THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

Calculation of LEU Fuel Burn-up and Core Life Time Estimation of BAEC TRIGA Research Reactor Using 2D-TRIGLAV Code

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Abstract:
The BAEC TRIGA research reactor's (BTRR) core lifetime estimation and burn-up calculation were both carried out using the deterministic computation analysis tool TRIGLAV. Since it reached its first criticality in 1986, the BTRR has been used for nuclear research, instruction, training, and the manufacture of radionuclides for around 815 megawatt days without any core reloading or fuel reshuffling. The individual and ring-by-ring fuel burn-up and the core excess reactivity of BTRR have been studied utilizing the TRIGLAV code. The calculated outcomes of the TRIGLAV code and the outcomes of the MVP-BURN code are contrasted. To validate the TRIGLAV code for BTRR core analysis, the initial criticality and operational core analysis metrics like effective multiplication factor and excess reactivity were calculated using the TRIGLAV code. The results from TRIGLAV were compared with experimental data and other codes' output data and showed good agreement between them. Actual operational data is contrasted with core excess reactivity data. While the core excess reactivity data will forecast the core life, the collected fuel burn-up information can be used to forecast the core life. The collected fuel burn-up data can be utilized to reload or reorder the fuel. The BTRR may be used safely for an additional 500 MWd by the burn-up and excess reactivity requirements, according to the calculated fuel burn-up, identification of the hottest fuel rod, and excess reactivity value.

Keywords: *TRIGLAV, BTRR, excess reactivity, burn-up, nuclear reactor*

1. Introduction

The TRIGA Mark-II research reactor [1] has a maximum thermal neutron flux of $7.46x10^{13}$ $n/cm^2/sec$ in the middle of the core and is light water-cooled. This graphite-reflected nuclear reactor is intended for continuous operation at a steady state power level of 3 MWt. The TRIGA reactor LEU fuel is made up of burnable poison Erbium, zirconium hydride (primary moderator), and 20 weight percent uranium enriched to 19.7% ^{235}U. Boron carbide (B_4C) serves as the neutron absorber component of the control rods. 100 fuel elements, including five fuelled follower control rods, six control rods, one air follower control rod, 18 graphite dummy elements, one central thimble, one pneumatic transfer system irradiation endpoint, and various light waters make up the BTRR LEU core. All of these components were positioned, supported, and arranged in seven concentric hexagonal rings (A, B, C, D, E, F, and G) of a hexagonal lattice, as shown in figure 1, between the top and bottom grid plates. It was given the go-ahead to carry out a number of nuclear research projects like neutron activation analysis, thermal neutron radiography, and neutron diffraction scattering experiments, as well as to train workers and create radioisotopes for application in medicine, industry, and agriculture.

The term ‘subcritical’ describes a system where the loss of neutrons is greater than the rate of neutron creation [2], and the neutron population gradually declines over time. Criticality is a nuclear term that relates to the balance of neutrons in the core. A system is said to be ‘supercritical’ when neutron production outpaces neutron loss, increasing the population of neutrons [2, 3]. When the neutron populations are stable, the production and loss of neutrons are perfectly balanced, and the nuclear system is in a critical condition [3]. By comparing the pace at which neutrons are created from fission and other sources to the rate at which they are lost through absorption, scattering, and leakage out of the nuclear reactor core, it is possible to determine the criticality of a system [4].

The neutron diffusion theory code is used to perform this analysis. The configuration of the initial core shape and neutron energy group constants for various homogenized regions of the core, along with the fission spectrum, are required. In this study, neutron group constants were obtained using the well-known 1-D neutron transport code WIMS-D/4 [5] and were utilized for the full core calculations with the TRIGLAV code [6] that is based on a 4-group time-independent diffusion equation in two-dimensional cylindrical (r,θ) configuration. The neutron diffusion algorithm is solved using the finite difference method with the iteration of fission neutron density. Burn-up calculation has been done by sub-routine TRIGRES. It calculates the burn-up increment of each fuel element. Burn-up information data are required for in-core fuel management for the BTRR to be used economically and effectively for different purposes, such as medical isotope production, fast neutron radiography, etc. Information on each fuel element burn-up, as well as ring-by-ring information, is required for this. The purpose of this study is to calculate the BTRR core lifetime using the TRIGLAV code based on the burn-up data up to 1400 MWD, along with core excess reactivity.

2. Brief Description of TRIGLAV Code

A 4-group time-independent homogeneous neutron diffusion equation in a two-dimensional cylindrical shape serves as the foundation for the TRIGLAV software package. The following formula is the diffusion equation for the neutron energy group g:

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

Where,
Φ^g = Neutron flux
D^g = Diffusion constant
$\sum_r^g$ = Removal cross-section; ($\sum_r^g = \sum_a^g + \sum_{g'=1,g'\neq g}^4 \Sigma^{g'\to g} + D^g B_z^2$)
B_z^2 = Axial geometrical buckling, user-defined on TRIGLAV input
$\Sigma^{g'\to g}$ = 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: $F = \sum_{g=1}^4 \nu^g \sum_f^g \Phi^g$ (2)

The finite difference approach is used to solve the diffusion problem. Fission density iterations are used to solve the finite difference equations. The inner iterations approach inverts each group equation [7] (Wachspress, 1966).

The BAEC TRIGA Mark II reactor core shape is modified to the two-dimensional difference mesh. The graphite or water reflector, along with seven fuel rings, makes up the TRIGA Mark II reactor core. As a result, figure 1 depicts either 8 (A,..., G fuel rings with reflector) or 7 (A, B, C, D, E, F fuel rings and reflector) radial zones.

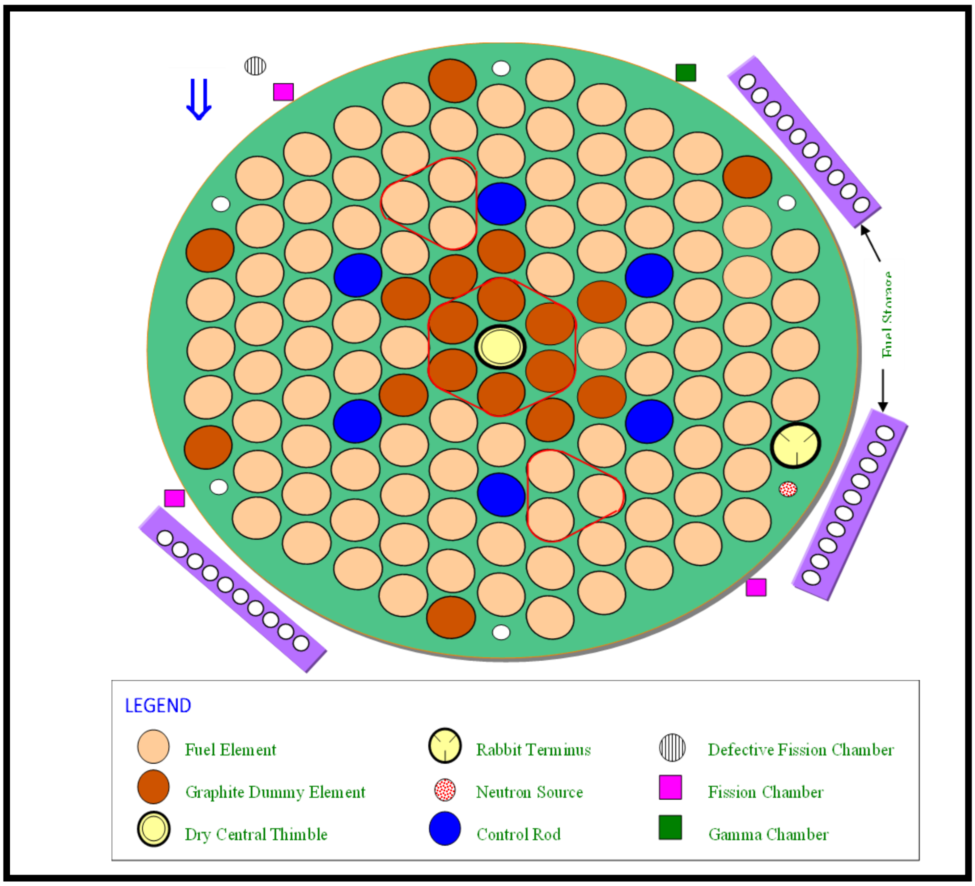

Figure 1: Operational Core of BTRR with 100 Fuel Elements

Only the reflector region is homogeneous, whereas all fuel rings are made up of unit cells. The burn-up option in WIMS is used to calculate the unit cell cross-sections at the specified burn-up. Fuel element burn-up (BU1 in [MWd]) is indicated on the input. To accommodate the recommended burn-up value BU1, it is divided into n intervals, each 1MWd in size, and a reminder of the proper size (interval n + 1).

BU_1 = nb+γ,

γ = BU_1 mod b

b= 1MWd

If necessary, subroutine TRIGRES then determines the burn-up increase for each element. The burn-up time step t and reactor power P are obtained from TRIGA2D.Temporary file INP from the fission density distribution F (r,) stored in the TRIGA2D.p file. Element powerPel values are calculated. Following is a normalization of element power.

$$P_{el} = \beta p \frac{c}{v} \int F(r,v)dV \ldots\ldots\ldots..(3)$$

Burn-up increments are then calculated as follows.

$$\Delta BU_{1,el} = P_{el}\Delta t \ldots\ldots\ldots\ldots \quad (4)$$

Burn-up values in percent ($\Delta BU_{2,el}$) are determined for each fuel element according to relations presented in equation 5, which are calculated using WIMS code and built into the code.

$$Y=0.00+1.31x-2.63e^{-3x2} + 5.20e^{-6x3}\ldots\ldots\ldots\ldots \quad (5)$$

Results of TRIGRES are burn-up increments $\Delta BU_{1,el}$for all fuel elements in the reactor core $\Delta BU_{1,el}$in [MWd] and $\Delta BU_{2,el}$in [%]). They are automatically added to the burn-up of elements in ELEM.INP so that ELEM.OUT contains an updated burn-up of elements in the core. The power of elements and burn-up of all elements in the core is also written to the output file TRIGRES.OUT and are later rewritten to the final output file TRIGLAV.OUT [6].

3. Input File Preparation for TRIGLAV Code

The TRIGLAV code package contains three subroutines:

- Average of neutron cross-section subroutine,
- TRIGA2D subroutine, and
- BURN subroutine

Assuming that the core has a cylindrical geometry with an annular graphite reflector, the TRIGA2D is an independent code that is used to calculate the multiplication factor, neutron flux, and power distribution in two-dimensional geometry [6]. It is suitable for the standard TRIGA Mark-II research reactor configuration. The distance between rings is equal to the distance between the positions of the components in a specific ring. Based on information about the core geometry, material composition, and cross-sections, TRIGA2D determines the flux of neutrons for all energy groups and the multiplication factor, keff. All of the program's subroutines are started by TRIGLAV, which also modifies temporary files. Reactor core input (TRIGLAV. INP) and element data input are the two input files needed to accomplish that (ELEM. INP). These files need to be on the computer in the same location as the directory.

All output files that belong at TRIGLAV. OUT (Reactor core output) and ELEM. OUT is executed by TRIGLAV (element data output). The output files will be saved in the computer's same directory as the input ones. In order to provide additional references for the output data, the batch function also creates the log file TRIGLAV.LOG. Figure 1 depicts the TRIGLAV code package's computation scheme. The text editor program can be used to manually prepare the input file. All of the parameters can be viewed and modified by the manipulator. This operation can be conducted conveniently from there once it has been created. The user can use the same program to review the calculation results once all unit cell and diffusion calculations have been completed.

All output files that are intended for the TRIGLAV. OUT (Reactor core output) and ELEM. OUT directories are executed by TRIGLAV (element data output). The computer's output files will be stored in the same directory as the input ones. For further references to the output data, the batch method also creates the TRIGLAV.LOG log file. The TRIGLAV code package's calculating scheme is displayed in figure 1. The input file can be manually created using a text editor program. The manipulator can choose to inspect and modify every parameter. This process can be readily carried out from there once it has been prepared. The user can use the same program to check the results of the computation once unit cell and diffusion calculations are complete. The BTRR safety analysis report serves as the source for all other input data. The water is thought to be 400 0C warm. The estimate uses an average power of 2.4 MW.

4. Results and Discussions

The BTRR fuel burn-up was computed using 50 Megawatt Day (MWD) steps up to a burn-up of 200 MWD, and the burn-up step after that was taken as 100 MWD up to a burn-up of 1400 MWD. To precisely track changes in burn-up parameters, smaller burn-up steps are first taken. Figures 2, 3, and 5 show the average burn-up for rings at 700, 800, and 1200 MWD, respectively. Dry Central Thimble (DCT) is present in Ring A, while the graphite dummy element is present in Ring B. These two circles are, therefore, absent from the figures. These graphs compare the TRIGLAV burn-up computation to the MVP-BURN code. The outcomes of these codes, which are given above, show a very good agreement with one another.

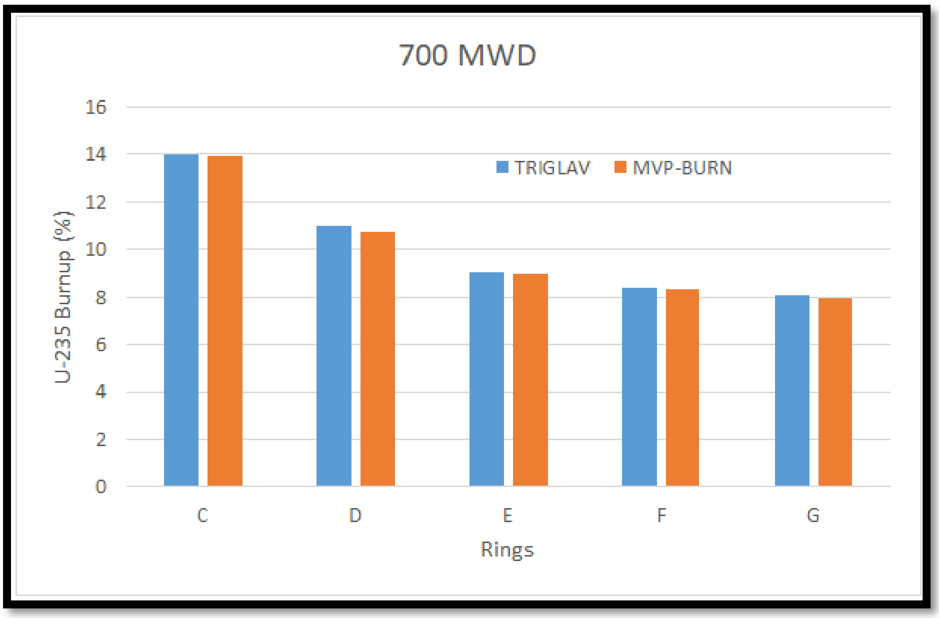

Figure 2: Core Burn-up Data Comparison at 700 MWD

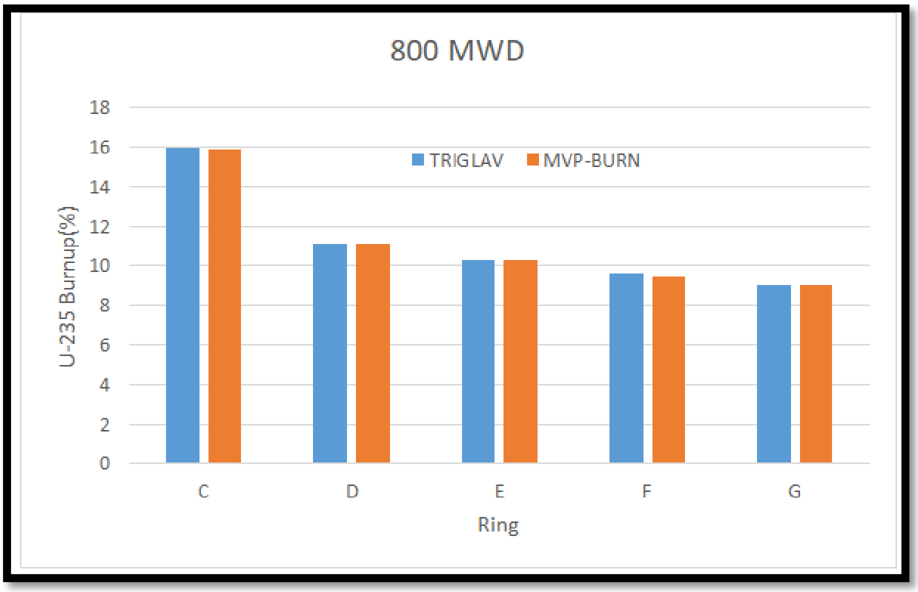

Figure 3: Core Burn-up Data Comparison at 800 MWD

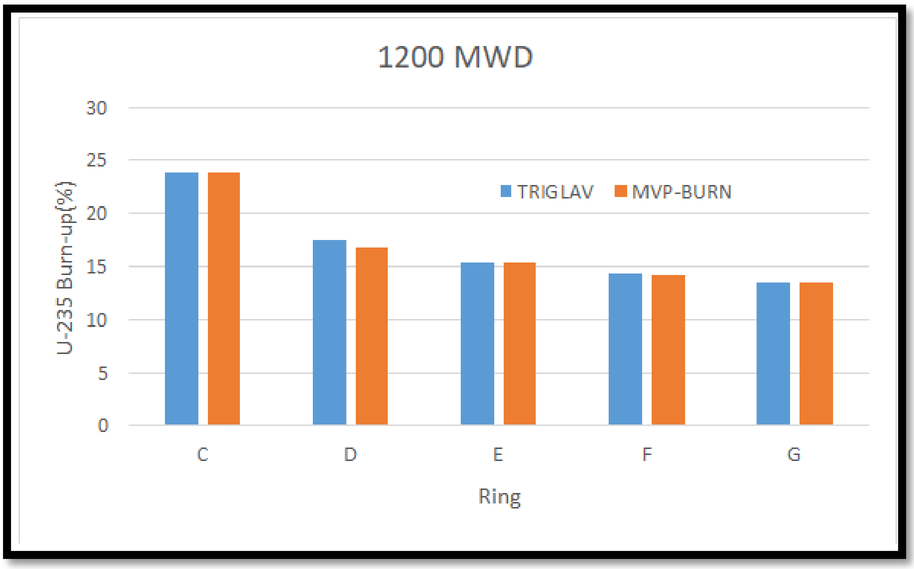

Figure 4: Core Burn-up Data Comparison at 1200 MWD

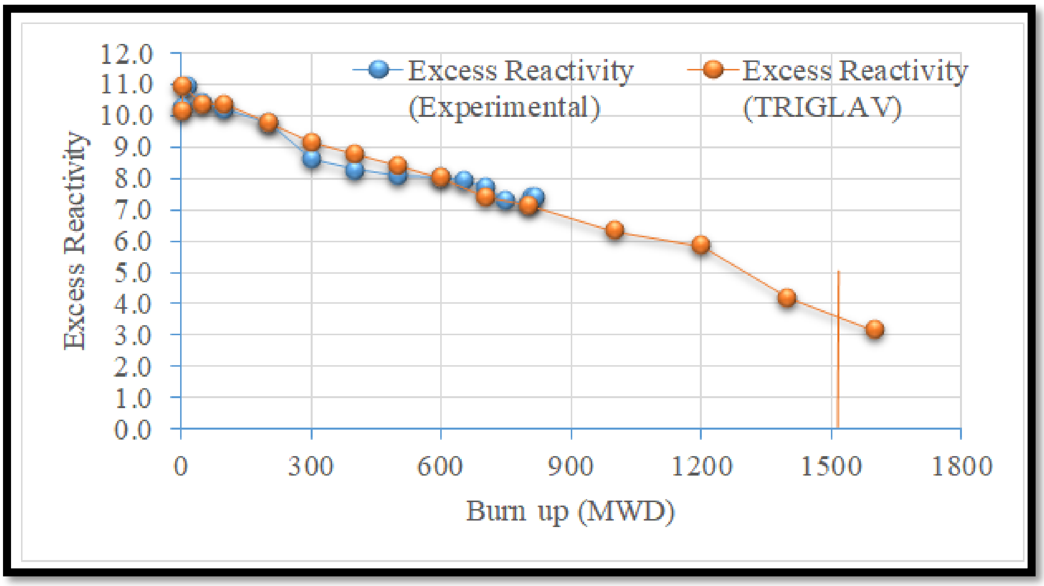

Figure 5: Core Excess Reactivity Comparison

Figure 5 shows the excess reactivity value from the operation logbook plotted with TRIGLAV results. Due to the core's conversion to Dry Central Tube (DCT) in 1988 from Wet Central Tube (WCT), initial data displays a zigzag pattern (Salam et al., 2016). This switch resulted in an increase in the fresh core excess reactivity from 10.27 to 10.94 dollars. The fuel is burned up, reducing the extra reactivity. The TRIGLAV value and the real excess reactivity data from the experimental results are nicely aligned. The real excess reactivity at an 800 MWD burn-up condition is $7.4, but the TRIGLAV value is $7.14.The TRIGLAV result differs by 3.51% from the real excess reactivity.

The fuel life has been estimated using core excess reactivity. After 1300 MWD burn up, TRIGLAV estimates that the extra reactivity in the current core design will be $5.0. The BTRR may be run at around 1300 MWD considering surplus reactivity in the present core configuration because the minimum 5$ excess reactivity is needed for sustainable operation at critical conditions (2).

During reactor operation, radioactive fission products accumulate on the inner side of the fuel cladding component. The majority of the fission products among them are gaseous. Fission gas pressure also rises along with the increase in fuel burn-up, resulting in significant yield stress on the cladding material. For TRIGA fuel, the maximum permitted individual fuel burn-up is close to 50% (9). Per the TRIGLAV analysis, the greatest ring-wise burn-up is still within the safe range, even at 1400 MWD burn-up.

5. Conclusion

The BTRR can only run at a maximum output of 2.4 MW due to a periodic safety review that an expert group conducted due to the BTRR's aging. The TRIGLAV code is used to determine the BTRR core excess reactivity, individual fuel burn-up, and ring-wise burn-up. A very good alignment can be seen while comparing the computed burn-up result to the burn-up data of the MVP-BURN code. The estimated result has been compared with the real protracted operational value in the situation of core excess reactivity. Only 3.51% of the computed extra reactivity using the TRIGLAV code differs from the real data.

According to the anticipated calculation outcome, the reactor can be operated at full power for up to 1300 MWD burn up. The lack of TRIGA fuel is currently a key operational limitation for the BTRR. The reactor can be used for its intended function in full force, according to the projected burn-up. As the burned core has not yet been reshuffled or reloaded with a fresh fuel rod, the computed burn-up information can be used to do so. This code can be utilized to teach students about core management and demonstrate it to them, both of which will significantly aid in the development of manpower in the field of nuclear science and engineering.

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