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Analysis of Initial Criticality, Neutronic Parameters of Operational Core and Burn-up Calculation of BAEC TRIGA Research Reactor Using TRIGLAV & TRIGAP Codes

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Abstract

Since 1986, the TRIGA Mark-II Research Reactor (BTRR) has been operated by the Bangladesh Atomic Energy Commission (BAEC) without any reshuffling or reloading. On September 14, 1986, it reached criticality for the first time when 50 fuel elements containing Low Enrichment Uranium (LEU) were added to the initial core. The measured excess reactivity through the criticality experiment, conducted at a power level of 50 watts, was 0.19 $. This work aims to: (i) analyze the BTRR's initial criticality; (ii) use the TRIGLAV code to develop an initial critical TRIGA physical model; and (iii) investigate neutronics parameters and burnup calculation of BTRR's operational core. BTRR's operational core's Effective multiplication factor (k_{eff}), critical buckling, initial excess reactivity of the initial core, excess reactivity, and power are the computed parameters of the core. Effective multiplication factor (k_{eff}), critical buckling, excess reactivity of the initial core, power distribution per fuel element of the operational core, burnup calculation, and critical mass are the computed parameters of the core. The calculated findings show good agreement with experimental values when compared to the experimental values taken from the reactor operational data log book. This analysis will be essential to improve the basic neutronics data of initial critical experiments of BTRR. Compared to the TRIGAP result and operational data, the computed excess reactivity and k_{eff} findings are found to be reasonable. The excess reactivity calculated by TRIGLAV code differs from the real data by just 0.68%. The MVP-BURN code is likewise in line with the burnup computation in the current burnup scenario. This investigation will likely lead to the finalization of a feasible in-core fuel management strategy for fuel rod reshuffling or fresh fuel reloading.

Keywords: TRIGLAV, Initial criticality, Research Reactor, MVP-BURN, Critical mass, and Neutronics.

1. Introduction

The light water-cooled, graphite-reflected TRIGA Mark-II research reactor (Atomics, 1981) is intended for continuous operation at a steady state power level of 3 MW_{th}, with a maximum thermal flux of 7.46x 10^{13} n/cm^2/sec in the center of the core. The fuel for the reactor is made up of 20 weight percent Uranium that has been enriched to 19.7% of ^{235}U, Zirconium Hydroxide ($ZrH_{1.6}$), the primary moderator, and burnable poison Erbium. The neutron absorber material in the control rods is boron carbide (B_4C). The reactor's initial LEU core comprises 50 fuel elements (including 5 fueled-follower control rods), 6 control rods (1 air follower control rod), 18 graphite dummy elements, 1 central thimble, and 1 pneumatic transfer system irradiation terminus and other light waters. As seen in **Fig. 4**, all of these components were positioned and supported between the top and bottom grid plates, forming seven concentric hexagonal rings (A, B, C, D, E, F, and G) of a hexagonal lattice. It was commissioned to carry out a number of fundamental nuclear research endeavors, including neutron activation analysis, neutron radiography, and neutron scattering experiments. It was also responsible for producing radioisotopes for use in industry, agriculture, and medicine, as well as educating personnel in these sectors.

The nuclear word "criticality" describes the balance of neutrons in the core, whereas "subcritical" describes a system in which the rate of neutron loss exceeds the rate of neutron creation (Hasan *et al.*, 2022), resulting in a decreasing neutron population over time. A "supercritical" system is one in which the rate of neutron production exceeds the rate of neutron loss, increasing the population of neutrons (Antonopoulos-Domis & Paraskevopoulos, 1983; Hasan *et al.*, 2022). When the neutron populations are constant, the nuclear system is in a critical condition, indicating that the rate of neutron production and loss is perfectly balanced (Antonopoulos-Domis and Paraskevopoulos, 1983). The criticality of a system may be determined by comparing the rate of neutron production from fission and other sources to the rate of neutron loss from absorption and leaking out of the reactor core (Khan *et al.*, 2011; Haque *et al.*, 2025).

This study is carried out using the neutron diffusion theory code; fission spectrum data, the geometry of the initial core, and group constants for different homogenized sections of the core are required. Also, group constants were generated with the well-known 1-D transport theory code WIMS-D/4 (Askew *et al.*, 1966) and TRIGLAV code (Peršič *et al.*, 2017), based on a four-group time-independent diffusion equation in two-dimensional cylindrical (r,θ) geometry, is used for core calculations. Using the finite difference approach and the fission density iteration, the diffusion equation is solved. Using the reactor physics computer code TRIGLAV, the study aims to construct the first critical core model of the BAEC TRIGA reactor and evaluate its first criticality experiment. The computed findings are verified against the experimental data. Additionally, the TRIGLAV code has been used to calculate excess reactivity and burnup under the current burnup condition.

2. Methodology

Reactor simulation codes

The BAEC TRIGA reactor's initial criticality experiment was examined using two reactor-engineering codes. These were (i) the 1-D neutron transport theory code WIMS-D/4 (Askew *et al.*, 1966) was used for the generation of group constants and cross-section data sets for different core regions (fuel or non-fuel) of the TRIGA reactor (ii) Global core calculations of the TRIGA Mark-II reactor were carried out using the 2-D neutron diffusion code TRIGLAV (Peršič *et al.*, 2017;), where WIMS-D/4 is integrated with the TRIGLAV code package. **Fig. 1** depicts the calculation scheme of the TRIGLAV code system.

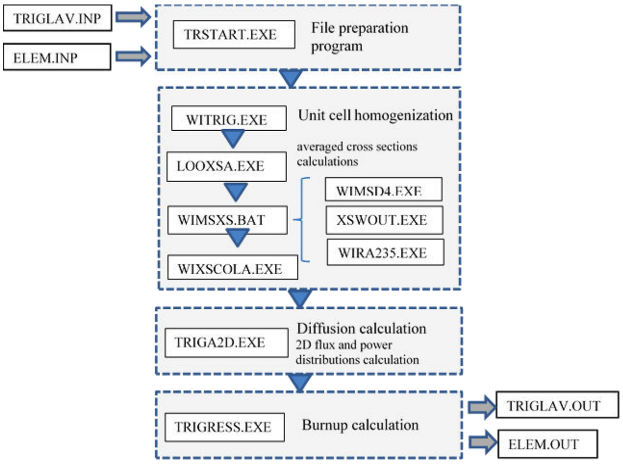


Fig. 1: Calculation scheme of the TRIGLAV code system.

Simulation methodology

The initial critical core's simulation approach was developed in two stages: first, by the WIMS-D/4 model for cell calculations and then by the TRIGLAV model for core calculations. Using the WIMS-D/4 code, typically with the 69-group library, unit cell computations were carried out in the first phase. The neutron spectrum in 69 energy groups is calculated using the so-called "spectrox" method in the WIMS-D/4 code. This information is then utilized to condense the neutron cross sections into 32 groups.

In the case of the fuel cells, an infinite lattice of identical fuel cells is treated by the so-called ‘‘pin cell” model defined by the input card CELL 6 (shown in **Fig. 2**). In contrast, the "cluster" model, defined by the input card CELL 7, which allows calculations of groups of cells composed in a macro-cell, is used in the case of the non-fuel cells (shown in **Fig. 3**). For lattice cell transport computations, the discrete ordinate transport option (DSN) is employed in both scenarios. In order to get the necessary few-group (4-group) cross-sections, flux and volume-weighted homogenization are used. In the last stage the derived homogenized cross-sections are used here the solution across the core domain is determined in the diffusion approximation using the finite difference approach with fission density iteration. A whole-core (**Fig. 4**) computation takes around a minute to complete on a single core of a contemporary personal computer.

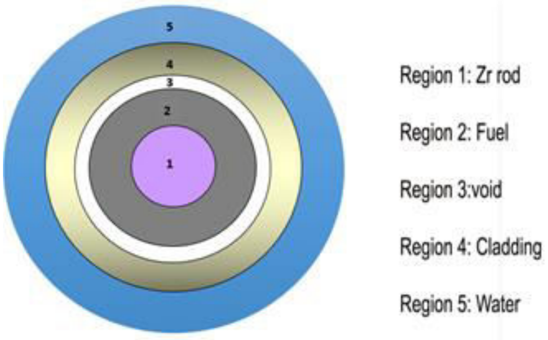


Fig. 2: Fuel cell model in WIMS-D/4 code.

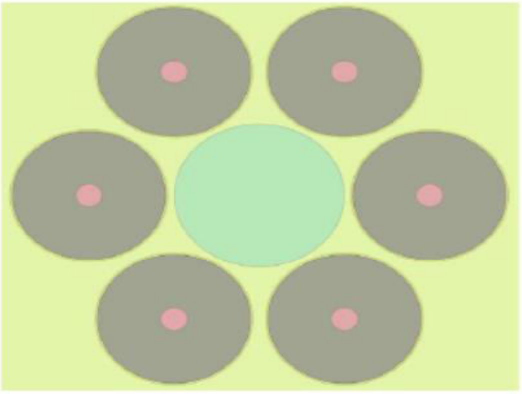


Fig. 3: Non-fuel cell model in WIMS-D/4 code.

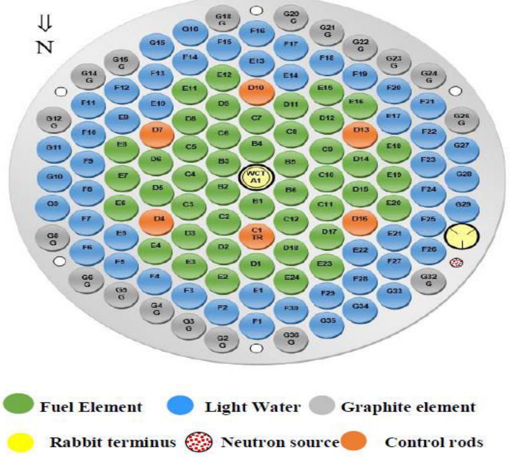


Fig. 4: Initial critical core of BAEC TRIGA Research Reactor.

After achieving the initial criticality with the 50 fuel elements the BTRR core has been rearranged and being field with 100 fuel elements, which is known as initial operational core. **Fig. 5** shows the initial operational core of BTRR with 100 fuel elements.

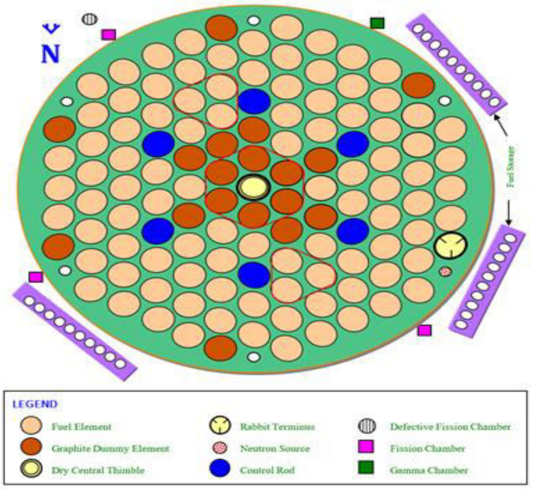


Fig. 5: BTRR operational core of BTRR with 100 fuel elements.

Brief Description of Neutron Diffusion Approximation in TRIGLAV Code

A 4-group time-independent homogeneous diffusion equation in two-dimensional cylindrical geometry serves as the foundation for the TRIGLAV program package. The following is the formulation of the diffusion equation for energy group g:

$$-\nabla D^g \nabla \Phi^g + \sum_r^g \Phi^g = \left(\frac{1}{k}\right)\chi^g F + \sum_{g'=1, g'\neq g}^{4} \Sigma^{g'\to g}\Phi^{g'}; \quad g = 1, \dots\dots, 4, \qquad (1)$$

Where,

Φ^g = neutron flux

D^g = diffusion constant

$\sum_r^g$ = removal cross section;

$(\Sigma_r^g = \Sigma_a^g + \Sigma_{g'=1,g'\neq g}^{4} \Sigma^{g'\to g} + D^g B_z^2)$

B_z^2 = axial geometrical buckling, user-defined on TRIGLAV input

$\Sigma^{g'\rightarrow g}$ = scattering cross section from group g' into group g

χ^{g} = part of fission spectrum in group g; (default TRIGLAV: $\chi_1 = 1, \chi_2 = \chi_3 = \chi_4 = 0$)

k = multiplication factor

F = fission density, which is defined as:

$$F = \sum_{g=1}^{4} \nu^{g} \Sigma_{f}^{g} \Phi^{g} \qquad (2)$$

The finite difference method is used to solve the diffusion problem. Fission density iterations are used to solve the finite difference equations. The inner iterations approach (Varga, 1967) reverses each group equation. The reactor core geometry of the TRIGA Mark II is fitted to the two-dimensional difference mesh. Six or seven fuel rings and a graphite or water reflector comprise the core of the TRIGA Mark II reactor. As a result, **Fig. 4** displays either 7 (A, B, C, D, E, and F fuel rings and reflector) or 8 (A,,G fuel rings and reflector) radial zones. The reflector ring is homogenous, whereas other fuel rings are made up of unit cells. There is just one-unit cell in the central "ring" A. There are 102 angular intervals for this design that coincide with the borders of unit cells. A minimum of 102 angular intervals are required to ensure mesh node homogeneity. The minimum depends on the number of fuel rings, but at least eight intervals are required for radial dimension r.

Input File Preparation for TRIGLAV Code

Three subroutines are included in the TRIGLAV code package: the BURN subroutine, the TRIGA2D subroutine, and the average of cross-section sub-routine. The TRIGA2D is an independent code that is used for the calculation of multiplication factor, flux, and power distribution in two-dimensional geometry (Peršič *et al.*, 2017), which is designed for standard TRIGA Mark-II research reactor geometry and assumed that the core has a cylindrical configuration with annular graphite reflector (Stancar *et al.*, 2016). The distance between rings is equal to the distance between any two positions of elements in a particular ring. TRIGA2D calculates the flux of neutrons for all energy groups, multi-plication factor, k_{eff} based on core geometry, material structure, and cross-section data. TRIGLAV starts all subroutines and manipulates temporally files within the program package. Reactor core input (TRIGLAV.INP) and element data input (ELEM. INP) are the two input files used for the TRIGLAV to do that. These files are located in the same computer directory.

All output files TRIGLAV.OUT (Reactor core output) and ELEM.OUT (element data output) are executed by TRIGLAV. The output files are stored on the computer in the same directory as the input ones. A log file called TRIGLAV.LOG is also written by the batch process for future use as a reference for the output data. **Fig. 1** displays the TRIGLAV code package's calculation scheme. The text editor application is used to manually prepare the input file. All of the parameters may be seen and altered by the manipulator. This process may be readily carried out from there after it is prepared. The user may use the same application to review the calculation results after all unit cell and diffusion calculations are complete.

3. Results and Discussion

The Prediction of Critical Buckling Value

The initial critical core was used to analyze the criticality of BAEC TRIGA reactor and its core configuration was shown in **Fig. 4**. The first step is to predict the buckling value of the core and it would be easier to calculate the criticality of the initial reactor core. The value of multiplication factor is observed by manipulating the value of buckling in the core. The value of buckling started at 0.005001 until it reaches the desired value to reach criticality. The values of buckling and multiplication factor and its curve are shown in **Fig. 6**.

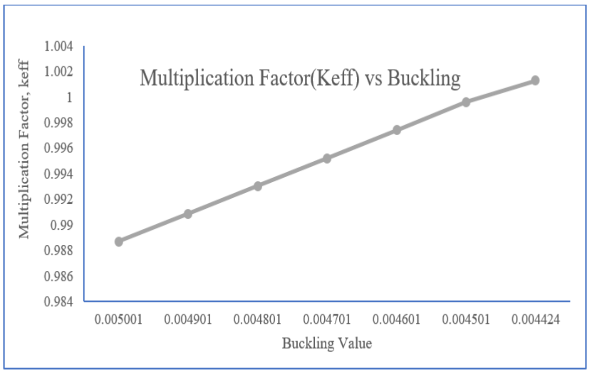


Fig. 6: Curve between multiplication factor and buckling value.

Assessment of number of fuel elements required for initial criticality

Each fuel element loaded in the core uses the same critical buckling value, 0.004424, after the prediction of the buckling value has achieved its criticality.

Burnable poison erbium, zirconium hydride, and 20% (wt.) uranium enriched to 19.7% of ^{235}U comprise up the TRIGA LEU fuel. Beginning with the first fuel element loaded into the core, the LEU core's multiplication factor is regularly monitored. The quantity of fuel elements required to reach the reactor core's initial criticality is then noted. **Fig. 7** shows a graph of the number of fuel elements vs the multiplication factor.

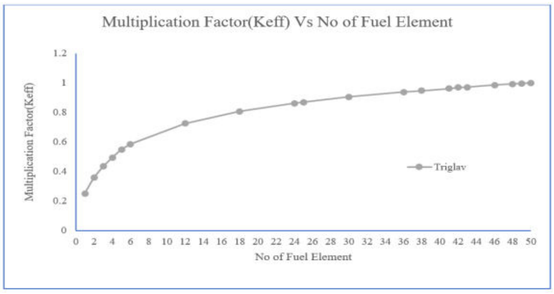


Fig. 7: Graph between number of fuel rods and multiplication factor.

From **Table 3** it may conclude that the core becomes critical after 50th number of fuel elements are loaded in the core and **Fig. 7** expresses that the multiplication factor increases with number of fuel elements.

The calculated k_{eff} value by TRIGLAV code is 1.0013161 (0.0042 %) while its experimental value (ROMU, 1986) is 1.0012746. Because it is a major basic parameter of nuclear reactor and its value depends on the material composition, the geometry of the core and nuclear data library. Hence, the calculated excess reactivity by TRIGLAV code is 0.1962 (3.26 %) $ while its experimental excess reactivity is 0.19 $. The calculated k_{eff} and excess reactivity values with experiment are shown in **Table 4**.

Table 1: Comparison between the calculated values of k_{eff} and excess reactivity with the experiment for initial core (50 FE).

Methods	k_{eff}	Excess Reactivity ($)
Experiment	1.0012746	0.190
TRIGLAV Code	1.0013161	0.196 (3.26 %)
TRIGAP Code	1.001308	0.195 (2.63%)

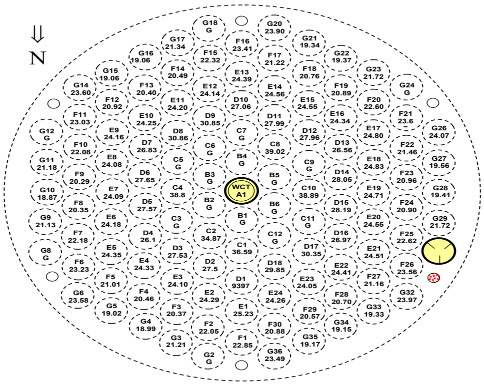
From **Table 1**, it may conclude that the calculated values of k_{eff} and excess reactivity show a reasonable agreement with the experiment. Besides, the % deviations are within acceptable limits. Consequently, in step 100 no. of fuel elements have been loaded to achieve the operational core configuration, and hence multiplication factor and the excess reactivity were found as below.

Table 2: Comparison between the calculated values of k_{eff} and excess reactivity with the experiment for operational core (100 FE).

Methods	k_{eff}	Excess Reactivity ($)
Experiment	1.077459	10.27
TRIGLAV Code	1.0744693	10.34 (0.68 %)
TRIGAP Code	1.0743390	10.32 (0.49%)

From **Table 2**, it may conclude that the calculated values of k_{eff} and excess reactivity show a reasonable agreement with the experiment. Besides, the % deviations are within acceptable limits.

In addition, the power per fuel element of the BTRR operational core which has been calculated using TRIGLAV code has been shown in **Fig. 8**.



*kW is used as unit of Power/fuel element (Fresh Core , 0 burnup condition, 2.4 MW power)

Fig. 8: Power per fuel element data.

Ring Wise Burn-up and core excess reactivity calculation

The ring wise burnup and excess reactivity of BTRR operational core has been calculated using TRIGLAV code. **Fig. 9** shows the calculated ring wise burnup of the core at 800 MWD using TRIGLAV code which shows a very good alignment with the data obtained from MVP-BURN code (RPED, 2021; Haque *et al*., 2025). Here ring no 1 stands for C ring, 2 is for D, 3 is for E, 4 is for F and 5 is for G ring respectively.

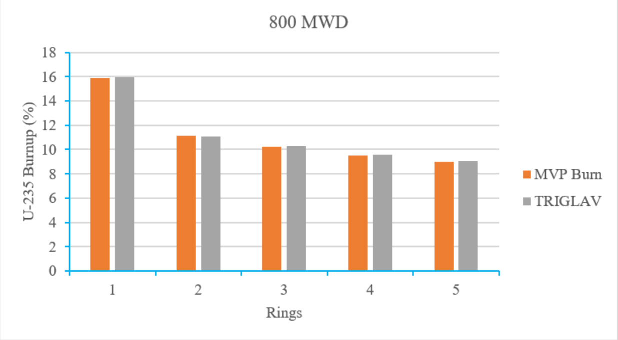


Fig. 9: Core burnup data comparison at 800 MWD.

Fig. 10 shows the excess reactivity calculation using TRIGLAV code at different burnup condition. This result has been compared with the experimental data achieved from the reactor operation log book (ROMU, 1986). It has also a great alignment with the experimental data and It shows that the excess reactivity will fall under 5 $ after 1200 MWD burn-up.

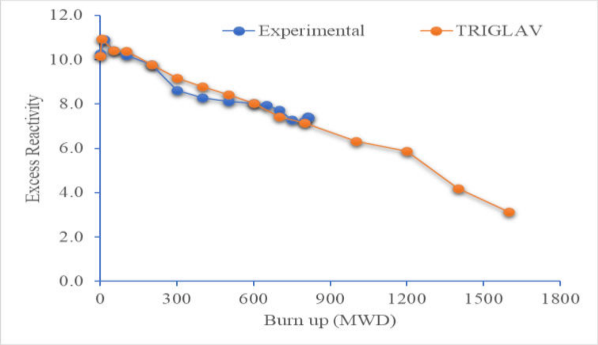


Fig. 10: Core excess reactivity comparison.

It has also a great alignment with the experimental data and It shows that the excess reactivity will fall under 5 $ after 1200 MWD burnup.

Ring Wise Burn-up and core excess reactivity calculation

The smallest quantity of fissile material (U-235) required for a sustained nuclear fission chain reaction is known as critical mass. Nuclear characteristics (i.e., nuclear fission cross-section), density, shape, enrichment, purity, temperature, and surroundings all influence a fissionable material's critical mass. The initial core becomes critical when 50 fuel elements are loaded in the core. The total mass of U-235 in 50 fuel elements is 4.794 kg. Hence, the critical mass of the initial critical core of the BAEC TRIGA Mark II Research Reactor is 4.794 kg of U-235.

Validation of the TRIGLAV Code against Other Sources

To test and validate the TRIGLAV code, the outcomes of experiments and other computer codes were compared with the results of the TRIGLAV code. The value of multiplication factor obtained from TRIGLAV output is 1.0013161 (0.0042 %). To validate the data, another simulation was performed using another 1-D deterministic neutron diffusion code TRIGAP (Mele & Ravnik, 1985) and the multiplication factor of the initial core that obtained by TRIGAP code is 1.001308 (0.0034 %) (RPED, 2021) while its experimental value is 1.0012746 (ROMU, 1986). The **Fig. 11** presents the multiplication factor vs. number of fuel elements for TRIGAV, TRIGAP and Experimental data for analysis of initial critical core of BAEC TRIGA reactor.

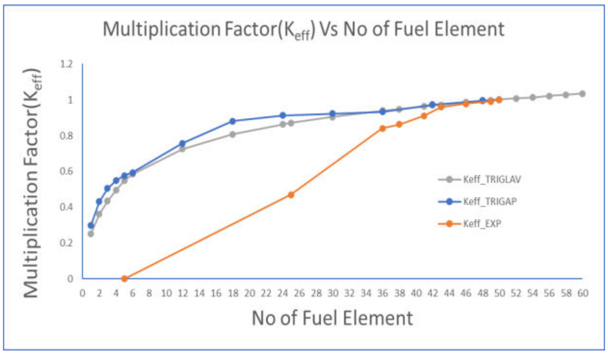


Fig. 11: graph of multiplication factor, k_{eff} against number of fuel elements for TRIGLAV, TRIGAP and experimental data.

Although with different method and approach to calculate the multiplication factor, TRIGLAV code is in a good agreement and is verified to 1-D neutron diffusion code TRIGAP that is specially designed for 3 MW BAEC TRIGA Research Reactor calculations. There is large discrepancy in the subcritical region of the curves obtained from the experimental data compared with the calculated results of TRI-

GLAV. Since it required the same amount of fuel elements to attain criticality, the multiplication factor value derived by TRIGLAV is still regarded as being in an acceptable range with TRIGAP. The very low k_{eff} value in the subcritical region is the cause of the significant difference between the TRIGLAV and experimental results. This may be because the detector only picked up a comparatively small number of signals. Besides, the discrepancy is found between TRIGAP code and TRIGLAV code in the subcritical reason due to the implications of the physical model with 1-D and 2-D simulations but near critical region shows well consistent with each other. All three curves become consistent, agreeing with each other in the near critical region, thus TRIGLAV computer code is verified. As the number of fuel elements added increases in the core, the neutron flux increases thus the multiplication factor increases too. The theory is accepted. Additionally, in case of burnup calculation and excess reactivity calculation TRIGLAV shows great alignment with MVP-BURN data as well as with the experimental data which has been shown in **Fig. 9** and **10** respectively.

4. Conclusion

A computational model of an initial critical core and an operational core of the TRIGA Mark-II research reactor in Bangladesh are developed using the chain of the computer codes WIMS-D/4 and TRIGLAV. The LEU fresh fuels are used in the models and these models are validated through the critical experiment performed on the first initial core configuration. The criticality experiment confirms that the initial core achieves its first initial criticality on the core loading of 50-LEU-type fuel elements. Similarly, the operational core contains 100 fuel elements. The calculated values of the multiplication factor (k_{eff}), critical buckling, initial excess reactivity of initial critical core, excess reactivity, and power distribution per fuel element of operational core burnup calculation and critical mass by the TRIGLAV code are well consistent with the experimental data for the initial and operational critical experiment, which indicates that the TRIGA physical model is accurate enough to reproduce the initial critical experiment and excess reactivity for both cores as well as for the core burnup and core excess reactivity calculations. Therefore, this analysis will be essential to improve the basic neutronics data of initial and operational experiments and core lifetime calculation for the 3 MW TRIGA Mark-II research reactors at AERE, Savar, Dhaka, Bangladesh.

5. Author Contributions

M.R.H.: Conceptualization, methodology, writing the manuscript. M.J.H.K.; and A.S.M.: Conceptualization finalization, checked the manuscript and editing. All authors who are involved in this research read and approved the manuscript for publication.

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7. Conflicts of interest

The authors sincerely admitted no conflicts of interest to declare.

8. References

Antonopoulos-Domis, M., & Paraskevopoulos, K. (1983). Reactor time constant at criticality. *Annals of Nuclear Energy*, *10*(10), 555–557.

Askew, J. R., Fayers, F. J., & Kemshell, P. B. (1966). *GENERAL DESCRIPTION OF THE LATTICE CODE WIMS.* Atomic Energy Establishment, Winfrith, Eng.

Atomics, G. (1981). Safety Analysis Report for the 3 MW Forced-Flow TRIGA Mark-II Reactor.

Haque A, Jahan N, Soner MAM, Hasan MR, Salam MA, Rahman MO, and Uddin MM. (2025). Safety assessment, vulnerability analysis and remedial measures for different systems of the BAEC TRIGA research reactor, *Int. J. Mat. Math. Sci*., *7*(2), 137-142. https://doi.org/10.34104/ijmms.025.01370142

Haque A, Hasan MR, Salam MA, Rahman MO, and Uddin MM. (2025). Gamma, beta and neutron dose rate level investigation at different key points of BAEC TRIGA research reactor. *Aust. J. Eng. Innov. Technol*., *7*(4), 233-243. https://doi.org/10.34104/ajpab.025.02330243

Hasan, M. R., Khan, M. J. H., & Mollah, A. S. (2022). Analysis of Criticality of Operational Core of BAEC TRIGA Research Reactor using Deterministic Code TRIGLAV. *4th International Conference on "Physics for Sustainable*

Development and Technology (ICPSDT-2022), " 67.

Khan, R., Stummer, T., Böck, H., & Villa, M. (2011). Neutronics analysis of the initial core of the TRIGA Mark II reactor. *Nuclear Engineering and Design*, *241*(5), 1463–1468.

Mele, I., & Ravnik, M. (1985). TRIGAP, A Computer Programme for Research Reactor Calculations. *IJS-DP-4228*.

Peršič, A., Žagar, T., Ravnik, M., Slavič, S., Žefran, B., Ćalić, D., Trkov, A., Žerovnik, G., Jazbec, A., & Snoj, L. (2017). TRIGLAV: A program package for TRIGA reactor calculations. *Nuclear Engineering and Design*, *318*, 24–34. https://doi.org/10.1016/j.nucengdes.2017.04.010

ROMU, (1986). Reactor Operational Data LOG BOOK.

RPED, (2021). Private Communication.

Stancar, Z., Barbot, L., and Snoj, L. (2016). Evaluation of the Effect of Burn-Up on Neutron Flux and Reaction Rate Distributions in the TRIGA Mark II Reactor. *PHYSOR 2016: Unifying Theory and Experiments in the 21st Century*.

Varga, R. S. (1967). Iterative solution of elliptic systems and applications to the neutron diffusion equations of reactor physics (Eugene L. Wachspress). *SIAM Review*, *9*(4), 756–758.

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