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Validation of EUREKA-2/RR Code for Analysis of Pulsing Parameters of TRIGA Mark II Research Reactor in Bangladesh

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Some parametric studies on pulsing mode for fresh core of TRIGA Mark II research reactor in AERE, Savar, have been carried out with coupled thermal-hydraulics code EUREKA-2/RR in association with neutronics code SRAC. At the beginning, role of some important parameters in pulsing like delayed neutron fraction (β_{eff}) and reactivity insertion have been studied keeping prompt neutron life time (l_p) fixed at 33.4 µ-sec. After a series of experiments, we found that the pulsing peak that is consistent with the Safety Analysis Report (SAR) is for the delayed neutron fraction (β_{eff}) of 0.007 and reactivity insertion of 2$. Study has determined the pulsing peak of the fresh core for this particular condition to be 857.86 MW which is 852 MW according to SAR. Experiment also shows the pulsing peak increases with the increase of reactivity insertion whereas decreases with increase of delayed neutron fraction. With the utilization of the particular values of these parameters, pulsing parameters like prompt energy released, reactor period, pulse width at half maxima, alongwith safety parameters including peak power and clad maximum temperature, have been analyzed. The clad maximum temperature for fresh core is simulated to be 144.54 MW, which is much less than the SAR Value, ensuring the validity of codes and the safety of pulsing in that particular condition.

Keywords : Pulsing, EUREKA-2/RR, Safety analysis report

1. Introduction

The inherently safe and water-cooled graphite-reflected TRIGA Mark II research reactor was commissioned at Bangladesh Atomic Energy Commission (BAEC) in 1986 to effectively implement of multipurpose uses of it. Among these, the reactor is utilized in wide range of applications in basic and applied science in nuclear chemistry, nuclear and particle physics. Furthermore, the reactor is used for neutron activation analysis, for the production of radioisotopes (^{131}I, ^{99m}TC, ^{46}Sc), education, training of students and for technical personal. BAEC is committed to achieve international level of safety in operation, maintenance and utilization of research reactor. Keeping this in mind, BAEC has participated in various international projects on improvement of research reactor operation and utilization so as to acquire current knowledge and information with regard to safety of research and to apply it for the benefit of its own facilities.

One of the fundamental characteristics of this reactor is operating at different modes for use of different purposes. TRIGA in BAEC has been operating since its commissioning mostly in steady state to get steady flux. Pulsing, another mode of operation of TRIGA can generate very high flux within a fraction of second.

Reactor Physics and Engineering Division (RPED) of BAEC has done so far some computational studies of TRIGA reactor in steady state as well as transient state but with small (slow) insertion of reactivity. Therefore it is necessary to simulate the role of peak parameters at pulsing mode to ensure reactor's safety and functionality of this system at diversified condition. The objective of this work is to validate EUREKA-2/RR code for performing pulsing parameters for fresh core that will help study pulsing operation of burnt core which will ease reactor operation group to install and operate pulsing with newly setup digital console safely, and utilization group to get instantaneous high neutron fluxes for various research and uses.

2. Pulsing Analysis of TRIGA Mark II

TRIGA Mark II reactor is light water cooled, graphite-reflected one, designed for continuous operation at a steady state power level of 3MW. The reactor fuel is composed of 20 wt% Uranium enriched to 19.7% and Zirconium Hydride, and is controlled by six control rods containing Boron Carbide (B_4C) as the neutron absorber material. Since its operation the reactor has been burnt for some 700 MWD until the end of 2012. Major TRIGA characteristics are mentioned in Table 1 bellow:

TRIGA reactors can be operated by four basic modes-manual, automatic, square-wave and pulsing. All the modes can be run both in natural and forced convection. Among these, manual and automatic modes are steady-state reactor conditions, which are used for manual reactor startup, change in power level, and steady-state operations, whereas, square-wave and

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pulsing modes are the conditions implied by their name [1]**.** Pulsing mode can generate very high flux within very short time and is shut down because of the inherent safety properties of the reactor. This mode has two different levels of sensitivities where low pulse has a full-scale sensitivity of about 25% of that of the high pulse scale. In the pulse mode of operation, the 1-KW interlock requires the reactor power level to be below 1 KW. Any kind of failure to meet this requirement will help alarm the transient rod fire circuit to ensure its safety.

Table 1. Characteristics of the TRIGA Mark II research reactor.

Fuel element	20 w/o U-ZrH 19.7% enriched
Total number of fuel in the core	100
Cladding	Stainless Steel 304L
Reflector	Graphite
Inlet temperature(ºC)	27
Active fuel length(cm)	38.1
Radius of Zr rod(cm)	0.3175
Fuel radius(cm)	1.81864
Clad outer radius(cm)	1.87325
Gap width(cm)	0.00381
Gap material	Helium
Flow area(cm^2)	5.3326
Hydraulic diameter(cm)	1.80594
Pressure(cm)	1.01408
Flow velocity(cm/sec): Natural convection mode Forced flow mode	 30.48 287.58
Power peaking factor	5.63

3. Modeling of TRIGA Core

3.1 SRAC

The SRAC (Standard Reactor Analysis Code) system is designed to perform neutronics calculation for various types of thermal reactors [2]**,** as well as key parameters required in reactor design or experimental analysis. The system covers production of effective microscopic and macroscopic group cross-sections, and calculations of static cell and core including burn-up analyses. A number of additions and modifications have been made to the functions and the library data of the earlier version of SRAC system (JAERI-1305) to establish it as a comprehensive neutronics code system. Major neutron data libraries (JENDL-3.3, JENDL-3.2, ENDF/B-VII, ENDF/B-VI.8, etc.) have been compiled and five elementary codes (PIJ, ANISN, TWOTRAN, TUD and CITATION) have been integrated in the current system for neutron transport and diffusion calculation. The system also includes the auxiliary code COREBN for multi-dimensional core burn-up calculation. The SRAC system can be executed in most of computers with the UNIX operating system or its similar one.

The group cross-section library in SRAC has been processed from the JENDL-3.3 based nuclear data where energy group structure of the current Public Libraries consist of 107 groups (48 thermal groups and 74 fast energy groups and 12 overlapping groups.). Using SRAC, various cells were tested and finalized to generate the cross section data. Taking these cross-section data into account and considering the specifications of TRIGA core summarized in Table 1, CITATION mode of SRAC has been used for the calculation of power peaking factors, $F_{R,}$ fraction of average power generating in all cells, of the fuel rods.

Table 2 shows the power peaking factors, F_R, of the higher and the lower five cells in descending order starting from the peak value of 1.7178 of C4 to the minimum value of 0.7117 of D16. So, it is found that the C4 is the hottest rod of the studied TRIGA core. Since the safety of the hottest rod ensures the protection of the core, the ultimate intention of this study, this rod was then tagged to be the targeted element and all the studied were concentrated to this cell. The axial power distribution of the hottest rod was also investigated with this code.

Table 2. Power peaking factors of some of the fuel cells in fresh core.

Cell position	Cell No.	Cell ID	Power Peaking factor
	1	C4	1.717811
	2	C10	1.691888
Top five cells	3	C8	1.662269
	4	C2	1.6217
	5	C1	1.443218
	96	D10	0.754573
	97	D4	0.751522
Bottom five cells	98	D13	0.739042
	99	D7	0.723129
	100	D16	0.711733

3.2 EUREKA-2/RR

EUREKA-2/RR provides a coupled thermal, hydraulic and point kinetics capability [3], which can analyze transient response of the core against the reactivity change caused by control rod withdrawal, coolant flow change and/or coolant temperature change. Especially, it can well simulate fast transient behaviors in serious reactivity accidents. In EUREKA modeling, the core can be represented by several regions in the code. Each region may have different power generation, coolant mass flow rate and hydraulic parameters.

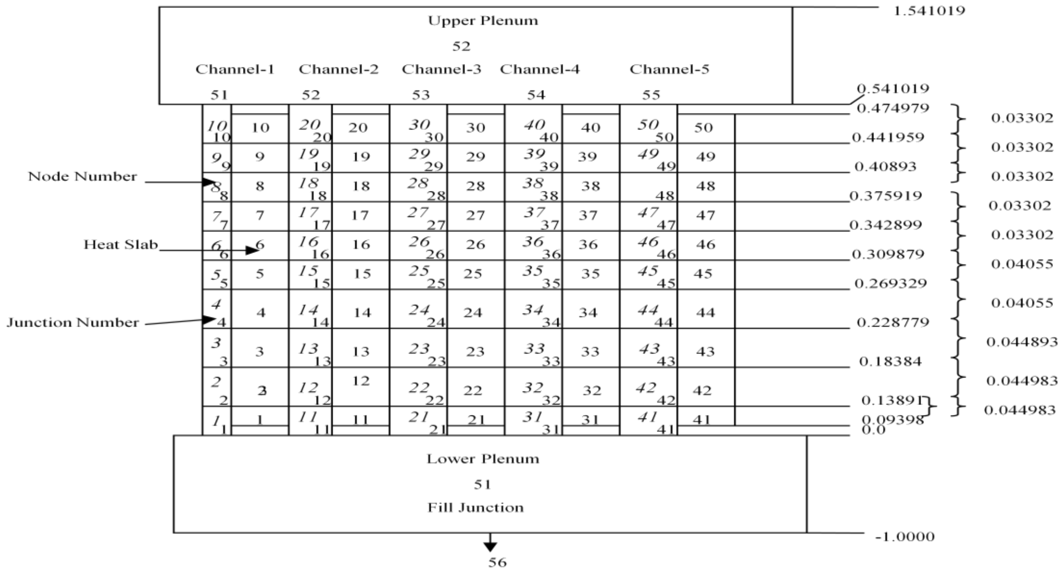

Figure 1. Schematic diagram of the model prepared for EUREKA-2/RR analysis.

The reactor power can be calculated from the reactor point kinetics equations with reactivity feedback including Doppler, void, moderator temperature and fuel rod expansion effects. The feedback reactivity effects can be evaluated by an importance weighted sum of the contribution in each region of the core. The heat conduction model is based on the method of the one-dimensional time dependent heat conduction equations. In order to transfer heat from a conductor into a cooling fluid, heat transfer correlations are utilized. "Heat transfer packages" is also incorporated in this code which was not in its previous version.

For the TRIGA core model, only the reactor core shroud containing 95 fuel and 5 fuel follower elements, was considered. The whole core was divided by five regions called channels, based on power generation, coolant mass flow rate and hydraulic diameters. Channel-1 was chosen as the hottest channel containing only the hottest fuel element with this maximum value of F_R of C4 with 1.7178. Accordingly, channel-2 contains four fuel elements with F_R ranges from 1.69 to 1.44, channel-3 contains 14 fuel elements with F_R ranges from 1.23 to 1.06, channel-4 contains 67 fuel elements with F_R ranges from 1.05 to 0.8872 and channel-5 contains lower 14 fuel elements with F_R ranges from 0.8836 to 0.711.

The fuel rods in each channel are defined by heat conductors called heat slabs while the coolant in the channel is represented by several nodes and junctions. In the present model, each channel consists of 10 heat slabs alongwith 10 nodes as shown in the Figure 1. The model altogether then consists of 52 nodes, 50 heat slabs and 56 junctions. According to Figure 1, junction No. 56 is the fill junction used to simulate the primary coolant flow in the core.

At the beginning of the use of EUEKA-2/RR we have taken the axial power fractions of the hottest rod with third order polynomial, $y = -4.650E\text{-}05x^3 + 9.952E\text{-}03x^2 - 6.672E\text{-}01x + 1.462E{+}01$ with $R^2 = 9.984E\text{-}01$. The axial power fractions have then been normalized for all other cells using their corresponding power fraction and the polynomial. Several modules of EUREKA, namely, DISSUE, ICETEA and PREDISCO have been successively used after we got neutronics data by MVP and SRAC. Figure 2 shows the diagram of EUREKA modules used:

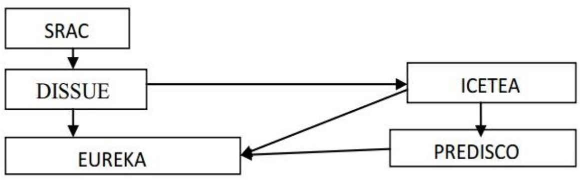

Figure 2. Flow diagram of modules used.

4. Results and Discussion

4.1 Pulsing Parameters Study

4.1.1 Reactivity

Based on neutronics, point kinetics and thermal hydraulics, EUREKA-2/RR code simulates TRIGA core for pulsing analyses under insertion of different amount of reactivity greater than 1 \$. Using the reactor specifications cited in SAR, along with initial reactor power 100 W and prompt neutron life time, l_p, of 33.4 μ-sec, pulsing analyses have been performed considering inserted reactivity of 1.5 \$, 1.75 \$ and 2 \$, respectively. Table 3 presents the results in terms of reactor power and fuel clad temperature after reactivity induced transient. The peak power found as 273.68 MW, 452.49 MW, 857.86 MW at 10.15, 10.11, 10.09 sec for the reactivity insertion of 1.5 $, 1.75 $ and 2 $, respectively. Similarly, the peak clad temperatures were calculated as 99.07 ^oC, 125.56 ^oC and 144.54 ^oC for 1.5 $, 1.75 $ and 2 $ of reactivity insertion, respectively. The table illustrates that with the degree of increase of inserted reactivity, transient power with associated peak clad temperature increases, which is expected. Also, it is noticed from the table that reactor power rose to the peak value of 857.86 MW at 2 $ insertion of reactivity which is close enough to the SAR value of 852 MW for the same amount of reactivity insertion, reported earlier in an annual report [4]. Again, it is seen from the table that the measured clad temperatures found for different amount of reactivity insertion are far below the design limit of clad temperature, 500^{o}C for BAEC TRIGA core, which indicates the reactor remains in safe condition during these fast reactivity insertions.

Table 3. Change of peak power and peak clad temperature with fast reactivity insertion

Reactivity Inserted, $	Peak Power, MW	Peak Clad Temperature ^{o}C
1.5	273.68(10.15)	99.07
1.75	452.49(10.11)	125.56
2	857.86(10.09*)	144.54

*The value in the parentheses is the time (sec) required to get the peak power.

4.1.2 *Delayed Neutron Fraction*

The kinetic parameters considered here are mean lifetime of prompt neutron (l_p) and effective delayed neutron fraction (β_{eff}). Considering reactor specifications from SAR [1] with reactor initial power 100W and keeping l_p = 33.4 μ-sec as a constant, a series of simulations have been performed against the variation of parameter, β_{eff}..

Table 4 shows the decrease of reactor peak power and peak clad temperature with the increase of β_{eff}, which is expected. It is also noticed that at β_{eff} =0.0070, reactor peak power has raised to 857.86 MW at 2 $ insertion of reactivity which is close enough to the experimental value of 852 MW at 2 $ insertion of reactivity.

Table 4. Delayed neutron fraction parameters.

β_{eff}	Peak Power MW	Clad Temperature °C
0.0065	1622.51	156.59
0.0067	1288.13	147.89
0.0069	1003.24	147.00
0.0070	857.86	144.54

4.2 *Safety Parameters Study During Pulsing*

Pulsing analysis of fresh core is essential to investigate the validity of transient study of the fresh core by EUREKA-2/RR as the available SAR value is only for this core condition. The ultimate intension of this study is to determine the pulsing parameters of burnt core which will practically be operating by digital console installing in BAEC. Pulsing study for the fresh core has been conducted with prompt neutron life time (l_p) of 33.4 μ-sec, delayed neutron fraction (β_{eff}) of 0.007, the insertion of reactivity of 2$ and the initial power of 100W.

The peak power of 857.86 MW, consistent to SAR, has been calculated with this experiment. Pulse width at half maxima was calculated to be 13.45 msec, compared to the SAR value of 15.87 msec, whereas the prompt energy released from this transient operation was 16.94 MW-sec compared to the SAR value of 18.3 MW-sec. In addition, the reactor period of the reactor was found to be 5.99 msec compared to the SAR value of 4.32 msec. Since the pulsing peak powers are almost same both for the code and SAR and a bit less of pulse width for the code, the simulated value of prompt energy by the code was found to be comparatively less whereas the reactor period a bit bigger. Tables 5 and 6 show the neutronics data used, and the comparison between EUREKA-2/RR and SAR values of safety parameters, respectively, whereas Figures 3 and 4 show the variation of peak power and temperature in the hottest rod respectively.

Table 5. Neutronics data used for safety study.

Parameters	Fresh core
Prompt neutron life time, l_p, μ-sec	33.4
Coolant velocity, cm/sec	287.58
Delay neutron fraction, β_{eff}	0.007
Power peaking factor	5.39
Initial power, Watt	100
Reactivity, $	2

Table 6. Comparison of pulse parameters for fresh core.

Parameters	SAR	EUREKA-2/RR
Maximum power, MW	852	857.86
Reactivity inserted, $	2	2
Prompt energy, MW-sec	18.3	16.94
Pulse width at half maximum, msec	15.87	13.45
Reactor period, msec	4.32	5.99

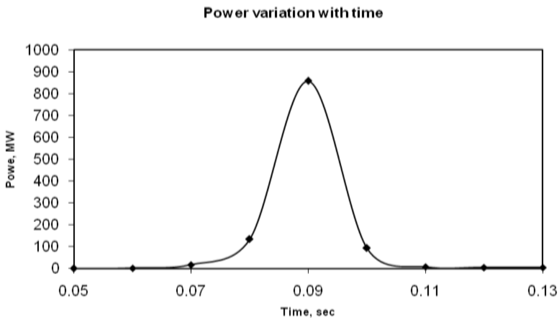

Figure 3. Power change with time in fresh core.

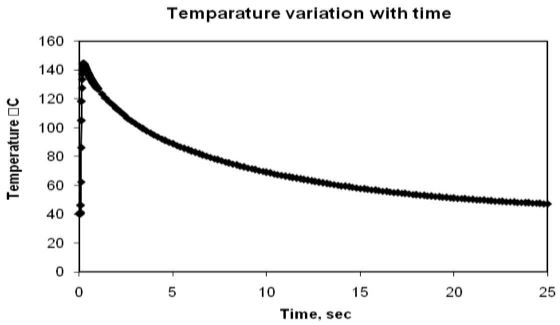

Figure 4. Temperature change with time in fresh core.

5. Conclusion

Detailed pulsing analysis for fresh core in the view point of neutronics and safety analysis has been carried out in this study. It has been found from the study that consistent result with SAR is for prompt neutron life time of 33.4 µ-sec and delayed neutron fraction of 0.007 with the insertion of 2$. The peak power is found to be 857.86 MW whereas the reactor period for fresh core is 5.99 msec. Peak clad temperatures are determined to be 144.54 ^{o}C. In addition, the energy released during pulse peak is 16.94 MW-sec whereas the pulse width at half maxima is 13.4 msec. The pulsing width indicates the unavailability of mechanical system during pulsing and necessity of inherent safety and the safety of the system. Results of most of the parameters for fresh core are in good agreement to the SAR, which validates EUREKA-2/RR. Therefore, the obtained data will be helpful to further study of burn core, and to operate the reactor with digital system installing.

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