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Research paper

Initial Criticality Analysis of Malaysia's TRIGA Research Reactor Using TRIGLAV Computer Code

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Abstract

Malaysian Nuclear Agency hosts the 1MW Thermal TRIGA MARK II research reactor since 1982. It first initial criticality was achieved on 28th June 1982 with loading of solid fuel elements like Uranium Zirconium Hydride. TRIGA MARK II started its operation of the research reactor on the same year with a 1MW power generation. Training, Research, Isotope Production and General Atomic (TRIGA) is designed to successfully actualize the variety fields of fundamental nuclear research, the manpower training and the production of radioisotopes. This study deals with the initial criticality analysis of the TRIGA research reactor using TRIGLAV reactor physics computer program. For this purpose, a model of its initial core will be developed and simulated using the software and the results will be validated against the experimental result as mentioned in the final safety analysis report (FSAR). The TRIGLAV computer code solves the neutron diffusion equation by using a finite differences method with iteration of fission density. TRIGLAV is based on four group time independent diffusion equation in two dimensional cylindrical (r, θ) geometry. TRIGLAV can also be applied for criticality of reactor, fuel burn-up calculations, and power distribution and flux distributions calculations of the core and also the reactivity predictions of the reactor.

Keywords: *Criticality, TRIGA MARK II, RTP, TRIGLAV, WIMSD-4*

1. Introduction

A nuclear term, 'Criticality' can be defined as the balance of neutrons in the core while 'Subcritical' refers to a system where the number of neutron decreases per time hence the rate of neutron loss is greater than the production rate of neutrons [1]. In other hand, 'Supercritical' is a system when the production rate of neutrons is greater than the loss rate of neutrons and hence the number of neutrons will increases [1, 2]. The nuclear system is in critical state when the neutron populations remain constant meaning there is an equal balance between the production rate and the loss rate of neutrons [2]. Criticality can be calculated through comparing the rate when the neutrons are produced from fission reaction and the rate which the neutrons are lost through absorption and leakage out of the core [3].

Puspati TRIGA Reactor is the one and only operational nuclear research facility in Malaysia that is located in Dengkil, Bangi and the research reactor reached its initial criticality on 28th June 1982 with an excess reactivity of $0.15 [4]. The fuel comprises of 8.5wt%, 12wt% and 20wt% with 20% of Uranium-235 weight. The reactor is a mixed core type of reactor and it used a pool type tank that has a cylindrical core arrangement and is surrounded with graphite that is used as a reflector and is cooled by natural convection. The top and bottom grid plate is made of Aluminium-6061. Reaktor TRIGA PUSPATI (RTP) has four control rods (3 control rods are fuel follower and 4th one is air follower) and they are made from boron carbide [5]. The 1MW Puspati TRIGA MARK II was designed to incorporate the facilities for advanced neutron and gamma radiation studies and also for isotope production, sample activation, and students training (mostly internship) [4, 5].

The TRIGLAV, the diffusion theory based computer code, has been widely used for the neutronic calculations like criticality and fuel burnup and analysis of the core management [6]. Based on diffusion approximation of neutron transport equation, TRIGLAV is a deterministic code which used WIMS (Winfrith Improved Multigroup Scheme) for reactor lattice cell calculation to get an averaged cross section data for a unit cell. TRIGLAV program package is developed for reactor calculation that uses a mixed core type of reactor like in TRIGA Research Reactor [7]. This computer code can be used for burnup fuel elements calculations, power and flux distributions calculations and also to predict the criticality for research reactor by using simulation and coding of the core.

Winfrith Improved Multi-group Scheme (WIMS) is an open structure program that includes a variety of methods connected together to produce a calculation that significantly deal with most issues regarding to Thermal Reactor Physics [8]. It is the most comprehensive and adaptable programming package that is accessible for neutron calculations. The users can tailor their strategies according to their selection criteria to get the ideal evaluation to address the concerning issues. Besides that, WIMS functioned as an examiner to examine issues regarding reactor that consecutively from basic homogeneous cells to a complex entire core calculations [8, 9]. In advanced, it also links to the entire core code and also acts as a lattice code to generate a library of cell constants for the reactor [10].

The objectives of this paper is to develop the model of the TRIGA research reactor core specifically TRIGA MARK II in Malaysia and to perform the first criticality analysis by using reactor physics computer code, TRIGLAV and the results is validated against the available reference results. For this purpose, TRIGLAV computer code is used to put all material's cross section into the reactor core. While in the meantime, WIMSD-4 will generate the material cross section for every single fuel rod. Input files like fuel element input file and reactor core input file will be constructed in the TRIGLAV Computer Code. Then, the WIMSD-4 program will be executed in the programming of TRIGLAV to perform all necessary calculation needed for this study.

2. Methodology

The key target of this study is to analyze the criticality of TRIGA Puspati Mark-II reactor core by using WIMSD-4 code that is assimilated in TRIGLAV package. The methodology for this research study comprises of few stages that lead to the final result for the primary target. There are five stages included in order to finish this research study. The first step is to identify the background study and understand about the scope of his research study. The second step consists of literature review that consider on how this research study could be perform by gathering all related information to be examined and discussed while the third stage is the selection process in determine the suitable coding to analyze the TRIGA reactor core for criticality calculation purposes. The fourth stage comprises of analyzing the modeling software for coding calculation. Last but not least, the fifth phase that include the documentation needed for this research work.

2.1. Neutron Transport Equation

The ability to sustain a chain reaction by fission neutron can be defined as nuclear criticality that is characterized by the eigenvalue for neutron transport equation, keff. Criticality also known as multiplication factor that can be define as the ratio of the number of fission neutrons in the generation divided by the number of fissions in preceding generation [11]. To simplify,

$$k = \frac{\text{number of fissions in one generation}}{\text{number of fissions in preceding generation}}$$

For the system to be critical, keff must be equal to 1 (keff =1). In this case, the chain reaction will sustain itself which means the chain reaction for the core is normal. Meanwhile, for the system to be subcritical (keff <1), the chain reaction will not sustain itself in fission neutron and as for supercritical system (keff >1), the number of fissions will increases to the rate of time [12]. The formula of keff can be calculated using Boltzmann Transport Equation or known as Neutron Transport Equation [13]. The equation is as follows;

$$k_{eff} = \frac{\rho_a \int_V \int_0^\infty \int_E \int_\Omega \nu \sigma_f \phi \, dV dt dE d\Omega}{\int_V \int_0^\infty \int_E \int_\Omega \nabla \cdot J dV dt dE d\Omega + \rho_a \int_V \int_0^\infty \int_E \int_\Omega (\sigma_c + \sigma_f + \sigma_m)\phi \, dV dt dE d\Omega}$$

This equation comprises with energy (E), direction of neutron (Ω), neutron current flux (J), flux (Φ), neutron velocity (v), time (t) and reactor volume (V), material or atom density (ρa) by meant of **σc, σf, σm** are microscopic cross section for capture (n, pn) fission and multiplicity (n, xn) respectively. This equation can derived from Neutron transport equation. Unfortunately, it is not easy to get the criticality factor approach using neutron transport equation. This is because too many parameters are needed. The complexity of the geometry and the uncertainty of neutron particles itself are uncertain and need to be calculated. Thus, to overcome these problem approximations, deterministic code of TRIGLAV or called as diffusion code is used for this research study.

2.2. Preparation Input File in TRIGLAV

TRIGLAV is divided into three subroutines; subroutine for average of cross section, subroutine for TRIGA2D, and BURN. The TRIGA2D is an independent code for calculation of multiplication factor, flux and power distribution in 2-D cylindrical geometry [6]. It is intended for reactor physics calculations of stationary thermal multiplying systems in four group diffusion approximations. It is also designed for standard TRIGA MARK II research reactor geometry and assumed that the core has cylindrical configurations with annular graphite reflector [14]. The distance between locations of elements in a given ring is equal to a distance between rings (see Fig.1.)

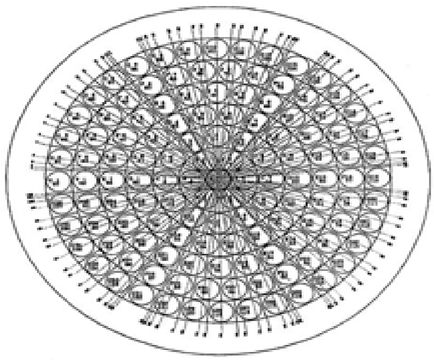

Fig. 1: Geometry of TRIGA MARK II reactor assumed in TRIGA2D. Presented are unit cells and basic subdivision into zones in r and θ directions. [15]

On the basis of core geometry, material structure and cross section data, TRIGA2D calculates the flux of neutrons for all energy groups and multiplication factor, keff. By these, the criticality of TRIGA MARK II can be calculated by using the simulation from TRIGLAV package. To simplify, the TRIGLAV software is run by batch procedure program named TRIGLAV.EXE file. TRIGLAV will starts all subroutines and manipulates temporally files within the program package. To do so, TRIGLAV requires two input files TRIGLAV. INP (Reactor core input), ELEM. INP (element data input) and these files must be in same directory in the computer while all other executable subroutines may be in separate directory (see Fig. 2.).

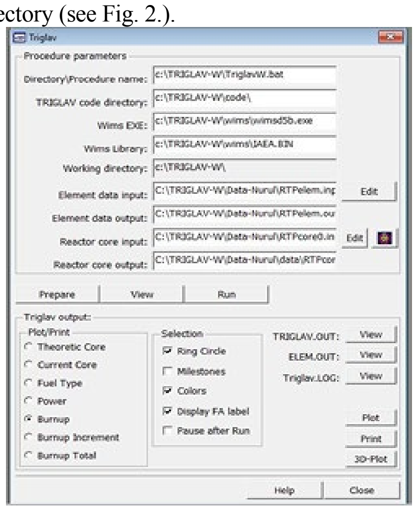

Fig. 2: Main TRIGLAV window used to access and edit TRIGLAV input files, procedure files and output files. [7]

After the program package execute all output file which are TRIGLAV. OUT (Reactor core output) and ELEM. OUT (element data output), the output files will be written to the directory of the input files in the computer. The batch procedure also writes log file TRIGLAV.LOG for further references for the output data. Optionally, flux output data can be written on special file named TRIGA2D. FLU. This can only be done if the flux distribution of the core is needed in the data output. The flow chart of TRIGLAV program package is presented underneath (see Figure 3).

The input preparation of the procedure controlling the TRIGLAV computation has to be prepared with all appropriate data that is needed. This procedure had to be prepared manually in TRIGLAV package like CONtext. The user has the possibility to view and change all the parameters, but it is not necessary to change this all the time because it will cause confusion. After this procedure is prepared, it can conveniently executed pressing on the "RUN" button and it will starts the whole calculation procedure including all subprograms indicated in the flow chart. After all unit cell and diffusion calculation are finished, the user can inspect the results of calculation using the same program (CONtext program that is designated in TRIGLAV software).

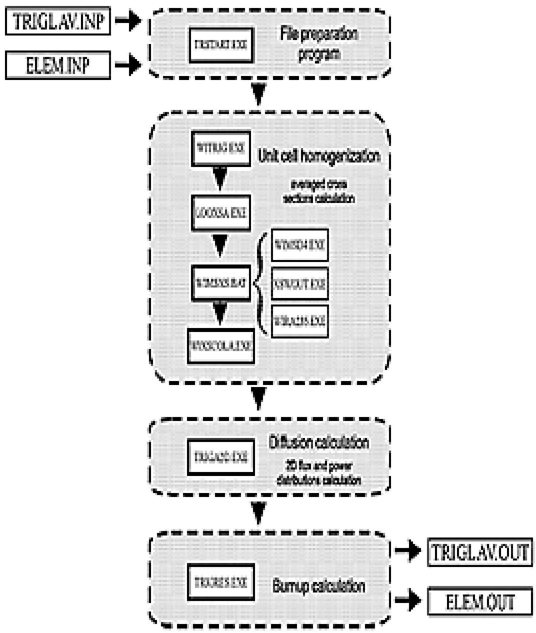

Fig. 3: Schematic flow-chart of the TRIGLAV program package. [7]

3. Results and Discussion

The application of TRIGLAV computer code to the TRIGA reactor core would predicts the number of fuel elements required to gain its initial criticality by using inverse multiplication method. The reactor core will be loaded by adding one-by-one fuel element against the multiplication factor for the reactor.

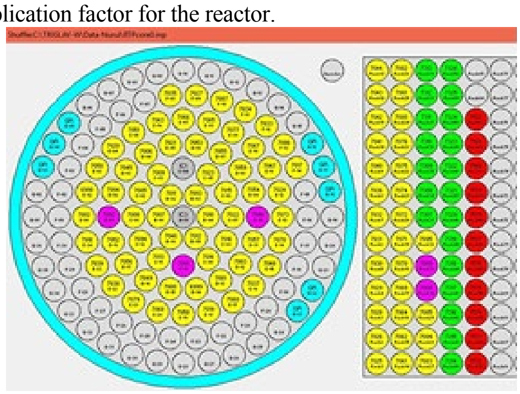

Fig. 4: The RTP Core-0 configuration of TRIGA MARK II.

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3.1. The Prediction of Buckling Value

In this paper, RTP core-0 will be used to analyze the criticality of TRIGA PUSPATI and the core configuration of the core is shown above. The first step is to predict the buckling value of the core. By doing so, it would be easier to calculate the criticality of the reactor core. The value of multiplication factor is observed by manipulating the value of buckling in the core. The value of buckling started at 0.0050 until it reach the desired value to reach criticality. The table below shows the result from the experiment.

Table 1: The value of buckling and multiplication factor, k_{eff}

Buckling	Multiplication factor, keff
0.00500	0.993806
0.00495	0.994987
0.00490	0.996174
0.00485	0.997361
0.00480	0.998551
0.00475	0.999744
0.00470	1.000938

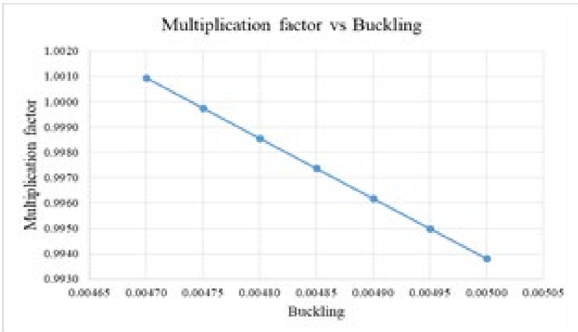

Fig. 5: Graph of multiplication factor, keff against buckling

From the graph, we can see that if the buckling value increases, the multiplication factor decreases. The number of buckling used in this study is 0.00475.

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3.2. The Number of Fuel for Standard Fuel 8.5wt%

After the prediction of buckling reached its criticality, the same buckling value is used for each fuel elements load in the core. The multiplication factor of the core is observed frequently starting from the 1st fuel element with 8,5wt% that is loaded to the core. Upon that, the number of fuel elements that is needed to make the reactor core to achieve its first criticality is recorded.

Table 2: The number of fuel elements and multiplication factor, keff

Number of fuel elements	Multiplication factor, keff
1	0.2929197
6	0.5007886
12	0.6078430
18	0.7286279
24	0.7979340
30	0.8462939
36	0.8846865
42	0.9172812
48	0.9447955
54	0.9652336
60	0.9844740
66	1.0009383

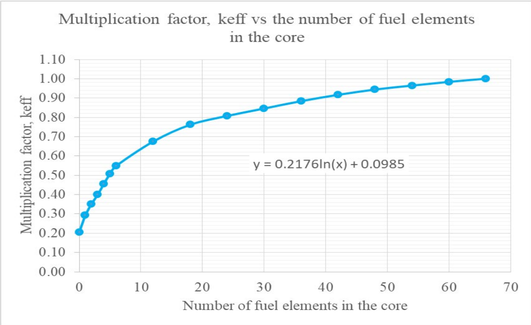

Fig. 6: Graph of multiplication factor, keff versus number of fuel elements in the core for 8.5wt% of fuel.

3.3. The Number of Fuel for Standard Fuel 12wt%

After the simulation for standard fuel with 8.5wt& is done and its multiplication factor is recorded. The experiment is repeated using fuel elements with 12wt%. The fuel elements is loaded to the reactor core begin with the 1st number of fuel elements. The same buckling value is used for this type of fuel which is 0.0047. The multiplication factor for each fuel elements and the increment number of fuel element to reach the first criticality is recorded and the graph is plotted.

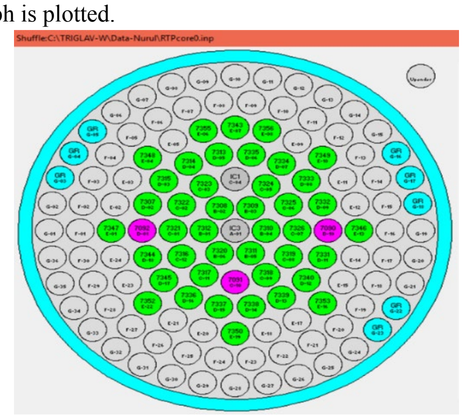

Fig. 7: The configuration of standard fuel with 12wt% of TRIGA MARK II when it reached criticality at 42 number of fuels

3.3. The Number of Fuel for Standard Fuel 12wt%

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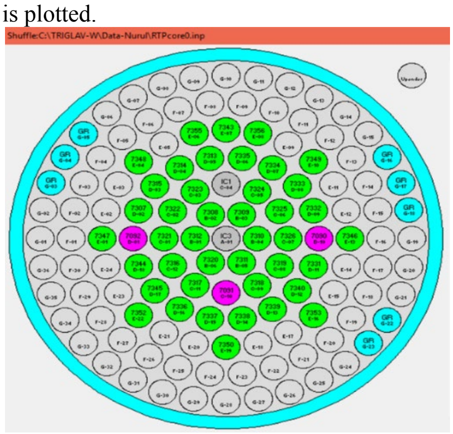

Fig. 7: The configuration of standard fuel with 12wt% of TRIGA MARK II when it reached criticality at 42 number of fuels

Table 3: The number of fuel elements for standard fuel 12wt% and its multiplication factor, keff

Number of Fuel	Multiplication factor
0	0.2048090
1	0.3177570
2	0.3871622
3	0.4445554
4	0.5058098
5	0.5614273
10	0.7006575
15	0.7905914
20	0.8483955
25	0.8964390
30	0.9349461
35	0.9659772
40	0.9930531
41	0.9975343
42	1.0022748

Based on Table 3 it can be seen that by using TRIGLAV software, calculation for multiplication factor for standard fuel with 12wt% of the Malaysia's TRIGA MARK II reactor core is 1.0022748. The graph below shows the number of fuel elements added into the core to reach criticality versus its multiplication factor.

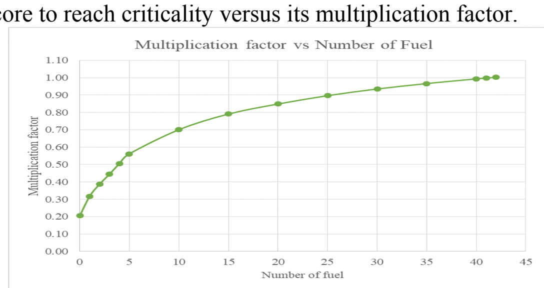

Fig. 8: Graph multiplication factor versus number of fuel elements in the core for 12wt% fuel

3.4. The Number of Fuel for Standard Fuel 20wt%

The same procedure is repeated by loading fuel elements with 20wt% to the reactor core begin with the 1st number of fuel elements. The same buckling value is used for this type of fuel which is 0.0047. The increment of multiplication factor and the number of fuel element that is needed to make the reactor core with fuel elements of 20wt% to achieve its first criticality is recorded.

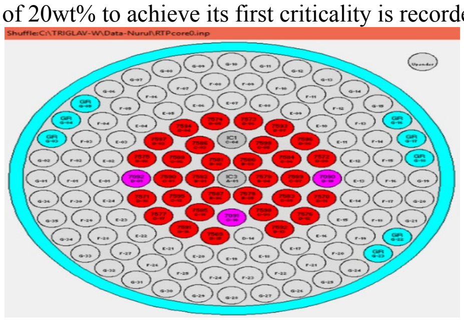

Fig. 9: The configuration of standard fuel with 20wt% of TRIGA MARK II when it reached criticality at 31 number of fuels

Table 4: The number of fuel elements for standard fuel 20wt% and its multiplication factor, keff

Number of Fuel	Multiplication factor
0	0.204809
1	0.3579095
2	0.438943
3	0.5022688
4	0.5681443
5	0.6256844
10	0.7661159
15	0.8517867
20	0.9134776
25	0.9573923
28	0.9821622
29	0.9890782
30	0.9956395
31	1.0051655

Based on Table 4 it can be seen that by using TRIGLAV software, calculation for multiplication factor for standard fuel with 20wt% of the Malaysia's TRIGA MARK II reactor core is 1.0051655. The graph below shows the number of fuel elements added into the core to reach criticality versus its multiplication factor.

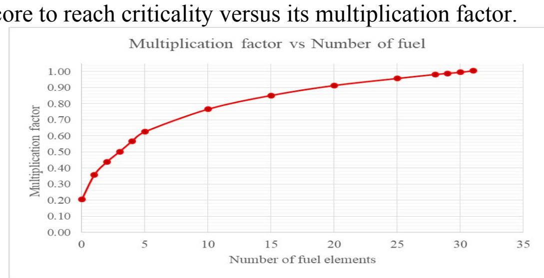

Fig. 10: Graph multiplication factor versus number of fuel elements in the core for 20wt% fuel.

3.5. Criticality Comparison between Types of Fuels

As can be seen in the above figure, fuel with 20wt% requires only 31 number of fuels to reach the first criticality compared to 42 number of fuels for 12wt% and 66 number of fuels for 8.5wt%.

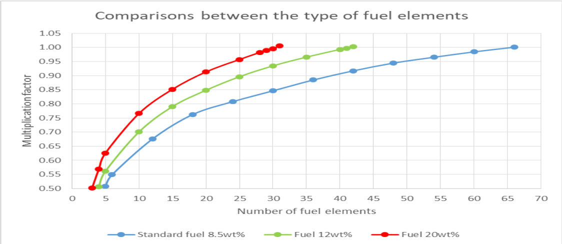

Fig. 11: Graph multiplication factor versus number of fuel elements in the core for all types of fuels

3.6. Validation against other Sources

Based on references, the multiplication factor of the TRIGA PUSPATI MARK II reactor core that was calculated using MCNP program is 1.00132. Besides that, the experimental result from the same references shows that the multiplication factor by experiment data in year 1982 is 1.001051 [16].

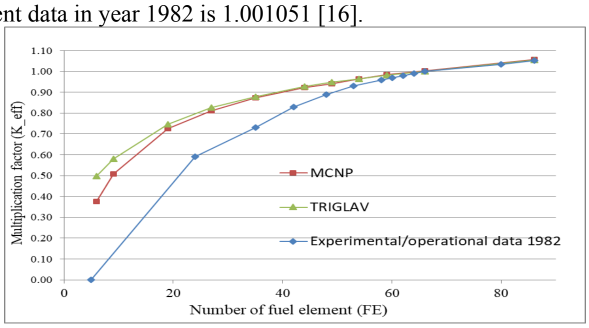

Fig. 12: Graph of multiplication factor, keff against number of fuel elements for MCNP, TRIGLAV and experimental data.

As can be seen in Fig. 12, despite with different method and approach in calculate the multiplication factor, keff, TRIGLAV computer software is in a very good agreement and is verified to MCNP software. Even though there is a great inconsistency in the subcritical region of the curve in the calculated results of TRIGLAV compared to the experimental results in year 1982, the keff obtained from TRIGLAV is still considered to be in an agreeable manner with MCNP as it reached the same number of fuel elements to reach criticality. The large discrepancy between TRIGLAV calculated and experimental results is due to a very low of keff value in the subcritical region. This may be due to the relatively small number of signals received by detector. The discrepancy found in TRIGLAV calculation maybe due to the simplications of the model itself unlike MCNP that has a great advantages compared to TRIGLAV. All three curves become consistent, agreeing with each other in the supercritical region, thus TRIGLAV computer code is verified. As the number of fuels elements added is increases, the neutron flux increases thus the multiplication factor increases too. The hypothesis is accepted.

4. Conclusion

In a nut shell, the computational calculation of TRIGA PUSPATI Mark-II reactor core criticality analysis is developed by using WIMSD-4 computer code that ois embedded in TRIGLAV computer code. TRIGLAV is used to develop a versatile and accurate full model of the TRIGA reactor as it assume every location in the core is treated homogenously and the computational of the reactor core is important for criticality calculation. The results simulation of this core is then compared with other references and experiments for validation purposes like MCNP and the experimental data from year 1982. The TRIGLAV results of the criticality for the reactor core are agreed with the experimental result and also with the MCNP results based on the references. The core become critical after 66th number of fuels are inserted in the core for standard fuel of 8.5wt%. While for 12wt% is 42 number of fuel elements and 31 number of fuel elements for 20wt% of Uranium.

Acknowledgment

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