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Calculation of Control Rod Worth of TRIGA Mark II Reactor Using Evaluated Nuclear Data Library JEFF-3.1.2

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Abstract : *The present work consists of a theoretical study of control rod worth of TRIGA Mark II research reactor using the evaluated nuclear data library JEFF-3.1.2. The data files of the evaluated nuclear data library cannot be used directly as input to neutronic or other applied calculations. These data files are to be converted to preprocessed files and then to post processed into multi-group files, which are then directed into specially formatted working libraries. These libraries are compatible with the neutronic codes. This subject involves computer software using knowledge of ENDF-6 formats, thermal effects, shelf-shielding factors in resolved and unresolved resonance regions, transfer matrices of various Legendre orders etc. The chain codes NJOY99.0, WIMSD-5B and CITATION are used to evaluate the control rod worth of six control rods of TRIGA Mark II research reactor. The obtained results of control rods worth are compared with experimental results of TRIGA at Atomic Energy Research Establishment, Savar, Dhaka, Bangladesh; and the reliability of the method was confirmed.*

Keywords: *JEFF-3.1.2, NJOY99.0, WIMSD-5B, CITATION, TRIGA Mark II*

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I. Introduction

The science of atomic radiation, atomic change and nuclear fission was developed from 1895 to 1945, much of it in the last six of those years. Over 1939-45, most development was focused on the atomic bomb. From 1945 attention was given to harnessing nuclear fission energy in a controlled fashion for naval propulsion and for making electricity. The prime focus has been on the technological evolution of reliable nuclear power plants since 1956 [1]. The device in which a nuclear reaction is maintained and controlled for the production of nuclear energy is delineated as nuclear reactor. Nuclear reactors serve three general purposes. Civilian reactors are used to generate energy for electricity and sometimes also steam for district heating. Military reactors create materials that can be used in nuclear weapons. Research reactors are used to develop weapons or energy production technology, for training purposes, for nuclear physics experimentation, for producing radio-isotopes for medicine and research. The chemical composition of the fuel, the type of coolant and other details important to reactor operation depend on reactor design. Most designs have some flexibility as to the type of fuel that can be used. Nuclear research reactors are neutrons factories, in which the main purposes are to generate and utilize neutron flux of sufficient intensity for research, testing and other applications [2]. There are six types of research reactor are available in the world. These are Aqueous homogeneous reactor, Argonaut class reactor, DIDO reactor, TRIGA reactor, Miniature neutron source reactor, SLOWPOKE reactor. TRIGA is the highly successful class reactor. TRIGA (Training, Research, Isotopes, General Atomics) reactor is the most widely used non-power nuclear reactor in the world provided by General Atomics (GA), USA. GA produces three types of TRIGA which are TRIGA Mark I, TRIGA Mark II and TRIGA Mark III. Almost 66 TRIGA reactors have been installed at universities, government and industrial laboratories and medical centers in 24 countries [3]. These reactors are used in many diverse applications, including production of radioisotopes for medicine and industry, treatment of tumors, nondestructive testing, basic research on the properties of matter, for education and training. The safety features of this fuel also permit flexibility in sating with minimal environmental effects.

Control rod is one important component in a nuclear reactor. In nuclear reactor operations, the control rod function is to shut down the reactor. Control rod worth calculation is used to specify safety margin of reactor. Temperature reactivity coefficients of fuel and coolant are one of the inherent factors that can control reactor power. This study has been done about control rod worth calculation by using the rod displacement method. The reactor core has been simulated by using NJOY99.0 [4], WIMSD-5B [5] and CITATION [6,7] codes to perform neutronic calculations. The more reliable nuclear data library JEFF-3.1.2 is used to calculate the control rod worth of the TRIGA Mark II research reactor.

II. Calculation Technique

The three computer program; NJOY99.0, WIMSD-5B and CITATION, and the data files of evaluated data library JEFF-3.1.2 are used in this research.

The updated version NJOY99.0 of NJOY has the capability to process data in ENDF-6 format [8], which is used in JEFF-3.1.2. The chain of NJOY99.0 modules [9] are used to generate the 69-group cross section library from the basic data files of JEFF-3.1.2 is shown schematically in Fig.1.

The new version code WIMS-D, formally to be identified as WIMSD-5B, developed on the basis of the old WIMSD version of Atomic Energy Authority (AEA) Technology; was implemented on operating system with Lahey F77l3 FORTRAN compiler. In this version, additional possibilities proposed by the code users have been included. The unique WIMSD structure is used with 69 energy group; i.e. 14 fast group, 13 resonance group and 42 thermal groups [10].

The CITATION code is designed to solve problems involving the finite-difference representation of diffusion theory treating up to three space dimensions with arbitrary group- to-group scattering. Depletion problems may be solved and fuel problem may be managed for multi-cycle analysis.

The core of the 3 MW TRIGA Mark II research reactor consists of a total 100 fuel elements (including 5 fuel follower control rods), 6 control rods (with one transient rod), 18 graphite dummy elements, 1 central thimble (CT) and 1 pneumatic transfer system irradiation terminus. Fig.2 shows the core configuration of TRIGA Mark II research reactor. All these elements are placed and supported in between two grid plates and arranged in 7 hexagonal rings A, B**,** C, D, E, F and G of a hexagonal lattice. The geometry of the core-consists of concentric layers of hexagons with an equidistant pin rod array of hexagonal symmetry is shown in Fig.3. The function of six control rods placed in D-ring are listed in table-1. The reactor fuel is composed of 20 wt% Uranium enriched to 19.7% Zirconium hydride (ZrH) (prime moderator) and burnable poison (Er-167). The reactor is controlled by 6 control rods, which contain boron carbide (B_4C) as the neutron absorber material.

Three dimensional X-Y-Z slab geometry (Cartesian coordinate system with orthogonal axes) were used in this work where, X, Y and Z express width, height and depth, respectively. The reactor core was simulated taking width of 113.18cm, height of 136.12 cm and depth 90.30 cm. The present reactor core having the region width was divided by 49 meshes, region height by 53 meshes and region depth by 41 meshes. The three dimensional TRIGA core were simulated in the direction of X-Y-Z for seven collapsed energy group from 69 group. The position of six control rods is shown in Fig.4. The mesh points are chosen such that they give the best results considering the physical geometry of the cell. Thus, the generated TRIGA library that contains diffusion coefficient, absorption cross section and production cross section were customized to interface with CITATION.

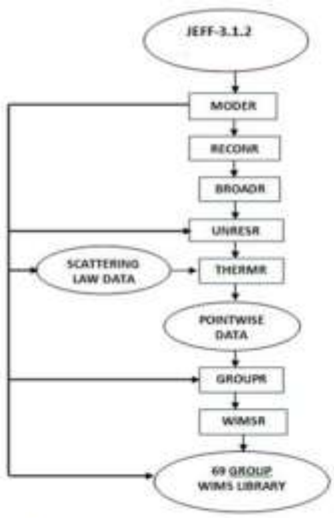

Figure 1: Nuclear data processing step of code NJOY99.0

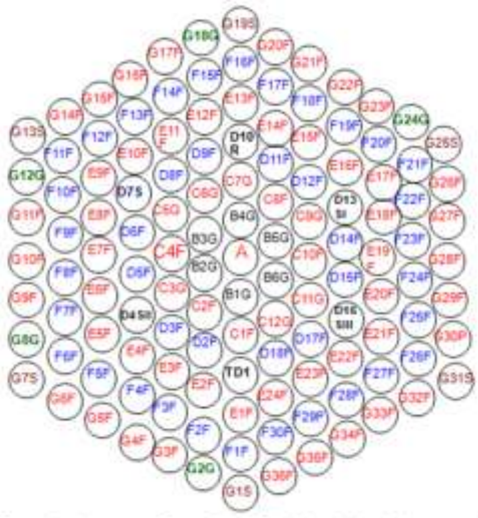

Figure 2: Core configuration of TRIGA Mark-II reactor in three dimensions

A recent study provides the validation of the data files of JEFF-3.1.2 & JENDL-4.0u for the theoretical study of TRIGA Mark II research reactor [11, 12].

These methods can be dynamic or static and the experimental measurements could be used as a set of benchmark cases in the verification of all the six control rods are positioned at different locations of D-ring of the reactor core. The control rod worth calculations were performed in this study, by rod insertion method using JEFF-3.1.2 nuclear data library. The simulation started with all control rods completely in withdrawn position. To calculate a new k_{eff} one of the control rods were inserted fully at the desired location in D-ring of the core.

The following definition of reactivity was used to calculate the values of reactivity associated with each of these k_{eff} values,

$$\rho = \frac{k_{eff} - k_{fc}}{k_{eff} \times k_{fc} \times \beta} \quad \text{(in dollar, \$)}$$

Where, β is the effective delayed neutron fraction for $U - ZrH$ type fuel with a value of 0.007 that is used to convert the unit from $\Delta k/k$ to dollar.

The control rod worth for a position in the D-ring was determined by comparing k_{eff} and $k_{eff\ 0}$ and reactivity ρ .

$$\rho = \rho_0 - \rho_1 = \left[\left(1 - 1/k_{ff,0}\right) - \left(1 - 1/k_{eff}\right)\right] \times \frac{1}{\beta} = \left(\frac{1}{k_{eff}} - \frac{1}{k_{eff,0}}\right) \times \frac{1}{\beta}$$

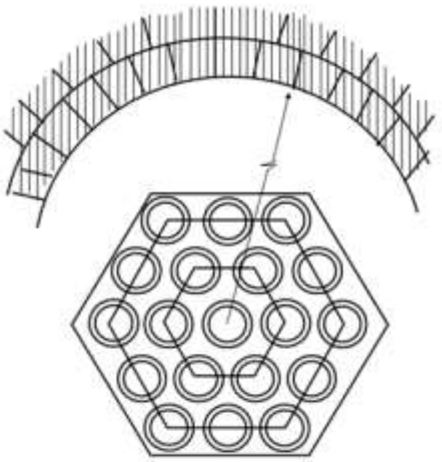

Figure 3: Concentric layers of hexagons with equidistant pin rod arrays

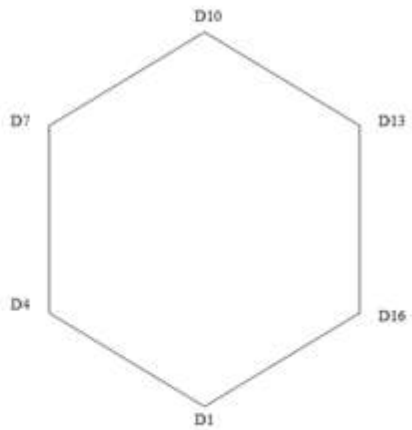

Figure 4: control rod position in the D ring of the core of TRIGA Mark-II

Therefore worth (ρ) for Transient control rod is

$$\rho_{d1} = \frac{k_{fc} - k_{d1}}{k_{fc} \times k_{d1} \times \beta} \$$$

For Shim-I rod

$$\rho_{d13} = \frac{k_{fc} - k_{d13}}{k_{fc} \times k_{d13} \times \beta} \$$$

For Shim-III rod

$$\rho_{d16} = \frac{k_{fc} - k_{d16}}{k_{fc} \times k_{d16} \times \beta} \$$$

The worth of other three control rod was calculated in analogous way.

Table: 1 Activity of control rods of TRIGA Mark II

Control Rod Id	Name	Activity
D13	Shim I	Used for coarse control to change reactivity in relatively large amounts.
D4	Shim II	Used for coarse control to change reactivity in relatively large amounts.
D16	Shim III	Used for coarse control to change reactivity in relatively large amounts.
D10	Regulating	Used for coarse control to change reactivity in relatively large amounts desired power or temperature.
D7	Safety	Furnished to fast shutdown in the event of an unsafe condition.
D1	Transient	For instant control in the pulse mode operation.

III. Result And Discussion

The determination of the reactivity worth of individual control elements and the effects of such elements on the power distribution in the core is important to the safe and efficient operation of a reactor. Once a control rod is calibrated, it is possible to evaluate the magnitude of other reactivity changes by comparing the critical rod positions before and after the change [13]. The control system of a reactor must have the ability of shutting the reactor down safely at any time. Most reactors contain control rods made of neutron absorbing materials that are used to adjust the reactivity of the core control rods are used for improper control, fine control and fast shutdowns. Typically materials for control rods include Silver, Indium, Cadmium, Boron or Hafnium. Material used for the control rods varies depending on reactor design. The material selected should have good absorption cross section for neutrons and a long lifetime as an absorber.

Table 2: Worth of different control rods of TRIGA Mark II

Rods	CITATION (JEFF-3.1.2) (in dollars)	MCNP4C (in dollars)	EXPT. (in dollars)
SHIM I (D13)	2.95	2.80	3.06
SHIM II (D4)	2.68	2.74	2.82
SHIM III (D16)	2.84	2.87	3.12
REGULATING (D10)	2.73	2.67	2.78
TRANSIENT (D1)	2.22	2.31	2.24
SAFETY (D7)	2.61	2.62	2.73
Total	16.03	16.01	16.75

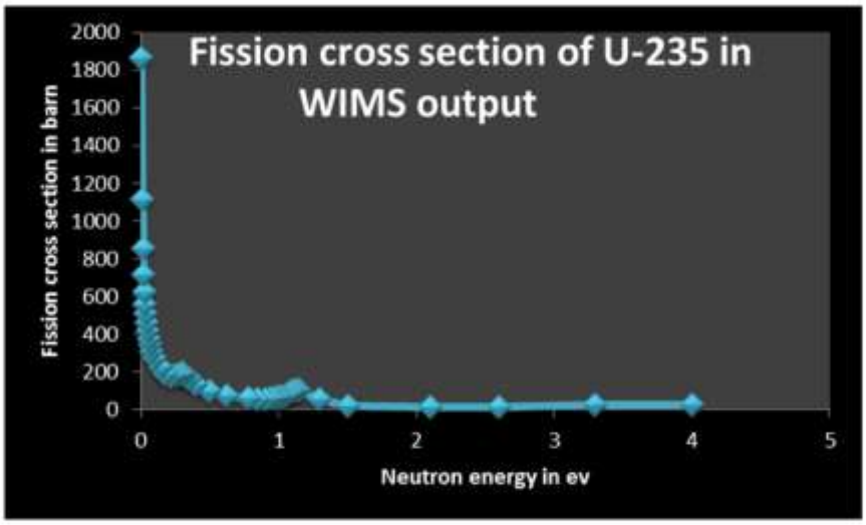

Figure 5: Fission cross section of U-235 in WIMS output for JEFF-3.2.1

JEFF-3.1.2 is the more reliable data library for the safety analysis of TRIGA MARK II [14]. That's why JEFF-3.1.2 is chosen for the calculation of worth of control rod of TRIGA Mark II. The efficiency of control rods depend largely upon the ratio of neutron flux at the location of the rod to the average neutron flux in the reactor. In TRIGA Mark II research reactor there are around 17 isotopes. U-235 and U-238 plays an important role in the fission chain reaction. Fission cross section of U-235 and U-238 in the WIMS output are calculated and plotted in Fig.5 and Fig.6 respectively. It is observed that the fission cross section of U-235 is significantly larger than U-238.

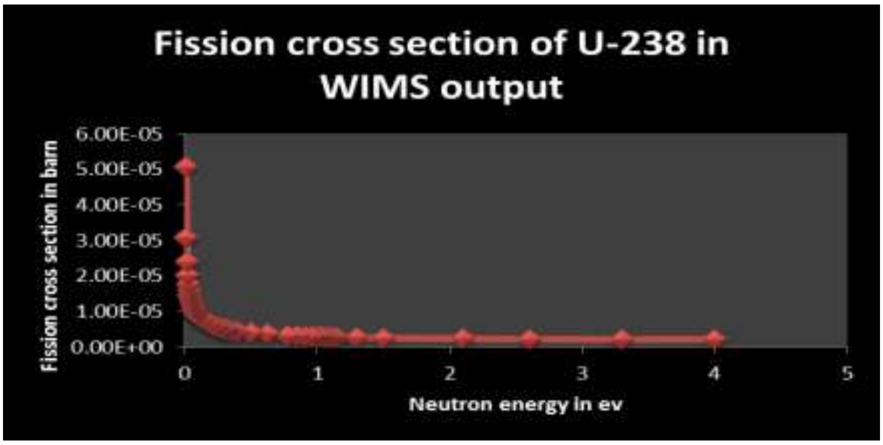

Figure 6: Fission cross section of U-238 in WIMS output for JEFF-3.2.1

The control rod has highest effect if it is placed where the flux is at maximum. If a reactor has only one control rod, the rod should be placed in the center of the reactor core. If additional rods are added to this simple reactor, the most effective location is where, the flux is maximum. Numerous control rods are required for a reactor that has a large amount of excess reactivity. The change in reactivity caused by control rod motion is referred to as control rod worth. There are several experimental techniques used to measure the reactivity

The calculated control rod worth is shown in table 2 and the comparison with experimental and MCNP4C values [15,16] is graphically shown in Fig.7. WIMS-CITATION calculation were performed for the fresh core with no fuel burn up using the cross section library based JEFF-3.1.2. It is observed that the worth is maximum for Shim-I rod and minimum for transient control rod are 2.95$ and 2.22$ respectively. The calculated values show very good agreement with MCNP4C and experimental results.

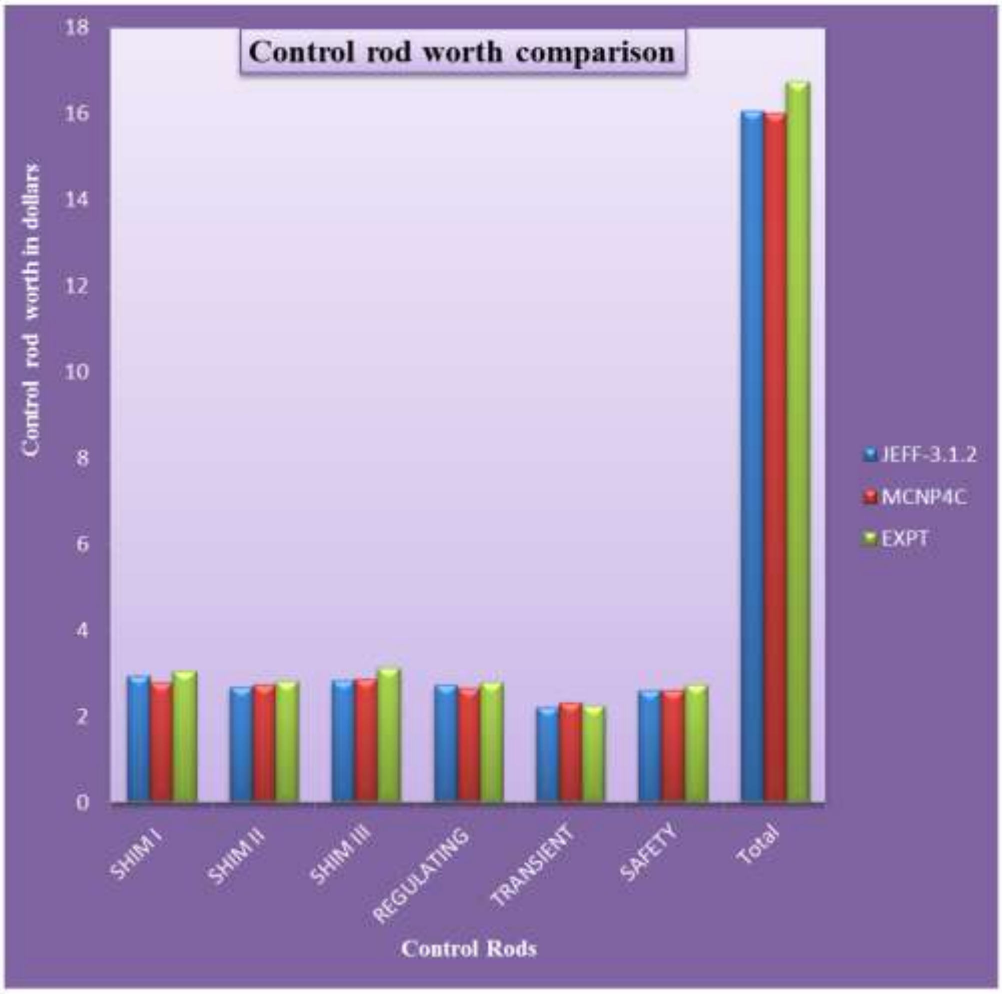

Figure 7: Control rod worth comparison for TRIGA Mark II

IV. Conclusion

The essential constraint of the control system of the reactor core is that it would be capable of providing compensation for all short-term reactivity changes in the sufficient margin to shut down the reactor under the jammed rod condition. The reactivity insertion of TRIGA core is extremely sensitive to power, so the control rod worth must be calculated to control the power as well as the temperature increment. In addition, in research reactors, reactivity and reactivity increments play an important role in safety and controlled operational. The calculated total control rod worth values obtained by JEFF-3.1.2 library is 16.03 $. This value is close to the experimental one (16.75 $) but very close to MCNP4C value (16.01 $).

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