dimensions of all types of FE(s) are same i.e. 3.75 cm in diameter and 72.06 cm in length. The detailed geometric and material specifications of all three fuel types are given in Table 1 [5]. This paper briefly describes the MCNP model of the current core and its validation through criticality and reactivity distribution experiment.

Table 1: TRIGA Mark II fuel types and their geometrical and material specifications.

Fuel Type	102 type	Type 104	FLIP
<b>Fuel meat</b>			
Material	U-ZrH	U-ZrH <sub>1.65</sub>	U-ZrH <sub>1.65</sub> -Er
Density (g/cc)	6.279	6.02	5.913
Length (cm)	35.6	38.1	38.1
Radius (cm)	1.797	1.822	1.822
Mass of U per F.E	184.028	184.028	194
U in Fuel (Wt. %)	8.0	8.50	8.50
Mass of U <sup>235</sup> per F.E	36.77	36.77	135.8
Enrichment (Wt. %)	20	20	70
<b>Burnable Poisson</b>			
Material	2 Sm-disks	1 lower Mo-disk	1.6 wt. % of Er
Density (g/cc)	7.6	10.28	-----
Length or thickness (cm)	0.075	0.02	-----
Diameter (cm)	3.58	3.63	-----
<b>Axial Reflector</b>			
Material	Graphite	Graphite	Graphite
Density (g/cc)	1.6	1.6	1.6
Upper Gr. Length (cm)	10.21	6.80	-----
Lower Gr. Length (cm)	10.21	9.39	-----
Diameter (cm)	3.58	3.63	3.63
<b>Central Zirconium Rod</b>			
Material	-----	Zr	Zr
Density (g/cc)	-----	6.5	6.5
Length (cm)	-----	38.1	38.1
Diameter (cm)	-----	0.635	0.635

<b>Fuel Cladding</b>			
Material	Al-1100 F	304-SS	304-SS
Density (g/cc)	2.71	7.9	7.9
Thickness (cm)	0.076	0.051	0.051
<b>Overall dimensions</b>			
Total length (cm)	72.06	72.06	72.06
Outer diameter (cm)	3.750	3.750	3.750

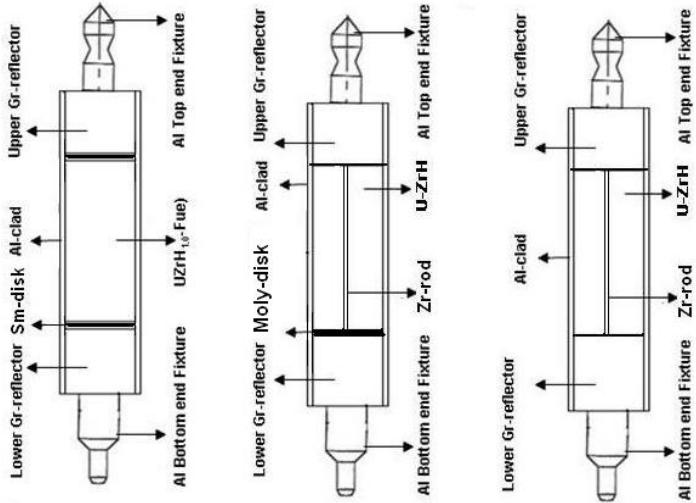


Figure 2: The 102-type FE (left), 104-type FE (middle) and FLIP-type FE (right).

### 1.1 MCNP Model of the Current Core

The MCNP is a Monte Carlo based neutronics behaviour simulating radiation transport computer program. It simulates neutron, photon and electron independently and also treats their coupled behaviours. In the MC process, probability distributions are randomly sampled to mimic the actual event happening in the reactor core [6]. The MCNP model of the TRIGA Vienna is equipped with the JEFF 3.1 neutronics data library.

The original MCNP model employing fresh fuel of the TRIGA Mark II was modified into the current core model. Keeping the same geometrical and material inventory assumptions, few main modifications were performed in the already developed model. First, addition of different types of FE(s) to the core over its operational reactor history which makes the current core a completely mixed core of three different types of fuels. Second, because of having more than 48 years of irradiation history, the current core model has been applied with burned fuel material composition [3]. In the application of the burned fuel material composition to the model, only the effective material composition was taken into account. A study on the effective material composition for TRIGA fuel [8] was found and the isotopes having their reactivity effect up to  $\pm 10$  pcm were considered in this paper. The burned fuel composition was calculated by using the ORIGEN2 code and verified by gamma spectroscopy of the Cs-137isotope at Atominstutute [7].

Figure 3 presents the MCNP Model of the current core and different types of FE (s) of the TRIGA Mark II research reactor of Vienna. It includes all main components of the reactor. Inside the reactor core, there are 83 fuel elements, 3 control rods, one source element and two pneumatics transfer systems in the F-ring of the core lattice. Outside the core, this model simulates the annular graphite reflector, thermal column, radiographic collimator, four beam tubes and water tank [7].

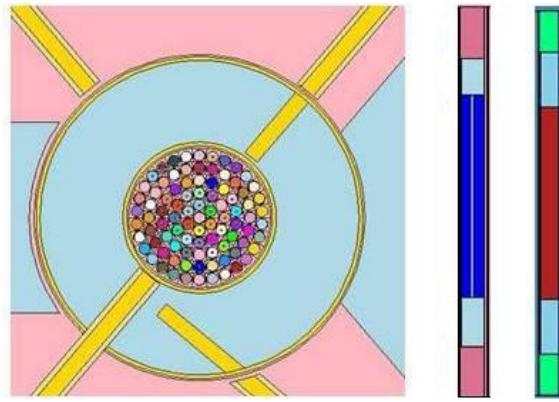


Figure 3: Top view of the MCNP Model of the reactor (left), 104 and FLIP FE (middle) and 102-type FE (right).

## 1.2 Model Validation [3]

This model is based on first criticality experiment, the original model was confirmed by first criticality experiment performed in March 1962. The reliability of the current core model needs its confirmation. Therefore two different experiments were performed at ATI to verify the current core MCNP model. These experiments include another criticality experiment and reactivity distribution experiment. Both experiments measure the effective multiplication experiment of the reactor core.

### *Criticality Experiment*

To perform this experiment, 10 FE(s) were chosen in the current reactor core. These selected FE(s) have little effect of the control rods in their vicinity. These FE(s) were removed from the core and placed in the storage positions within the reactor tank. The selected positions of FE(s) are B05, B06, C09, C10, D13, D14, E17, E18, F21 and F22. The Figure 4 marks the positions of these FE (s) with “x” sign. The start-up source was kept in the core for the duration of this experiment. The FE (s) were added to the core one by one recording the neutron signal from a fission chamber. According to this experiment, at the addition of 78<sup>th</sup> FE (D14), the core achieved its criticality while all three control rods were fully out.

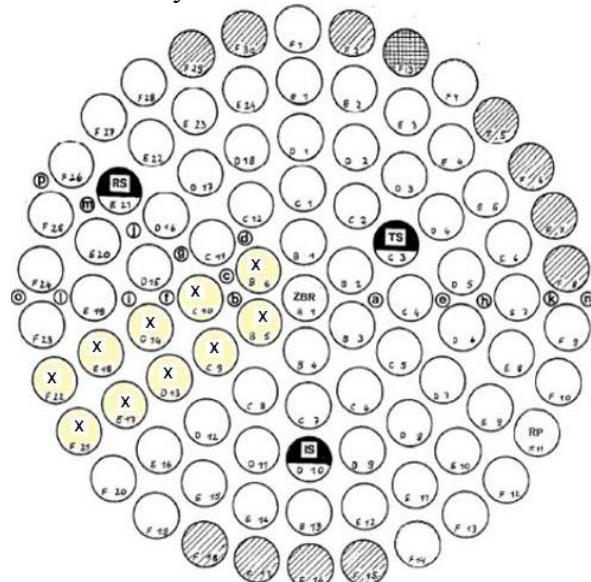


Figure 4: The selected profile of the radial flux density measurements.

The S73d (or S73u) represents the neutron count rate when 73 FE(s) are in the core with all three CR(s) in fully down (or fully up) positions respectively. Similarly the symbol Sxxd (or Sxxu) is used for neutron count rate after each addition of a FE. The ratios (Sxxd/S73d and Sxxu/S73u), after each addition of FE, were calculated. The experimental observations is shown in the Figure 5. This brown line in this figure shows that reactor core become just critical after the insertion of FE number 78 with all CR(s) in completely up positions. With the control rod in completely down position, the linear extrapolation shows that core will become critical after adding FE no 87.

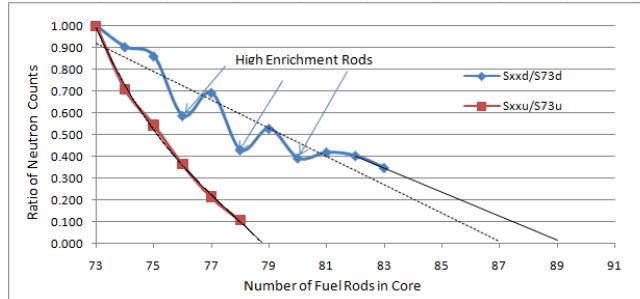


Figure 5: Experimental results of the critical experiment at the TRIGA Mark II reactor.

The current core MCNP model was applied to the critical experiment. The model was applied for each addition of FE, in both positions of CR(s) (fully up and fully down positions). For each model execution, 50000 particle histories with 100 cycles of neuron life were applied for criticality calculations. Each calculation took about 200 minutes of computational run time. The simulated results are in Figure 6, indicating that core achieves its criticality on addition of 78th FE keeping all control rods in fully up positions. Keeping all three CR(s) fully down positions, the core may become critical on addition of 87<sup>th</sup> to 89<sup>th</sup> FE depending upon the extrapolation size [6].

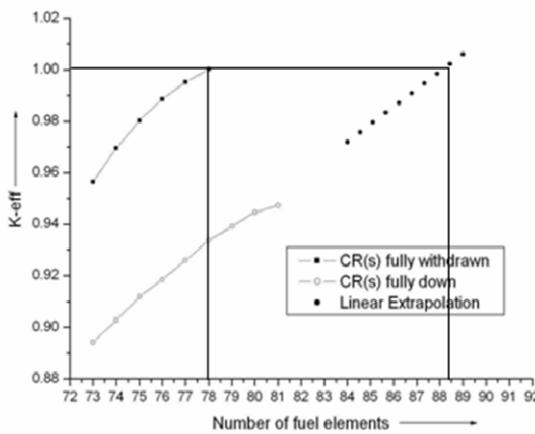


Figure 6: The MCNP results of current core criticality experiment.

### Reactivity Distribution Experiment

The validation of the model was extended to the reactivity worth distribution experiment. In this experiment, five FE(s) in different ring positions were measured for their reactivity worth. Keeping the burn-up group approximation [5] and control rod effects into consideration, the five FE(s) were selected for this experiment. The fuel identification numbers of these FE(s) are 10077(B05), 10198(D05), 7301(C01), 2133(E16) and 2184(F20).

Using the shim rod calibration curve, performed on June 29, 2009, the reactivity worth measurements of each FE(s) was measured. This experiment was performed at the current core configuration as shown in Figure 1. During each measurement, the FE was replaced by water.

The current core MCNP model was modified for each reactivity calculation of the selected FE. The same experimental conditions were applied to the model keeping the same geometrical and material approximations. These calculations were performed with total 150 cycles of iteration on a source size of 50000 particles per cycles. To decrease the statistical error estimates, first 25 cycles were skipped. For each execution of the model, the calculating FE was replaced by water. From the output, k-eff for each FE was obtained to calculate the corresponding reactivity worth in dollars using the value of effective delayed neutron fraction ( $\beta$ ) as 0.0073 [6].

The comparison between theoretical and experimental results are shown in Figure 4.8. The difference between calculations and measurement will be discussed in the next section.

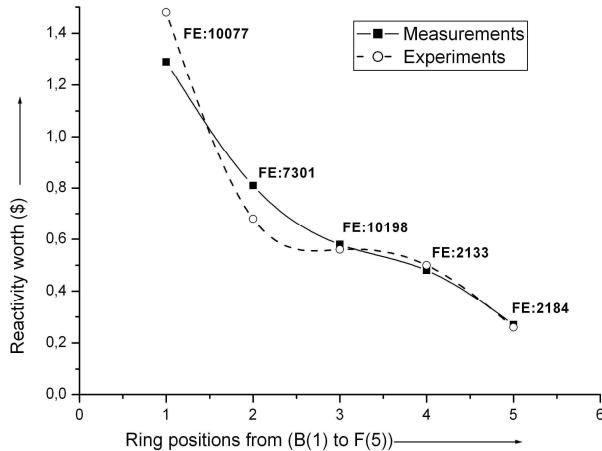


Figure 7: The comparison between the MCNP experimental results [4].

## 2 DISCUSSIONS

### 2.1 Criticality Experiment

Both the experimental results in the Figure 5 and the MCNP results in Figure 6 are agreed on the fact that that the current core approaches the criticality when 78th FE (2109 in position D13) is added to the core. The simulation calculates the 1.31 cents positive reactivity insertion when FE 2109 is inserted into the core while the experimental curve in Figure 4.6 confirms the positive reactivity insertion but gives no value due to its experimental limitations. In case of CR(s) fully down position, both experimental and theoretical results agree and show that the reactivity of each FE is different. This may be because of each FE has different fissile material composition and hence has different effect on the core reactivity.

Both Figures 5 and 6 agree that the core does not reach its criticality on addition of all 83 FE(s) keeping all three CR(s) in fully down position. This is due to the shut down margin of all three CR(s). If the linear fit of the experimental data points (Figure 5) is extrapolated, the core may become critical on addition of the 88th FE approximately. In case of MCNP results, when a linear fit of the theoretical data is extrapolated, the core may attain its criticality on addition of 88th FE in the core assuming that each additional FE insertion follows the average reactivity trend.

## 2.2 Reactivity Distribution Experiment

This experiment is performed with the core configuration as shown in Figure 1. Generally, the MCNP results are consistent with the experimental results. The reactivity of each FE is different due to different irradiation. The irradiation of FE(s) is not uniform as most of the FE(s) were reshuffled during their irradiation [8]. Figure 7 compares the theoretical (MCNP) and experimental results of reactivity distribution experiment and confirm the fact that inner FE (of B and C rings) are more reactive than the outer rings FE(s) (D, E, F). The calculations are closer to the experimental results in the outer ring positions (i.e. D, E and F) than the inner ring positions (i.e. B and C-ring) of the core. It may be because of, when FE is inserted into the core; more severe local neutron flux density distribution is deformed in inner ring position than the outer rings (D, E and F). The other possible reason of the deviations between the MCNP results and experimental observations is due to the burn-up group approximation.

All FE(s) in the current core have been divided into sixteen groups on the basis of their burn up values [5]. Each group has its average burn up value. The FE having the burn up value closest to the average group value represents that group in the current core MCNP model. Such FE is named as group indicator. The current core model is applied with the effective material composition of 16 FE(s). This assumption is called burn up group approximation. This burn up group approximation has also its role in the deviations between the theoretical results and experimental observations.

## 3 CONCLUSION

The MCNP model employing the fresh fuel was modified to the current core MCNP model. The burn up group approximation is applied and the current core MCNP model incorporates the effective burned fuel material composition of the core. The criticality and reactivity distribution experiment was performed to verify the current core MCNP model. The model predicts the criticality of the current core on core loading of 78 FE(s) while the criticality experiment on the current core confirms the model prediction. In the reactivity distribution experiment, five FE(s) from different ring positions were measured for their reactivity worth. This experiment verifies the MCNP simulated reactivity values of five selected FE(s) in the current reactor core.

## 4 EPILOGUE

During the past decades the Atominstitute never had a real reactor physics group in contrast to the Institute Josef Stefan. During the 1980ies I met Matjaz Ravnik at various IAEA training courses which we carried out together in South East Asia, ever since this time we stayed in touch and cooperated on various reactor physics topics. Matjaz Ravnik and Andrej Trkov tested also their reactivity meter at our TRIGA resulting in several common publications. During the past 3 years my co-author Mr.Khan started to get deeply involved into MCNP TRIGA core calculations and renewed our cooperation with the IJS again. In this respect he went to IJS for a week of detailed discussion and received very valuable information from Dr.Ravnik's experience. In this way it must be stated here that through the assistance of Dr.Ravnik the ATI entered back into the field of core calculations research, this is the reason that we want to dedicate this paper in memory of Dr.Ravnik.

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