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TRIPOLI-4 Simulation of the FNG Copper Benchmark Experiment and the Tritium Production in the Lithium Diamond Detector for ITER-TBM

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For the future ITER (International Thermonuclear Experimental Reactor) operation needs, several D-T fusion neutron experiments have been conducted at FNG (Frascati Neutron Generator) facility. These FNG experimental results are useful to validate neutron transport codes and nuclear data libraries. The TRIPOLI-4 Monte-Carlo radiation transport code has been widely used on radiation shielding, criticality safety and fission reactor physics fields to support nuclear energy research and industrial applications. With the growing interest in using the TRIPOLI-4 code for ITER applications, a key issue that arises is whether or not the released TRIPOLI-4 code and its associated nuclear data libraries are verified and validated for the 14 MeV fusion neutronics calculations. Copper is a key material used in different components of ITER tokamak machine and the FNG copper benchmark experiment funded by F4E (Fusion for Energy) was recently introduced into the OECD/NEA SINBAD database. In the first part of this work, TRIPOLI-4 calculations were performed to simulate the D-T fusion neutron transport in a pure copper block of FNG-Cu experiments. The reaction rates were evaluated for various activation foils ($^{93}\text{Nb}(n,2n)$, $^{27}\text{Al}(n,\alpha)$, $^{58}\text{Ni}(n,p)$, $^{115}\text{In}(n,n')$, $^{197}\text{Au}(n,2n)$, $^{186}\text{W}(n,\gamma)$, and $^{197}\text{Au}(n,\gamma)$) versus penetration depth in the Cu block. To study the measurement tool of tritium production for the future ITER Test Blanket Module (TBM), the second FNG experiment analyzed in this work arranged a thin layer of ^6LiF (LiDia detector) placed inside a polyethylene cylinder and irradiated with FNG 14 MeV neutrons. TRIPOLI-4 simulation models were run to evaluate the tritium production in the LiDia detector. The purpose of this study is to investigate the TRIPOLI-4 calculations against the FNG experimental ones. TRIPOLI-4 calculation methods and results are reported.

Keywords: TRIPOLI-4 Monte Carlo Code, 14 MeV neutron transport, FNG-Cu experiment, Tritium Production Rate

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) is currently under construction at Cadarache in southern France. To support the ITER design and operation needs, several D-T fusion neutron experiments have been performed at the FNG (Frascati Neutron Generator) facility. The 14 MeV FNG neutron source is based on the $\text{T}(d,n)\alpha$ fusion reaction with a flux up to 1×10^{11} neutrons/s [1-2]. These FNG experimental data and results are available from the OECD/NEA SINBAD database and useful to validate neutron transport codes and nuclear data libraries [3].

The TRIPOLI-4 Monte-Carlo radiation transport code has been widely used on fission neutron shielding analyses [4]. With the growing interest in using the continuous-energy TRIPOLI-4 code for ITER neutronics applications, a key issue that arises is whether or not the released TRIPOLI-4 code and its associated nuclear data libraries are verified and validated for the 14 MeV fusion neutronics calculations. In this context, both experimental and computational benchmarks are being performed [5-7].

In this study, two recent published FNG benchmark experiments were investigated with the TRIPOLI-4 code using JEFF-3.3 nuclear data library. In the first part of

this work, simulation models were developed and verified. Several TRIPOLI-4 calculations were performed to optimize the simulation of D-T fusion neutron transport in a pure copper block ($60 \times 70 \times 60 \text{ cm}^3$) of FNG-Cu experiments [8-11]. Various activation foils, Nb, Al, Ni, In, W, and Au were chosen to measure the neutron reaction rates versus penetration depth in the Cu block.

To study the measurement tool of tritium production in the future ITER Test Blanket Module (TBM), the second FNG experiment analyzed in this work uses a single crystal diamond detector covered with a thin layer of ^6LiF placed inside a polyethylene cylinder (25.5 cm diameter and 25 cm height) and irradiated with FNG 14 MeV neutrons [12].

Due to the thickness of the Cu block, variance reduction techniques of TRIPOLI-4 calculations were necessary in order to investigate the D-T neutron deep penetration in Cu [6, 7, 13]. The calculation results including activation foils reaction rates for the FNG-Cu experiments and the tritium production rate per ^6Li atom per fusion neutron in the LiDia detector are presented.

2. FNG copper benchmark experiments

The FNG-Cu block is composed of 7 plates. Each Cu plate is 10 cm thick, 60 cm wide, and 60 cm height. The

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total copper weight of these plates is about 2.3 tons. These plates are placed on an Al support and held together by 4 bolted Al bars. Figure 1 shows the FNG copper block used in the experiments [8]. To reduce the scattering neutron contribution from the experimental room, the copper block was loaded in the FNG big experimental room at a height of several meters from the ground surface.

The first 6 copper plates facing the FNG D-T fusion neutron source have one or two cylindrical holes in which cylindrical copper rods containing the activation foils were placed into the experimental positions. These measurement positions lie on the horizontal mid plane of the Cu block at eight various penetration depths. During the experiments, the copper block was placed in front of the FNG tritium target at 5.3 cm from it [3].

To measure the fusion neutron penetration in copper block, seven dosimeter materials of activation foils were used. Related nuclear reactions for fast and thermal neutron activation foils include $^{93}\text{Nb}(n,2n)$, $^{27}\text{Al}(n,\alpha)$, $^{58}\text{Ni}(n,p)$, $^{115}\text{In}(n,n')$, $^{197}\text{Au}(n,2n)$, $^{186}\text{W}(n,\gamma)$, and $^{197}\text{Au}(n,\gamma)$. The diameters of these foils range from 1.27 to 1.8 cm. Their thicknesses range from 0.01 to 0.2 cm for fast neutron measurement foils and from 0.001 to 0.01 cm for slowdown and thermal neutron measurement ones [3, 9-11].

Figures 2 and 3 show the cross sectional views of the FNG copper benchmark experiment. Both the FNG target and the Cu blocks based on the published SINBAD models were taken into account in the models [3].

3. FNG Lithium diamond detector experiment

To investigate the tritium fuel cycle for fusion energy sustainability, different designs of TBM have been taken into account in the equatorial ports of ITER. The FNG Lithium diamond (LiDia) detector experiment was developed to study the on-line TPR (tritium production rate) monitors for the future ITER-TBM. This detector will be first tested with the HCPB TBM mock-up experiment at JET during the next D-T phase [7, 12].

The experimental configuration of FNG LiDia detector irradiation used in this study is presented in Figures 4 and 5. The LiDia detector based on the $^6\text{Li}(n,\alpha)\text{T}$ reactions was placed at the center of the polyethylene cylinder. This polyethylene neutron moderator is useful to slowdown the neutron energy and increase the $^6\text{Li}(n,\alpha)\text{T}$ reaction rates measurement sensitivity [15].

By using a diamond film with electrical contact layer based on the diamond like carbon and a 100 nm thick gold layer, the disc shape ^6LiF layer was deposited on the top of one electrode of the diamond base. The ^6LiF disc had a diameter of 3 mm and a thickness of 3.5 μm . The ^6Li enrichment in ^6LiF disc was 95%. Using the FNG 14 MeV fusion neutrons, the measurement capability of the calibrated LiDia detector was demonstrated [12].

4. TRIPOLI-4 calculations and results

TRIPOLI-4 is a general purpose Monte Carlo radiation transport code. The FNG-Cu experimental configuration was modelled with its native geometry package including surface and combinatorial defined volume cells. In this study the geometry model of a previous study was taken into account but the HCLL TBM mock-up was replaced by the FNG-Cu block [14].

To improve the calculations performance, a simplified model was also built for the TRIPOLI-4 calculations. As the mean free path of fast neutron in Cu block is several centimeters the homogeneous Cu block model can be prepared according to the data of Fig. 2 and 3. This simplified model can still keep the main features of this experiment and it can reduce important computational resources.

The accuracy achievable of this simplified model with respect to the full model was investigated and the difference of these two models on calculation results was very small compared to the uncertainty of measurement. This simplified model considering only the FNG target and the Cu block was also useful to verify and adjust other parameters such as variance reduction and nuclear data.

The FNG D-T fusion source was identical to that used in previous study [14]. Both the angular distribution and the associated neutron energy spectrum were defined in 179 segments.

Previous investigations show that fusion neutron deep penetration calculations is a challenging task [8, 14]. In order to decrease the variances of calculated results, especially for the deeper measurement positions, the INIPOND variance reduction techniques of TRIPOLI-4 were helpful in this work for the analysis of FNG-Cu experiments [6, 13].

For the FNG LiDia detector experiments the analog TRIPOLI-4 run was performed in order to treat the neutron slowing down and the neutron thermalization in an exact way. The thermal neutron up-scattering option was necessary for neutron collision with hydrogen in polyethylene [15].

4.1 FNG-Cu benchmark calculation results

Tables 1-5 show the TRIPOLI-4 (JEFF-3.3) calculated reaction rates and the measured ones for five fast neutron dosimeters in the FNG-Cu block. The normalization of calculation results was performed to one D-T fusion source neutron. Generally a good agreement was obtained between TRIPOLI-4 calculations and the measurement ones for the first 35 cm depth of the FNG-Cu block. Over-estimation of C/E was observed from the deeper penetration positions.

For the $^{93}\text{Nb}(n,2n)$ reaction rates (RR) results, this trend of increasing C/E values in deeper positions was already shown in Fig. 8 of Ref. [11] and in Fig. 7 of this reference, lower $^{65}\text{Cu}(n,n')$ reaction cross-section was shown when using the KIT revised evaluation of the JEFF-3.2 and the TENDL-2015 evaluation. The

threshold energy of $^{93}\text{Nb}(n,2n)$ reaction is around 9 MeV. A decrease in the $^{65}\text{Cu}(n,n')$ reaction cross-section for fast neutron (> 5 MeV) is helpful to push fast neutron transport towards deeper positions.

A similar C/E trend was also found for $^{27}\text{Al}(n,\alpha)$ and $^{58}\text{Ni}(n,p)$ reactions with lower threshold energies of reaction around 6 and 1.5 MeV respectively. The drop of C/E value to 0.73 at 57 cm depth for $^{58}\text{Ni}(n,p)$ reaction was also observed in Fig. 8 of Ref. [11]. The uncertainty of measurement 9.8% at this point may explain it. The under-estimation of $^{115}\text{In}(n,n')$ reaction rates by calculations is uniform from 3.58 to 57.2 cm depth in the Cu block and it confirms the previous study [11].

The threshold energy of $^{197}\text{Au}(n,2n)$ reaction is around 8 MeV and the 14 MeV reaction cross-section is about 2 barns. The C/E ratios presented in Table 5 show a good agreement between TRIPOLI-4 calculations and measurements but only 5 positions of measurements are available in the first 25 cm of the Cu block.

For slow neutron reaction rates results (Tables 6-8), the C/E ratios are generally lower than 1 (0.73 – 0.89 for $^{197}\text{Au}(n,\gamma)$ reaction, 0.41 – 0.58 for $^{186}\text{W}(n,\gamma)$ reaction, and 0.61 – 0.66 for $^{55}\text{Mn}(n,\gamma)$ reaction). This under-estimation of TRIPOLI-4 results is in good agreement with the MCNP Monte Carlo analyses by ENEA and KIT, and with the DORT calculations by JSI [3, 9, 11]. Recent study on the uncertainty of the nuclear data may explain these points [8].

4.2 FNG-LiDia benchmark calculation results

The TRIPOLI-4 code has been used to analyse previous OKTAVIAN benchmark experiments and to study the tritium breeding ratio (TBR) by using various nuclear data libraries [16]. As the TRIPOLI-4 calculated TBR values are nuclear data library dependent, it is essential to investigate the tritium production by using the latest version of TRIPOLI-4 code and nuclear data library.

Tables 9 and 10 show the TRIPOLI-4 calculated results for the FNG LiDia detector experiment. Two models were developed in this work. Model (I) is a simplified one considering only the fusion neutron slowing down in the polyethylene cylinder for physical parameters sensitivity test.

This sensitivity tests deal with the dimensions and the density of polyethylene, the dimensions and the density of ^6LiF , the distance between the FNG neutron source and the polyethylene cylinder, the thermal neutron up-scattering effect in polyethylene, the Al support of polyethylene, the neutron transport nuclear data libraries, the dosimetry files, and the variance reduction options of TRIPOLI-4 code.

One of these sensitivity tests confirmed the impact of the ^6LiF thickness [12]. Due to the strong thermal neutron attenuation and the self-shielding effect of the ^6LiF layer, the calculated TPR was sensitive to both the thickness and the density of the ^6LiF . Other tests results will be reported in a separated paper and some of them

are still in investigation by using an improved variance reduction option of TRIPOLI-4.

The model (II) is a full model including the FNG target as well as its cooling water, the Al support of polyethylene cylinder, and the experimental room walls.

Both the experimental tritium production rates and the MCNP5 calculation results from the Ref. [12] are presented in Tables 9 and 10. Generally a satisfactory agreement was obtained between TRIPOLI-4 calculations and those of MCNP5. They agree within two standard deviations of calculation uncertainties. Comparison between TRIPOLI-4 calculated TPR and measurement one is also acceptable considering the experimental error of 3.9 %.

5. Conclusion and discussion

TRIPOLI-4 Monte Carlo radiation transport calculations were performed in this study for the FNG-Cu D-T neutron deep penetration experiment and the FNG-LiDia detector experiment for tritium production rate monitoring. Both the full models, including the FNG experimental room and FNG detailed target, and the simplified models were taken into account.

A good agreement between TRIPOLI-4 (JEFF-3.3) calculations and measurements has been obtained for fast neutron dosimeter foils, $^{93}\text{Nb}(n,2n)$, $^{27}\text{Al}(n,\alpha)$, $^{58}\text{Ni}(n,p)$, $^{115}\text{In}(n,n')$, $^{197}\text{Au}(n,2n)$ in FNG-Cu benchmark experiment. For slow neutron results, TRIPOLI-4 provides similar trends and results to a previous study using MCNP5 code.

The calculation results of FNG-LiDia detector experiment depend on several parameters including the distance between the FNG target and the polyethylene cylinder, the density of the polyethylene, the thickness and the density of ^6LiF ,... etc.. A first evaluation with TRIPOLI-4 (JEFF-3.2) provides satisfactory benchmark results. Future work is necessary to quantify these parameters impact on this experiment in details.

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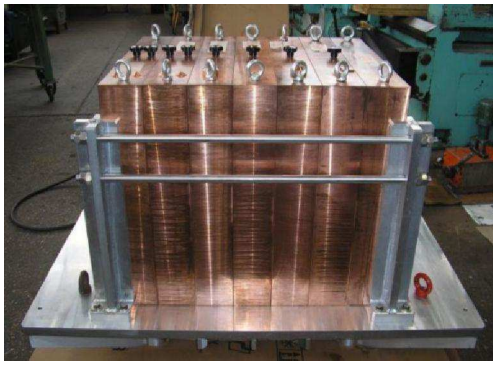


Fig. 1 FNG copper benchmark experiment (7 Cu plates held together by 4 bolted Al bars and 8 activation foils measurement positions at the D-T beam prolonged line) [8]



Fig. 4 The FNG target and the polyethylene cylinder for Lithium Diamond Detector experiment (LiF foil of LiDia detector is placed at the center of the polyethylene cylinder) [12]

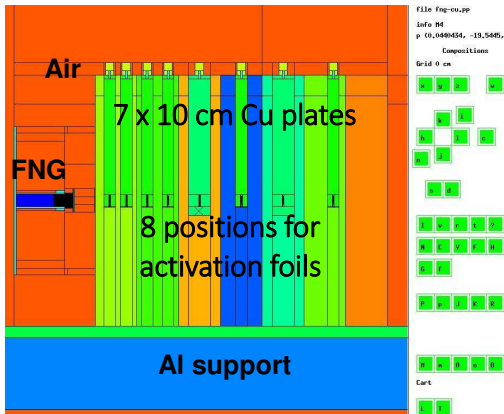


Fig. 2 FNG copper benchmark experiment (SINBAD model displayed by TRIPOLI-4 display tool T4G [17]). Lateral Y-Z view (from left to right: FNG head and 7 blocks of 10 cm thick Cu plates) The 8 positions for activation foils at the FNG D-T beam prolonged line are also displayed [3]

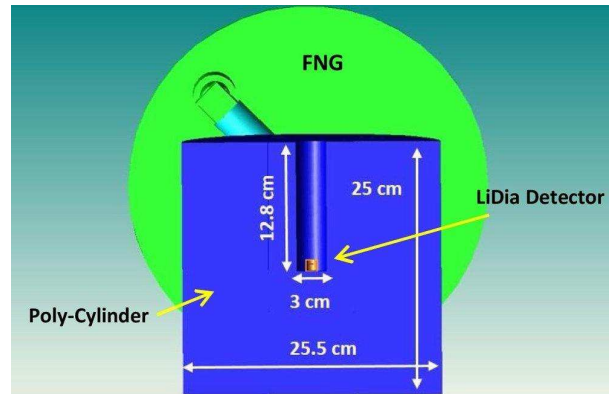


Fig. 5 The FNG polyethylene cylinder (Poly-Cylinder) and the Lithium Diamond Detector (LiDia Detector) [12]

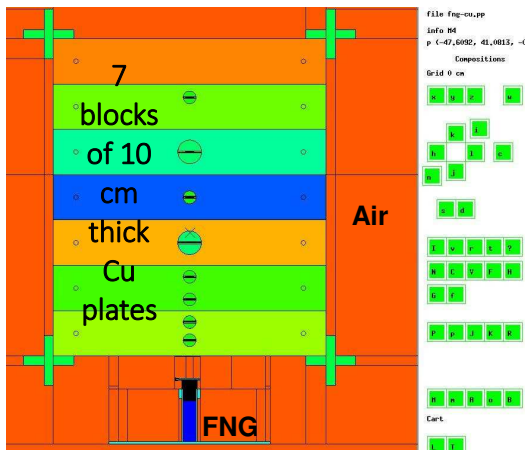


Fig. 3 Cross sectional view of the FNG copper benchmark experiment. X-Y view displayed by TRIPOLI-4 code (from lower to upper parts: FNG head, 7 x 10 cm Cu plates fixed in 4 Al cross bars. The 8 positions for activation foils placed under the Cu rods are also displayed.)

Table 1 TRIPOLI-4 (JEFF-3.3) calculated $^{93}\text{Nb}(n,2n)$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using Nb activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
3.57	3.37E-4 (0.08)	3.59E-4 (4.7)	0.94
7.57	1.01E-4 (0.14)	1.08E-4 (4.7)	0.94
12.56	2.89E-5 (0.26)	2.95E-5 (4.7)	0.98
17.56	9.62E-6 (0.46)	9.55E-6 (4.7)	1.01
24.05	2.17E-6 (0.99)	2.05E-6 (4.7)	1.06
35.06	3.30E-7 (2.30)	3.06E-7 (4.7)	1.08
45.07	6.34E-8 (6.60)	4.38E-8 (5.3)	1.45

Table 2 TRIPOLI-4 (JEFF-3.3) calculated $^{27}\text{Al}(n,\alpha)$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using Al activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
3.48	8.62E-5 (0.07)	8.77E-5 (4.4)	0.98
7.48	2.61E-5 (0.14)	2.80E-5 (4.4)	0.93
12.46	7.57E-6 (0.26)	7.89E-6 (4.4)	0.96
17.46	2.57E-6 (0.45)	2.54E-6 (4.4)	1.01
24.95	5.81E-7 (0.93)	5.96E-7 (4.6)	0.97
34.96	9.40E-8 (2.40)	8.20E-8 (5.7)	1.15
44.97	1.74E-8 (5.60)	1.33E-8 (5.2)	1.30
56.97	2.45E-9 (13.3)	1.81E-9 (11.3)	1.36

Table 3 TRIPOLI-4 (JEFF-3.3) calculated $^{58}\text{Ni}(n,p)$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using Ni activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
3.58	3.01E-4 (0.09)	2.96E-4 (4.8)	1.02
7.58	1.07E-4 (0.15)	1.09E-4 (4.7)	0.98
12.56	3.54E-5 (0.30)	3.51E-5 (4.8)	1.01
17.56	1.30E-5 (0.44)	1.20E-5 (4.9)	1.09
25.05	3.26E-6 (0.90)	2.88E-6 (4.8)	1.13
35.06	5.77E-7 (2.20)	4.32E-7 (5.4)	1.34
45.07	1.03E-7 (4.80)	7.47E-8 (8.9)	1.38
57.07	1.63E-8 (11.9)	2.22E-8 (9.8)	0.73

Table 4 TRIPOLI-4 (JEFF-3.3) calculated $^{115}\text{In}(n,n')$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using In activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
3.58	1.99E-4 (0.13)	2.37E-4 (4.7)	0.84
7.58	9.35E-5 (0.18)	1.16E-4 (4.7)	0.80
12.56	3.85E-5 (0.30)	4.78E-5 (4.7)	0.80
17.56	1.64E-5 (0.40)	2.05E-5 (4.8)	0.80
25.05	4.76E-6 (0.70)	5.81E-6 (5.1)	0.82
35.01	9.29E-7 (1.50)	1.09E-6 (4.8)	0.85
45.02	1.93E-7 (3.40)	2.28E-7 (4.7)	0.85
57.02	2.93E-8 (7.20)	3.25E-8 (5.5)	0.90

Table 5 TRIPOLI-4 (JEFF-3.3) calculated $^{197}\text{Au}(n,2n)$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using Au activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
3.53	1.61E-3 (0.23)	1.65E-3 (4.7)	0.98
7.53	4.78E-4 (0.32)	5.19E-4 (4.6)	0.92
12.51	1.36E-4 (0.43)	1.45E-4 (4.7)	0.94
17.51	4.65E-5 (0.50)	4.77E-5 (4.9)	0.97
24.99	1.03E-5 (0.65)	1.01E-5 (4.8)	1.02

Table 6 TRIPOLI-4 (JEFF-3.3) calculated $^{197}\text{Au}(n,\gamma)$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using Au activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
3.53	4.37E-4 (3.1)	5.97E-4 (4.6)	0.73
7.53	4.22E-4 (2.6)	5.40E-4 (4.7)	0.78
12.51	3.70E-4 (3.5)	4.69E-4 (4.6)	0.79
17.51	3.14E-4 (2.8)	4.00E-4 (4.7)	0.78
24.99	2.57E-4 (5.6)	3.09E-4 (4.7)	0.83
35.01	1.81E-4 (8.7)	2.04E-4 (4.7)	0.89

Table 7 TRIPOLI-4 (JEFF-3.3) calculated $^{186}\text{W}(n,\gamma)$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using W activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
3.5	1.79E-4 (5.4)	3.86E-4 (5.0)	0.46
7.3	1.72E-4 (5.3)	3.38E-4 (5.0)	0.51
12.49	1.51E-4 (4.7)	2.86E-4 (5.1)	0.53
17.49	1.46E-4 (7.6)	2.54E-4 (5.1)	0.58
24.97	1.10E-4 (7.1)	2.19E-4 (5.1)	0.50
34.98	6.51E-5 (8.9)	1.61E-4 (5.1)	0.41

Table 8 TRIPOLI-4 (JEFF-3.3) calculated $^{55}\text{Mn}(n,\gamma)$ reaction rates (RR) per fusion neutron for the FNG-Cu block shielding experiment using Mn activation foils

Depth in Cu block (cm)	Reaction rates RR (1E-24/neutron)		C/E (T4/M)
	TRIPOLI-4	Measured	
	RR (Std %)	RR (Error %)	
17.51	1.87E-5 (2.3)	3.02E-5 (5.6)	0.62
24.99	1.59E-5 (2.7)	2.61E-5 (5.9)	0.61
35.01	1.23E-5 (4.2)	1.86E-5 (5.9)	0.66
45.02	8.18E-6 (5.9)	1.30E-5 (5.6)	0.63

Table 9 Comparison between TRIPOLI-4 and MCNP5 calculated $^6\text{Li}(n,\alpha)\text{T}$ reaction rates per ^6Li atom per fusion neutron (TPR in $\text{s}^{-1} \text{at}^{-1} \text{n}^{-1}$) for the FNG-LiDia detector experiment by using JEFF-3.2 library

TRIPOLI-4 Model	Tritium production rate TPR		Ratio T4/M5
	TRIPOLI-4	MCNP5 [12]	
	TPR (Std %)	TPR (Std %)	
(I)	0.260 (1.2)	0.286 (1.6)	0.91
(II)	0.278 (1.4)	0.286 (1.6)	0.97

Table 10 Comparison between measured result and TRIPOLI-4 (JEFF-3.2) calculated $^6\text{Li}(n,\alpha)\text{T}$ reaction rates per ^6Li atom per fusion neutron (TPR in $\text{s}^{-1} \text{at}^{-1} \text{n}^{-1}$) for the FNG-LiDia detector experiment

TRIPOLI-4 Model	Tritium production rate TPR		Ratio T4/M
	TRIPOLI-4	Measured [12]	
	TPR (Std %)	TPR (Std %)	
(II)	0.278 (1.4)	0.298 (3.9)	0.93