Thermal Hydraulic Analysis of 3 MW TRIGA Research Reactor of Bangladesh Considering Different Cycles of Burnup

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A R T I C L E   I N F O

A B S T R A C T

Burnup dependent steady state thermal hydraulic analysis of TRIGA Mark-II research reactor has been carried out utilizing coupled point kinetics, neutronics and thermal hydraulics code EUREKA-2/RR. From the previous calculations of neutronics parameters including percentage burnup of individual fuel elements performed so far for 700 MWD burnt core of TRIGA reactor showed that the fuel rod predicted as hottest at the beginning of cycle (fresh core) was found to remain as the hottest until 200 MWD of burn, but, with the progress of core burn, the hottest rod was found to be shifted and another rod in the core became the hottest. The present study intends to evaluate the thermal hydraulic parameters of these hottest fuel rods at different cycles of burnup, from beginning to 700 MWD core burnt considering reactor operates under steady state condition. Peak fuel centerline temperature, maximum cladding and coolant temperatures of the hottest channels were calculated. It revealed that maximum temperature reported for fuel clad and fuel centerline found to lie below their melting points which indicate that there is no chance of burnout on the fuel cladding surface and no blister in the fuel meat throughout the considered cycles of core burnt.

INTRODUCTION

The 3-MW TRIGA Mark-II research reactor is the only reactor of Bangladesh that has been in operation over the last 27 years. Since its commissioning in 1986, the reactor has been engaged in production of radio-isotopes for uses in agriculture, industry and medicine all over the country as well as in conducting research and manpower training in various fields of nuclear science. To make the most effective use of reactor with the extension of its core life time, efforts have been paid in improving its in-core fuel management of the reactor by the calculation of different necessary parameters including individual fuel burnup at different cycles of reactor operation. Contribution of Huda *et al*. [1], Rahman *et al*. [2], Mahmood *et al*. [3] can be referred in this regard. In fact, for every modification of reactor core, it needs thermal hydraulic safety assessment prior to

its utilization. From this concern, this paper deals with the calculation of thermal hydraulic parameters of TRIGA core to ensure reactor have sufficient safety margins at every cycles of burn up during normal operation. Coupled point kinetics, neutronics and thermal hydraulics code EUREKA-2/R has been utilized for this purpose.

The 3-MW TRIGA Mark-II research reactor is a pool type, zirconium hydride moderated and light water cooled reactor. It operates at a steady state thermal power of 3 MW where the operation includes natural convection mode and forced convection cooling mode. In the natural convection mode, the fuel elements are cooled by water natural convection in the pool up to the maximum power level of 500 kW of the reactor. For higher power, forced convection cooling mode is required where heat removal system is provided for removing heat from the reactor pool water. The heat removal system contains a primary water system and a secondary water system. The primary system along with an online purification system contains the most unique design features. In the forced

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convection mode, coolant flow is maintained by simultaneous action of two pumps each supplying 50% of the total flow of 794 m³/h (3500 GPM). Heat generated in the reactor core is transferred to a water-to-water heat exchanger of primary loop, while the secondary loop water is cooled by an external cooling tower. It is worth noting that the reactor has a facility to operate at pulsing of 852 MW power in case of 2.00 dollar (1.4% dk/k) of reactivity insertion. However, this facility is yet to be put in practice because no demand has been made from the users.

EUREKA-2/RR[4] provides a coupled thermal, hydraulic and point kinetics capability. Based on core neutronics calculation at different cycles of burnup, three other utility codes, namely, DISSUE, ICETEA and PREDISCO [5] are used in succession to support the entire analysis. Figure 1 shows the successive use of these codes in order to provide data in preparing the input of EUREKA-2/RR.
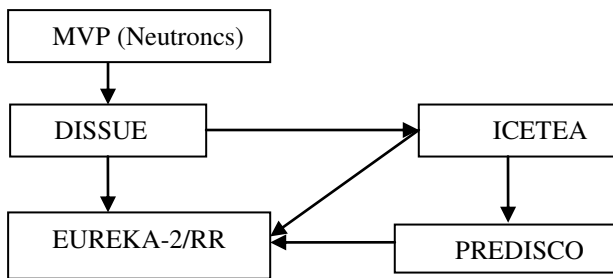

Fig. 1. An outline of the overall process followed in preparing the input of EUREKA-2/RR.

EXPERIMENTAL METHODS

Neutronic studies of the triga core

There is a link between neutronic analysis and thermal analysis of the reactor core since heat energy generated in the core is induced by the fission neutrons. If trace back reports of Huda *et al.*[1], Rahman *et al.* [2] , Mahmood *et al.* [3], it is recognized that individual fuel element burnup together with power peaking factors calculations have been carried so far for about 700 MWD burnt of TRIGA core until 2012. These previous calculations were mostly conducted by using three dimensional continuous energy Monte Carlo code MVP considering cross section data library JENDL3.3. If reviewing power peaking factors calculations at different cycles of burnup, it is found that C4 fuel element in the TRIGA core remains hottest up to 200 MWD

and onward from this, C10 becomes the hottest rod that continued up to 700 MWD of core burnt, as it is seen in Fig. 2. The locations of C4 and C10 fuel elements can be identified from the configuration of TRIGA reactor core as shown in Fig. 3. Due to shifting of hottest rods with the progress of core burnup, the present study calculates thermal hydraulics parameters initially to the extent of 200 MWD core burnt which was later extended to perform two more calculations considering 550 MWD and 700 MWD burnup cycles. As C4 is the hottest rod from the beginning to 200 MWD cycles of burnup, radial and axial power peaking factors of C4 considering fresh core (beginning of cycle) as well as 75 MWD and 150 MWD burnt core are taken into account. Similarly, radial and axial power peaking factors of the hottest rod, C10, have been considered for 550 MWD and 700 MWD cycles of burnt core. Table 1 shows the radial, axial and total peaking factor for the hottest rods at different burnup cycles.

Table 1. Peaking factors of C4 and C10 at different burnup cycles.

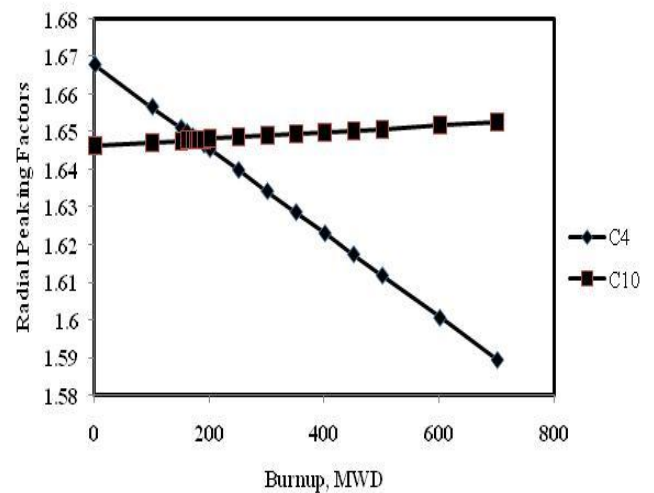| Peaking Factors	C4			C10	
	BOC	75 MWD	150 MWD	550 MWD	700 MWD
Radial Peaking Factor	1.668	1.660	1.651	1.651	1.652
Axial Peaking Factor	1.218	1.222	1.225	1.285	1.304
Total Peaking Factor	2.031	2.028	2.024	2.121	2.154

Fig. 2. Radial Peaking Factors of fuel elements C4 and C10 against core burnt.
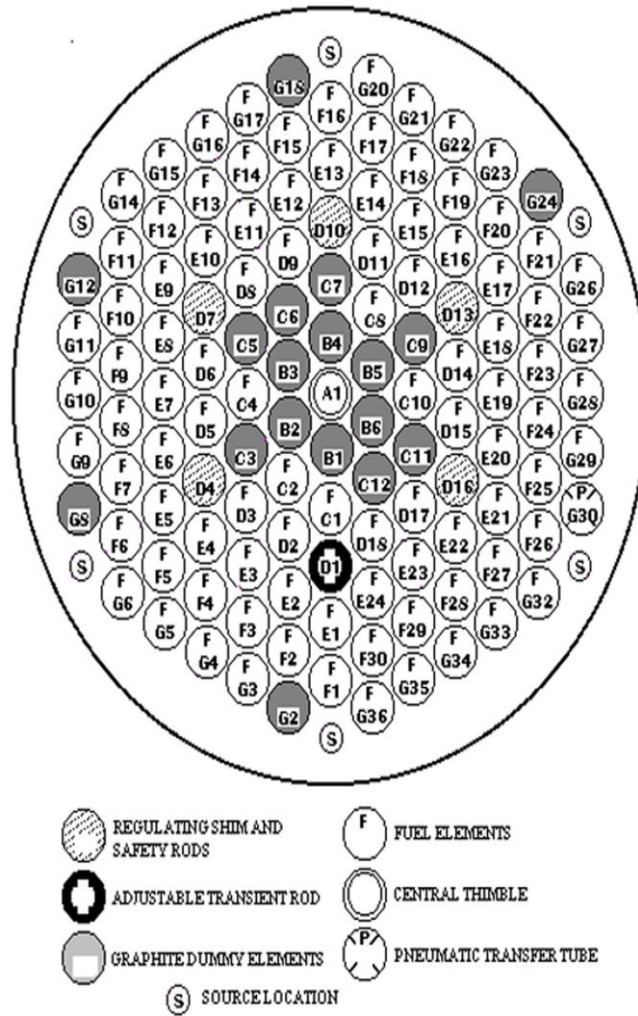
Fig. 3. Configuration of 3 MW TRIGA Mark-II Research Reactor.

Analytical model of triga core

For modeling, only fuel region in the core is considered. An upper and a lower plenum are located above and bottom of the core represent the reactor pool water as seen in Fig. 4.
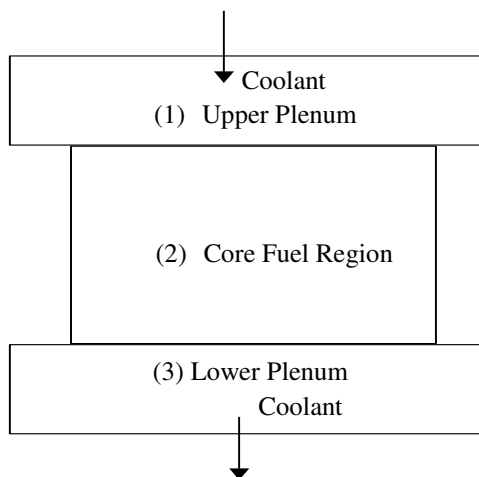

Fig. 4. Outline of an analytical model.

The core contains 95 fuel elements and 5 fuel follower elements are divided into 5 distinct channels. Each channel may contain one or more fuel elements. The distribution of these fuel elements among the channels are made on the basis of power peaking factors values of the fuel elements. The fuel rods in each channel are defined by heat conductors called as heat slabs while the coolant in the core is represented by several nodes and junctions. In the present model, each channel consists of 10 heat slabs along with 10 nodes as shown in the Fig. 5. The model in total then consists of 52 nodes, 50 heat slabs and 56 junctions. According to Fig. 5, Junction no. 56 is the fill junction used to simulate the primary coolant flow in the core. Table 2 gives other design parameters required for total thermal hydraulic analysis.

Detail about core modeling is introduced in my previously published work[6]. The same model that was validated before[6] under

steady state condition has been reconsidered in this present study, but, the variation of power peaking factors with the progress of core burnt have been taken into account during simulation of each cycle of burnup. This study, hence, is a complementary study aim to investigate the reactor thermal hydraulic behaviors at different cycles of core burnup.
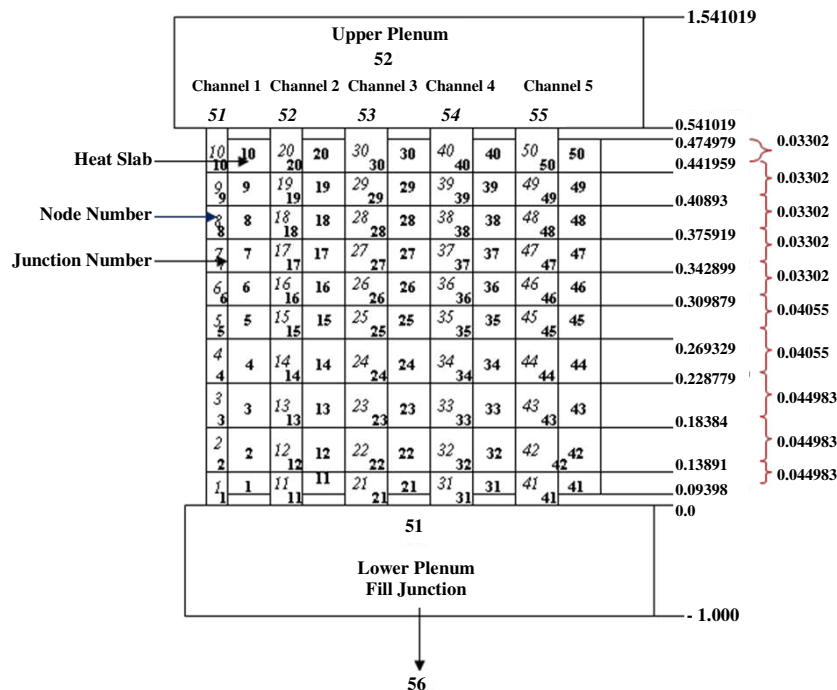
Table 2. Technical specification of TRIGA MARK-II Research Reactor.

Parameters	Design Value
Fuel Element (rod type)	20% w/o U-ZrH, 19.7% enriched
Total number of fuels in the core	100
Cladding	Stainless Steel 304L
Reflector	Graphite
Inlet Temperature °C (Full Power)	40.6
Radius of Zr rod (cm)	0.3175
Fuel radius (cm)	1.82245
Clad outer radius (cm)	1.87706
Gap width (cm)	0.00381
Active fuel length (cm)	38.1
Flow area (cm^2)	5.3326
Hydraulic Diameter (cm)	1.80594
Pressure (Pa)	1.60654×10^5
Friction Loss Coefficient	0.07
Pressure Loss Coefficient	1.81 (inlet); 2.12 (Outlet)
Pitch (cm)	4.5716
Mass Flow rate, kg/m^{2}s (a) Natural Convection Mode	145.20 (at 500 kW) 120.55 (at 300 kW) 81.03 (at 100 kW)
(b) Forced Convection Mode	3.2089×10^3
Coolant Velocity (cm/sec) (a) Natural Convection Mode (b) Forced Flow	30.48 287.58

Steady state thermal hydraulic analysis

The objective of thermal hydraulic core analysis is to ensure the operational temperature in the core does not exceed the design limit of temperature. To investigate this maximum temperature, the common approach in practice is to sort out the hottest fuel rod from the core. If it can be ensured the hottest fuel rod exhibits the temperature that remain below the core design limit, the remaining fuel rods then will presumably fall within this limit. As discussed before, C4 and C10 are the hottest rods for up to 200 MWD and 700 MWD core burnt, respectively, so the major focus of this study whether temperature of these hottest rods remain below the design limit.

In his study, major parameters such as fuel centerline temperature, fuel cladding temperature, bulk coolant temperature at different cycles of core burnup are being calculated considering the reactor operates at 3MW power during steady state operation. Prior to the analysis by EUREKA-2/RR, some preliminary data have to be be generated. Kaminaga[5] developed three utility codes to produced the entire input data of EUREKA-2/RR which are DISSUE, ICETEA and PREDISCO such as DISSUE calculates power fraction and void, Doppler, clad expansion and coolant temperature reactivity weighting factors for each heat slab based on core neutronic calculation, ICETEA calculates coolant temperature distribution and PREDISCO calculates pressure distributions in the coolant.
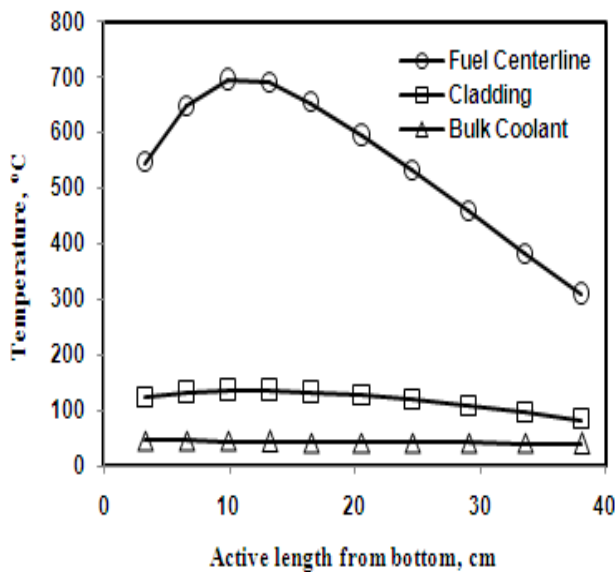

Fig. 5. Schematic diagram of the model prepared for EUREKA-2/RR analysis.
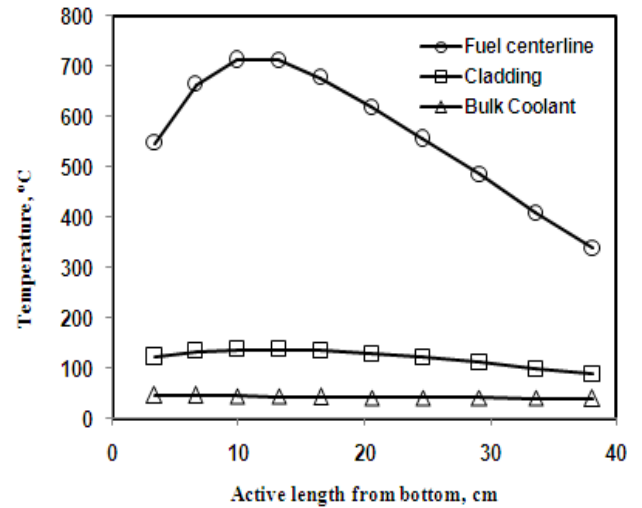
RESULTS AND DISCUSSION

The peak temperatures of fuel centerline, clad and bulk coolant of the hottest fuel element, C4, are reported in Table 3 considering beginning of cycles of 75 MWD and 150 MWD burnt core for reactor operated at 3MW power under steady state condition. It is seen that peak temperatures of fuel centerline and clad with associated bulk coolant temperatures decrease as total peaking factors decreases with the increase of burnup. Similarly, the same Table 3 contains the temperatures data for the next cycle hottest rod, C10. It is noticed that the peak temperatures of fuel centerline, clad and bulk coolant temperatures for the C10 hottest rod increases with 550 MWD and 700 MWD cycles due to increase of total peaking factors with the progress of burnup. Figures 6 and 7 present the axial distribution of temperature in the hottest channels C4 and C10 for 150 MWD and 700MWD burnt of TRIGA core, respectively.

Table 3. Temperatures of hottest channels at different cycles of core burnup.

Parameters	C4			C10	
	BOC	75 MWD	150 MWD	550 MWD	700 MWD
Bulk Coolant Temperature, $^{\circ}$C	46.74	46.67	46.66	46.67	46.94
Cladding Temperature, $^{\circ}$C	136.75	136.28	136.15	135.64	137.54
Fuel Centerline Temperature, $^{\circ}$C	703.16	697.31	695.79	689.22	712.79

Fig. 7. Axial temperature distribution in the hottest channel of C10 at 700 MWD burnt condition.

CONCLUSION

The burnup dependent steady state thermal hydraulic analysis has been carried out which shows that maximum temperatures of the hottest channel strictly depends on cycles of core burnup. Although there is temperature change in the hottest channel either decrease or increase with the progress of burnup, however, this change seems very little. Moreover, maximum temperature reported for fuel clad and fuel centerline found to lie below their design limit, 500°C and 950°C, respectively which indicates that there is no chance of burnout on the fuel cladding surface and no blister in the fuel meat throughout the considered cycles of core burnt.

ACKNOWLEDGMENT

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Fig. 6. Axial temperature distribution in the hottest channel of C4 at 150 MWD burnt condition.

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