

Analysis of the TRIGA Reactor Benchmarks with TRIPOLI 4.4

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ABSTRACT

In order to compare different up-to date advanced Monte Carlo neutron transport codes a new computational model of the TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI) was developed by using the TRIPOLI 4.4 neutron transport code.

In the paper, the model is presented (geometry, cross section library, assumption, etc.), and the TRIPOLI results are compared to the benchmark values and calculations with MCNP (another Monte Carlo code which is used at JSI).

Criticality configuration and flux distribution have been investigated to verify and validate the model. Criticality calculations have shown a difference of 300 pcm between MCNP and TRIPOLI. Thermal flux distribution has shown that a more accurate modelling is needed to describe other quantities.

1 INTRODUCTION

The TRIGA criticality benchmark experiment was performed at the JSI TRIGA in 1991 and was thoroughly evaluated [10]. It is described in the International Handbook of Evaluated Criticality Safety Benchmark [2]. Moreover reaction rate distribution measurements were performed in 2007 [3]. All these experiments were thoroughly analysed [3] and used for various purposes from testing of cross section libraries [4] to optimisation of irradiation facilities by using the Monte Carlo transport code MCNP [5].

Other Monte Carlo codes such as TRIPOLI [6] treat neutron scattering in a different way. As the TRIGA benchmarks are highly sensitive to the scattering nuclear data [4], they were chosen to perform comparison of reactor physics parameters calculated by two different advanced and up-to date Monte Carlo neutron transport codes TRIPOLI 4.4 and MCNP5.

The main objective of this project is to build the computational model of the TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI) by using the TRIPOLI 4.4 neutron transport code.

Experiments will be used to verify the calculations of k_{eff} with our computational model. In addition recently performed reaction rate distribution measurements of (n,γ) , (n,α) and (n,f) reactions will be used to verify the calculated reaction rates.

In the first part of the paper the computational model is presented (geometry, cross section library, assumption, etc.). In the second part the TRIPOLI results are compared against the benchmark values and MCNP calculations.

2 TRIGA RESEARCH REACTOR

or other components like control rods, a neutron source, irradiation channels, etc. Elements are arranged in six concentric rings: A, B, C, D, E and F, having 1, 6, 12, 18, 24 and 30 locations, respectively as shown by the figure 2

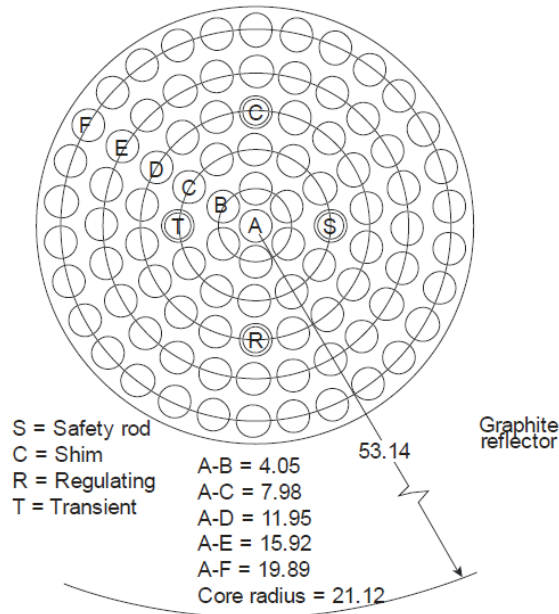


Figure 2: Core Configuration with Rod Locations Labelled (All dimensions are in cm)

The fuel is a homogeneous mixture of enriched uranium and zirconium hydride (U-ZrH). The enrichment and content of uranium in U-ZrH depends on the fuel type. The main physical characteristics of different TRIGA fuel rod types are presented in [1].

3 TRIPOLI

The TRIPOLI-4 [6] computer code was used in the calculation of the effective multiplication factor (k_{eff}) and of the various reaction rates investigated. TRIPOLI-4 is a general purpose radiation transport code. It uses the Monte Carlo method to simulate neutron and photon behaviour in three-dimensional geometries. All the calculations presented in this paper use the version 4.4 of the code. Different cross-section libraries (obtained in the package of the code from the NEA databank, Paris) were used (JEF-2.2, ENDF/B-VI.4, JEFF-3.1, and JENDL-3.3).

Criticality calculations were performed for 2000 active cycles of 5×10^5 neutrons each. The code discards the first few batches (5 on averages) in order to achieve convergence of the fission sources.

3.1 Multiplication factor k_{eff}

The TRIGA criticality benchmark model from the ICSBEP [2] was used for comparing the k_{eff} calculations. Two critical core configuration (denoted as core132 and core133) were investigated. They are presented schematically in figure 3.

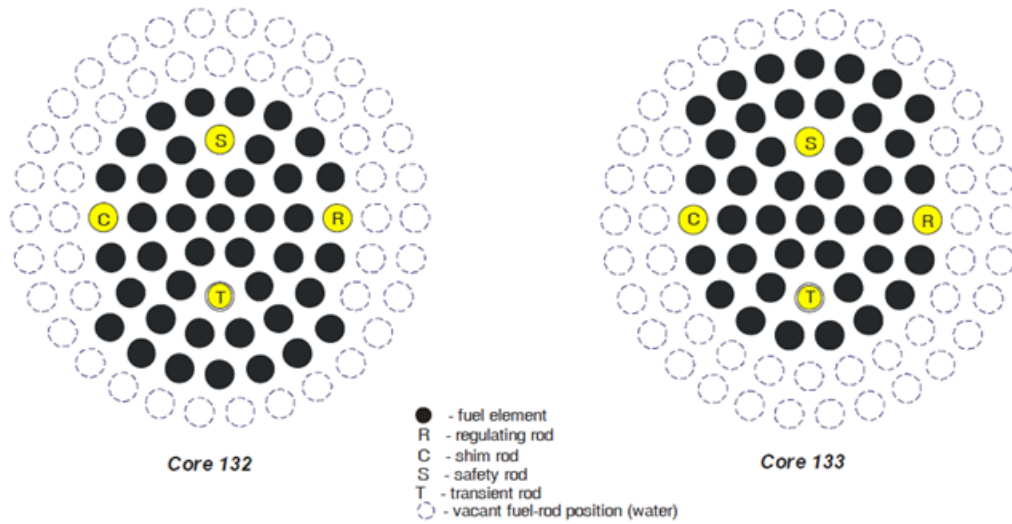


Figure 3: Configurations of the benchmark cores top view

For our calculation a simplified model, was used: structures which have a minor effect on k_{eff} were omitted or simplified to avoid complex modelling (more detail can be obtained in [1]). TRIPOLI benchmark model can be visualise in figure 4

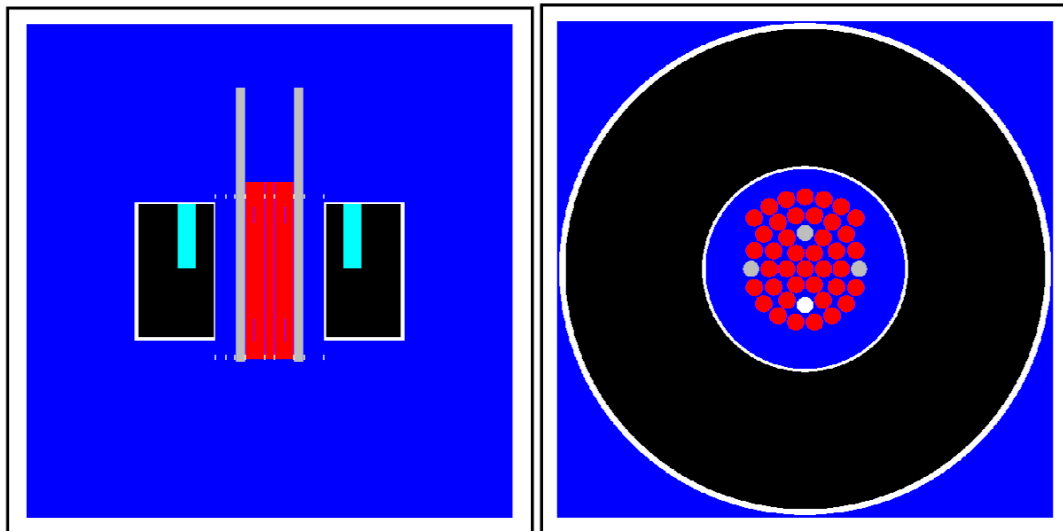


Figure 4: Side and top view of the TRIPOLI Computational model

The effective multiplication factor of the benchmark model is different from the experimental one due to geometry simplifications and uncertainties in the material and geometrical data of the benchmark model [1]. The differences in k_{eff} between the simplified “benchmark” model and the full model are presented in Table 1:

Table 1: Experimental and Benchmark-model k_{eff} with their uncertainties(measurement for experimental value and material for Benchmark-model value)

	Experimental k_{eff}	Benchmark-model k_{eff}
core 132	0.99865 ± 0.00015	1.0006 ± 0.0056
core 133	1.0031 ± 0.00015	1.0046 ± 0.0056

TRIPOLI calculations were made with different cross-section libraries. Results are presented in Tables 2 and 3 with the corresponding MCNP values [7], obtained from the same geometrical model to allow a comparison.

It should be noted that except for JEFF-3.1, nuclear data for all isotopes were not available for neutron reaction and so the missing nuclear data files were taken from JEFF-3.1, for JEF-2.2 and JENDL-3.3 calculations, and from ENDF/B-VII.0, for ENDF/B-VI.4 calculations as follows:

- ENDF/B-VI.4 were complemented with data from ENDF/B-VII.0 for isotope of S, Si and of H bound in ZrH (this element has a strong importance as shown in [3])
- JENDL-3.3 were complemented with data from JEFF-3.1 for isotope of H bound in UZr and in H₂O and C bound in graphite
- JEF-2.2 were complemented with data from JEFF-3.1 for isotope of Si and of H bound in ZrH.

In the following tables, C refers to computational value and E to experimental value.

Table 2: Calculated values of the benchmark k_{eff} using different cross-section libraries for the core 132

library\code	TRIPOLI	MCNP	C/E-1(TRIPOLI) in pcm	C/E-1(MCNP) in pcm
ENDF/B-VI.4	0.9988 ± 0.0001	1.0001 ± 0.0001	-180	-50
JEFF-3.1	0.9992 ± 0.0001	1.0019 ± 0.0001	-140	130
JENDL-3.3	0.9996 ± 0.0001	X	-100	X
JEF-2.2	1.0003 ± 0.0001	X	-30	X
ENDF/B-VII.0	X	1.0059 ± 0.0001	X	530

Table 3: Calculated values of the benchmark k_{eff} using different cross-section libraries for the core 133

library\code	TRIPOLI	MCNP	C/E-1(TRIPOLI) in pcm	C/E-1(MCNP) in pcm
ENDF/B-VI.4	1.0022 ± 0.0001	1.0048 ± 0.0001	-239	20
JEFF-3.1	1.0028 ± 0.0001	1.0063 ± 0.0001	-179	169
JENDL-3.3	1.0028 ± 0.0001	X	-179	X
JEF-2.2	1.0036 ± 0.0001	X	-100	X
ENDF/B-VII.0	X	1.0107 ± 0.0001	X	607

TRIPOLI calculated value discrepancy is less than 250 pcm at the maximum. Although only results for JEFF-3.1 allow a comparison between TRIPOLI and MCNP, since ENDF/B-VI.4 were modified for TRIPOLI. It can be observed that MCNP k_{eff} values are 300 pcm higher, the explanation of this observation is still under investigation but may be due to a different treatment of thermal scattering by each code

3.2 Neutron flux distribution

According to the results of criticality calculations, the TRIPOLI model describes the TRIGA benchmark core relatively well. However it should be noted that k_{eff} as the integral parameter is not very sensitive to neutron flux distribution. Hence, in order to compare the neutron flux distributions in the TRIGA reactor, we used the reaction rate distribution measurements using the neutron activation technique. In the experiment aluminium-gold (Al (99.9 wt. %) - Au (0.1 wt. %) foils (disks of 5 mm diameter and 0.2 mm thick) were irradiated

in 33 locations; 6 in the core and 27 in the carousel facility in the reflector (figure 5) (reference).

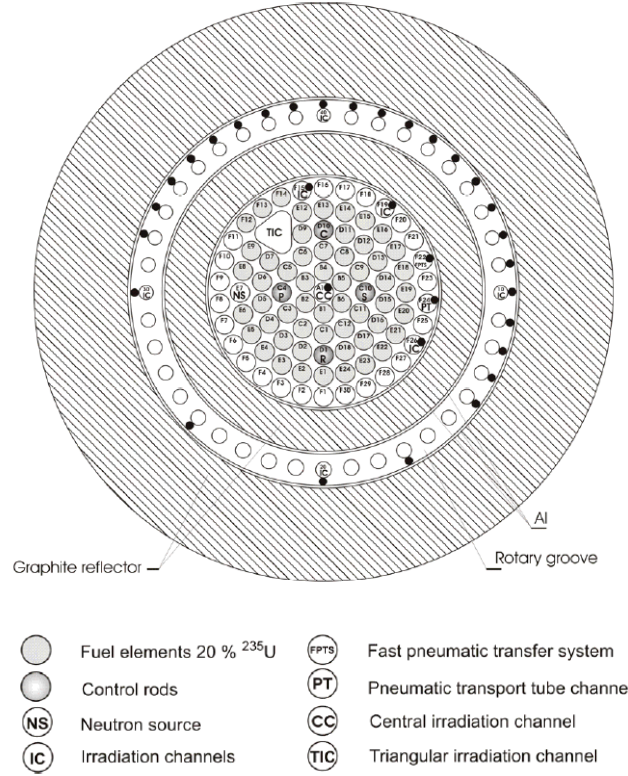
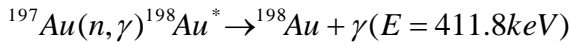
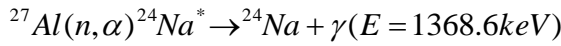


Figure 5: location of the Al-Au foil in the core

After irradiation, the activation of individual samples was measured using High-Purity Germanium detector (HPGe). The following two activation reactions were considered in the experiment:



(1)

The first reaction (n,α) has energy threshold at 5 MeV (blue curve in figure 6) and is thus convenient for investigation of fast neutron flux.

The cross section for the second reaction (n,γ) is the highest for energies below 10 keV (black curve Figure 6), making this reaction useful for investigation of thermal ($E < 0.625$ eV) and epithermal (0.625 eV $< E < 100$ keV) neutrons.

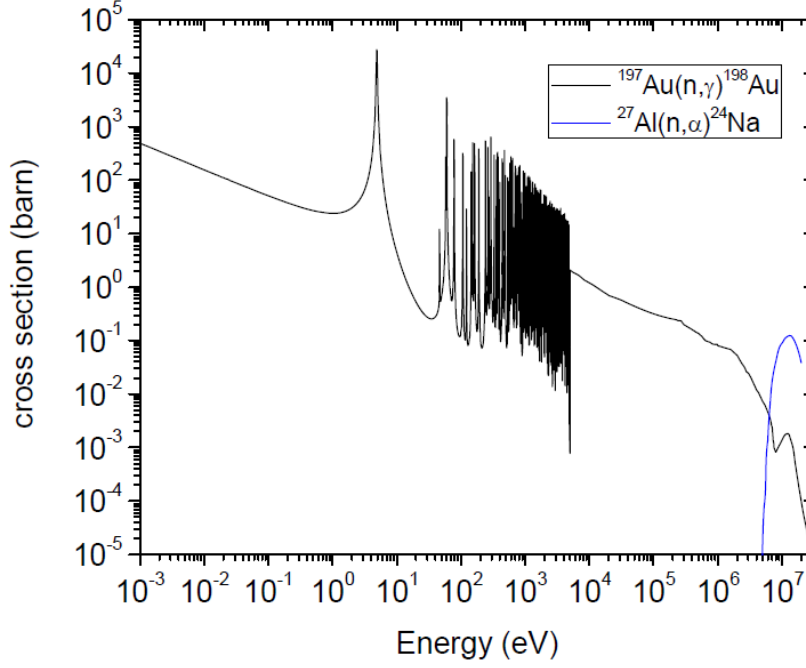


Figure 6: Cross sections of the activation reactions

In order to make these comparisons it was decided to adopt the same convention of normalisation as used in [3]. One should know that for this part, there are two main differences between MCNP and TRIPOLI results:

- TRIPOLI is used with JEF-2.2 library and the benchmark model.
- MCNP is used with ENDF/B-VII.0 library and a more accurate geometrical model [7], different from the one used in criticality calculations.

The choice of JEF-2.2 is due to neutron calculation problem in TRIPOLI for gold isotope.

Hence a proper comparison is not possible. The calculated and measured reaction rates in the core are normalised to the central channel (CC) are presented in Figure 7 and 8. The normalized specific activity in i -th irradiation channel in the core is defined as:

$$A_{i,norm}^{core} = \frac{A_i^{core}}{A_{CC}^{core}} \quad (2)$$

A very good agreement between TRIPOLI calculation and experimental data are observed, which emphasize adequate modelling of the reactor core:

- For aluminium, the average standard deviation is 1.5%
- For gold, the average standard deviation is 0.7%

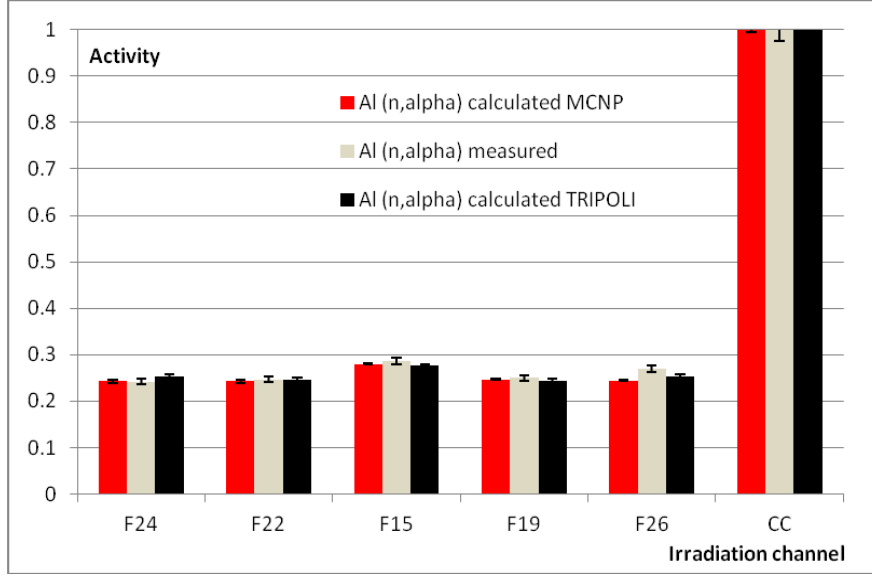


Figure 7: Normalised core activity for aluminium activation calculated by TRIPOLI (green), MCNP (blue) and measured (red)

A legend in the graph and using different textures would be nice.

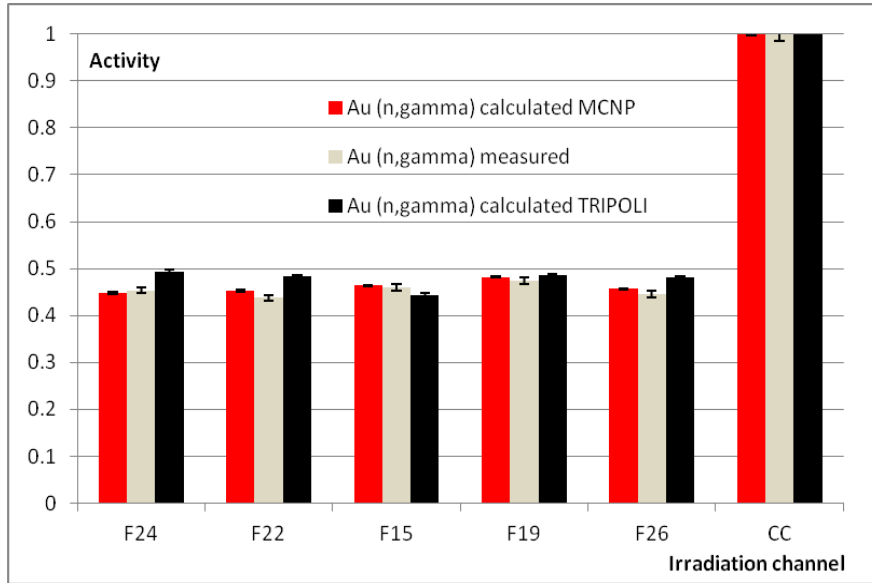


Figure 8: normalised core activity for gold activation calculated by TRIPOLI (green), MCNP (blue) and measured (red)

The calculated and measured reaction rates in the rotary groove (RG) normalized to the average of all RG irradiation channels are presented in figure 9 and 10. The normalized specific activity in i -th irradiation channel of the RG is defined as:

$$A_{i,norm}^{RG} = \frac{A_i^{RG}}{\frac{1}{N} \sum_{j=1}^N A_j^{RG}} \quad (3)$$

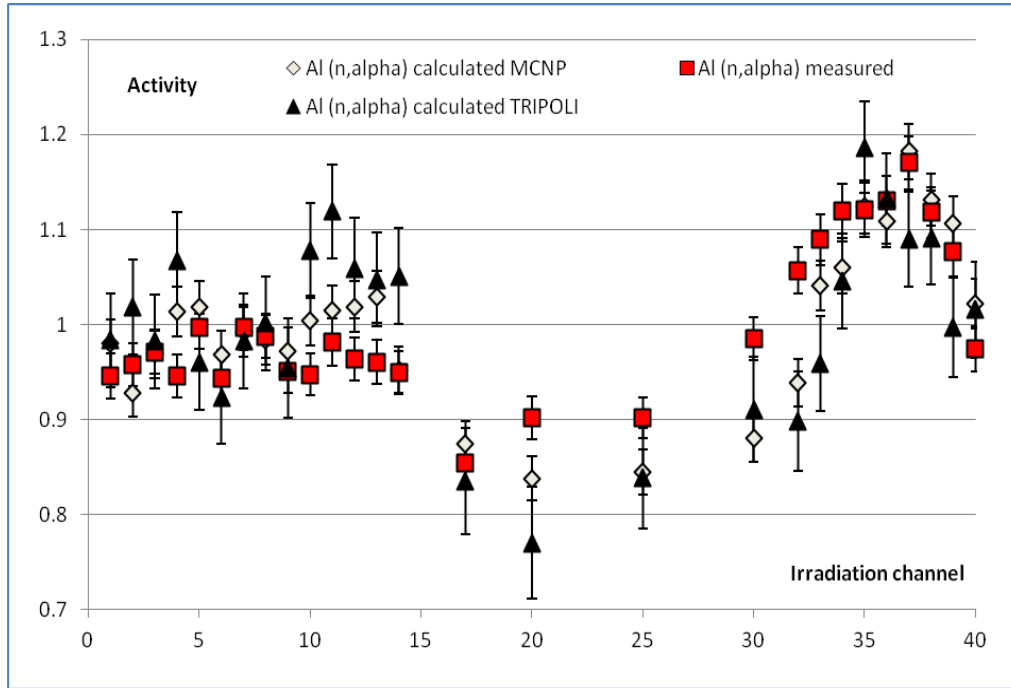


Figure 9: Normalised RG activity for aluminium activation calculated by TRIPOLI (green), MCNP (blue) and measured (red) with errors bars

Relative difference between TRIPOLI calculation and experimental data for aluminium are less than 7%. Further analyses will be performed to explain the difference. Nevertheless the trends of the distribution are similar.

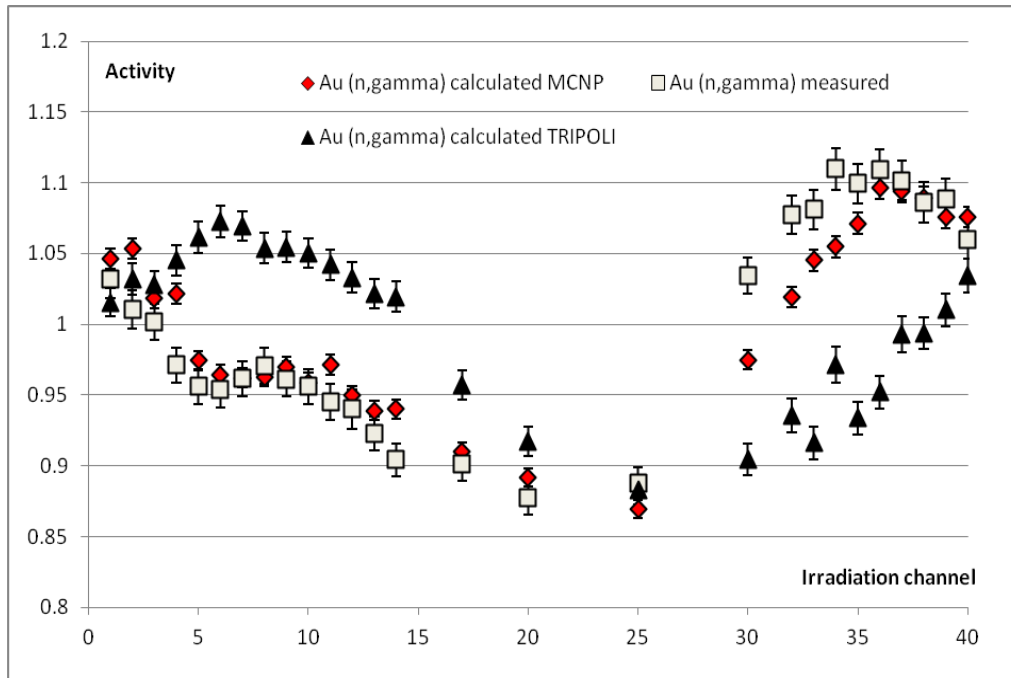


Figure 10: Normalised RG activity for gold activation calculated by TRIPOLI (green), MCNP (blue) and measured (red) with errors bars

In the case of gold activation the discrepancy observed using the TRIPOLI benchmark model is more important, showing that benchmark model is not accurate enough to describes

thermal and epithermal flux investigation, since the irradiation channels piercing the graphite reflector are not modelled. To investigate the attenuation of the neutron flux from the core to the RG, the so called attenuation factor was calculated, result are summarised in Table-4. The attenuation factor is defined as:

$$F_a = \frac{\frac{1}{N} \sum_{j=1}^N A_j^{core}}{A_{CC}^{core}} \quad (4)$$

Table 4: The experimental and calculated Fa factors for fast and thermal plus epithermal flux.

Reaction	$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$		$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	
	F_a	st. deviation	F_a	st. deviation
measured	0.02795	0.00068	0.12868	0.0019
calculated MCNP	0.0278	0.00005	0.14228	0.00003
relative difference [%]	-0.5	2.4	10.6	1.5
calculated TRIPOLI	0.0254	0.00025	0.15678	0.00033
relative difference [%]	-9.1		21.8	

CONCLUSION

Even though the order of magnitude is right, the flux relative difference is high for the reasons explained before. As the work is still in progress, future efforts will be devoted to evaluation of uncertainties and clarification and explanation of the discrepancies. In addition, longer runs will be performed to reduce the statistical uncertainties.

All in all, a good TRIPOLI benchmark model was built. Nevertheless more accurate model will be needed to investigate thermal and epithermal flux or any other physical quantities of interest for reactor physics such as kinetics parameter or power distribution.

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