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Impact of CHF correlations on DNBR of the TRIGA Mark II research reactor under different operational modes and burn-up conditions

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Abstract. *Departure from Nuclear Boiling Ratio (DNBR) is a crucial thermal hydraulics safety parameter for nuclear reactors. Hence selecting appropriate DNBR correlation is vital for design, licence and operation. The Bernath, Mirshak, and Tong correlations have been utilized in PARET/ANL code in this study to calculate DNBR in the TRIGA Mark II research reactor during both steady state and transient conditions, spanning from the beginning of cycle (BOC) to 1000 MWD of operation life. The findings reveal that the Bernath correlation yields the lowest values whereas Tong Correlation exhibits the highest values across all operational phases. Hence it can be concluded that General Atomics-suggested Correlation of Bernath is the most conservative for studying TRIGA reactor.*

Keywords: PARET/ANL; thermal hydraulics; burnup.
Classification numbers: 44.25.+f; 47.27.te; 28.50.Dr.

1. Introduction

The Bangladesh Atomic Energy Commission has been operating the TRIGA Mark II research reactor since 1986. This reactor is personalised for versatile applications, encompassing training, education, radioisotope production, and diverse research and development endeavors in neutron activation analysis, neutron scattering, and neutron radiography [1]. Specialized by its light water-cooled and graphite-reflected design, the reactor is accurately engineered for sustained operation at a consistent power level of 3000 kW (thermal). The robust safety protocols, primarily owing to the significant prompt negative temperature coefficient of reactivity inherent in its U-ZrH fuel-moderator composition, is a special feature of this reactor. The reactor's core comprises 100 fuel elements, including 5 fuel follower control rods and 2 instrumented fuel elements, arranged in a concentric hexagonal array within the core shroud. It is proficient in operating in both steady-state and pulsing modes, accommodating natural convection as well as forced convection cooling techniques. Remarkably, the natural convection mode remains effective up to 500 KW, beyond which the transition to forced convection mode becomes imperative.

Thermal analysis and neutronics of the reactor core are strongly correlated as heat generation is a result of fission neutrons. As the burn-up progresses, the power peaking factors undergo alterations due to the change in flux shaping, affecting the thermal hydraulics parameters. Also, these parameters alter during transient states of operation. This effect is the most vital for the change in power in the hottest rod, among all fuel rods. Hence, ensuring safety of the hottest rod in all states of the operation, the safety of the reactor can be ensured. Hence, by ensuring that the highest temperature observed in any fuel rod stays below the core design threshold, it can be reasonably assumed that the parameters of the remaining fuel rods will also fall within acceptable limits.

Thermal hydraulics, which deals with the process of heat transfer from the fuel to the coolant, plays a crucial role in nuclear engineering, especially when considering safety implications. This transfer is intricately linked to the boiling process of the reactor water during operation. When plotting the variation of heat flux on the heated surface against the temperature difference between the surface and the water, as depicted in Fig 1, the curve can be segmented into four distinct regions. As long as the fuel's heated surface remains below the saturation temperature of the coolant, only heat transfer in a single phase will take place. In Region I, single-phase convection occurs, while in Region II, subcooled boiling emerges when the bulk coolant temperature is below the saturation point, but the fuel's surface exceeds it. Region II, also known as the nucleate boiling region, witnesses the formation of vapor bubbles at the heated surface. Subsequently, the peak flux is reached when these bubbles amalgamate to create a vapor film on the surface, hindering the passage of heat and leading to a significant decline in heat flux despite a temperature rise. This maximum flux marks a design constraint known as the Departure from Nucleate Boiling (DNB) and is defined as the ratio of the critical heat flux to the heat flux achieved in the core. Thus, from the onset of nucleate boiling (ONB), region II progresses until the occurrence of DNBR. Regions III and IV harbor severe conditions that could potentially harm the heated material. However, before reaching these regions, a minimum threshold for DNBR is enforced as part of the thermal-hydraulic design. As the burn-up progresses, the neutronics parameters change, resulting in a change in the power distribution. This change of power distribution alters the power peaking factor. This phenomenon ultimately changes thermal hydraulics parameters. Hence, thermal hydraulics calculation aims to make sure safety parameters remain with its margins in the burned core.

One of the most important input parameters to be selected during the simulation of accident scenarios in a research reactor is the thermal-hydraulic correlation for DNBR. During mild and fast transients, the significant transient phenomena occur within a short time span, typically less than 1.0 s. The cladding temperature experiences a rapid escalation following the power excursion, with the transient being constrained solely by the considerable boiling phenomena that ensue. The anticipation of heat flux at DNB enables the code to designate the predominant boiling mechanism and subsequently forecast the power and temperature trends. Hence, it is important to select

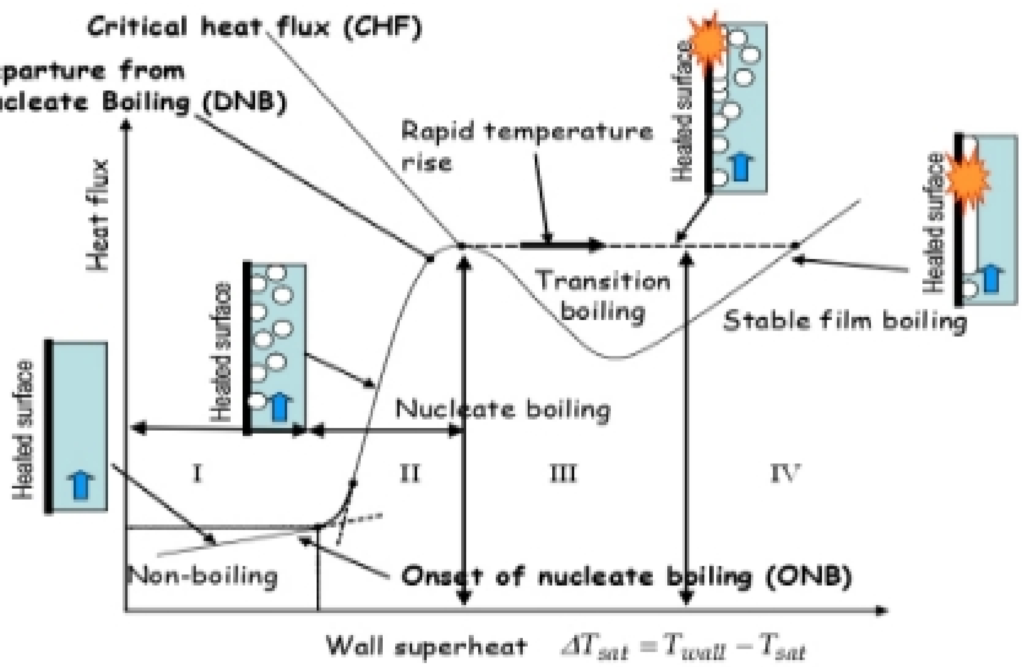

Fig. 1. Heat transfer through different regions of boiling coolant.

appropriate correlation during the analysis of core for design, licencing and operation. PARET-ANL has only three build in correlations:

1. Bernath Correlation [2],
2. Tong Correlation [3], and
3. Mirshak Correlation [4]

As a result, these three correlations have been chosen for this simulation. These correlations have been deduced from many experiments conducted on circular, annular, and rectangular coolant channels. The efficacy and performance of these correlations are outlined in Table 1 below.

2. DNB correlation range of applicability

Table 1. DNB Correlation Range of Applicability [5].

Correlation	Pressure (MPa)	Velocity (m/s)	Subcooling at DNB (˚C)	Hydraulic Diameter (m)
Bernath	0.10 to 20.60	0.0 to 17.0	0 to 176	0.00363 to 0.0924
Tong	5.51 to 18.96	0.3 to 10.8	0 to 126	0.00254 to 0.0137
Mirshak	0.17 to 0.58	1.52 to 13.72	5 to 75	0.00533 to 0.0117

Bernath correlation:

$$q_{DNB} = \left(61.84\frac{De}{De+\frac{\xi}{\pi}} + S''0.01863u\right) \times \left(57\ln P - 54\frac{P}{P+0.1034} + 283.7 - \frac{u}{1.219} - T_b\right)$$

and

$$S'' = \begin{cases} \frac{23.53}{De0.6}, & De \le 0.03048m \\ 90+\frac{3.048}{De}, & De \le 0.03048m, \end{cases} \tag{1}$$

where the variable units are: q (W/m^2), T_b (˚C), T_{sat} (˚C), P (MPa), u (m/s), D_e (m), and ξ (m).

2.1. Tong correlation

To formation of Tong Correlation is:

$$q_{DNB} = (0.23\times10^6 + 0.094G)(3.0+0.01\Delta T_{sub})(0.435+1.23e^{0.0093L/D_e})(1.7-1.4e^{-a})$$

and

$$a = 0.532\frac{(H_f - H_{in})}{H_{fg}^{3/4}}\left(\frac{\rho_g}{\rho_f}\right)^{-1/3}, \tag{2}$$

where, the variable units are: $q\,(W/m^2)$, $T_b\,(°C)$, $T_{sat}\,(°C)$, $P\,(MPa)$, $u\,(m/s)$, $D_e\,(m)$ and $\xi\,(m)$.

Mirshak Correlation

The Mirshak correlation is described by the following equation

$$q_{DNB} = 1.51(1+0.1198u)(1+0.00914\Delta T_{sub}) \times (1+0.19P), \tag{3}$$

where, the units of the variables are as follows: q(MW/m^2), u (m/s), P(bar), and ΔT_{sub}(˚C).

The TRIGA Mark II research reactor in Bangladesh is now 38 years old and has a low excess reactivity. Hence there is a dire need of expanding its operation life without compromising safety and ensuring maximum performance from utilizer's side. Hence choosing appropriate DNBR is a vital issue in the calculation of fuel management, license and operation of the burned reactor. In order to prevent the most adverse combination of mechanical and coolant conditions within the core, it is imperative to maximize the value of DNBR from unity as outlined in the Safety Analysis Report (SAR) [6]. In this context, a simulation of the TRIGA Mark II reactor was conducted for investigating the influence of the Tong, Mirshak, and Bernath correlations.

DNBR of the TRIGA Mark II research reactor has been conducted using various codes [7, 8]. The Bernath correlation has been applied earlier to calculate DNBR of the Beginning of Cycle (BOC) TRIGA core as recommended by General Atomic, the vendor of the reactor, due to its conservative nature [9]. However, no thermal hydraulics burn-up analysis has yet been performed where the conservation of this correlation can be validated. This study aims to demonstrate the efficacy of the Bernath correlation across various burned states and operational modes, focusing on transient conditions where the minimum DNBR is observed among all operation conditions. The ultimate goal of this study is to determine the effectiveness of correlations in the burned core and to select the appropriate one for safety, licensing, and fuel management of the burned core in the future.

3. Simulation method

The DNBR study of the steady state and transient state of the beginning of cycle (BOC) and burned core has been performed using PARET/ANL code. This code was chosen due to its general applicability, simplicity of coding, and rapid execution [10]. It is capable for utilization in forecasting the progression and consequences of non-destructive reactivity incidents in small reactor cores. This code integrates neutron kinetics, hydrodynamics, and heat transfer to achieve a comprehensive analysis. The reactor's power behavior is ascertained by numerically solving the point reactor kinetics equations. The transient temperatures within the fuel element are determined using a one-dimensional heat conduction equation resolved in axial segments. The solution to these equations is computed by considering the reactivity feedback from the initial time to the specific node. The feedback reactivity is derived from the cumulative impact of fuel rod expansion, moderator density variations, and fuel temperature effects. The PARET/ANL model features a water-cooled core comprising a maximum of fifteen fuel elements and their corresponding coolant channels. In our simulation, the entire core was segregated into two channels, with one channel accommodating the hottest rod and its coolant, while the other channel housed the remaining fuel and coolants. Each channel was subdivided into 10 equidistant nodes. For the PARET core, the Bernath Correlation, Mirshak Correlation, and Tong Correlation were selected to analyze DNBR under both steady state and transient reactor operations at the beginning of the cycle and during core burning.

The power peaking factors of BOC and burned cores utilized in this thermal hydraulic computation were calculated from our prior publication [11]. The hottest rod factors employed for BOC at 75 MWD, 150 MWD, 700 MWD, and 1000 MWD were found to be 1.668, 1.660, 1.651, 1.652 and 1.653, respectively. Among all these burnup states, the C4 fuel rod was the hottest rod until the core burnup of 75 MWD behind this C10 took this position. The thermal-hydraulic analysis was executed with a water inlet temperature of 40.6°C and an inlet pressure of 160.6 kPa, correlating to the hydrostatic pressure of water within the reactor channels. All steady-state operations were performed at the maximum operational capacity of 3 MW. Additionally, transient operations were carried out with a 2$ reactivity insertion on a 100-watt operational reactor. The prescribed mass flow rate for a downward forced coolant circulation was set at 3,500 gallons per minute, as stipulated in the conclusive safety analysis report. The essential parameters for the thermal-hydraulic assessment are presented in Table 2. Initially, our study was validated for the BOC core with the Safety Analysis Report (SAR). Subsequently, simulations were conducted for burnup calculations across various operational modes. The current core configuration of the TRIGA Mark II research reactor is delineated in Fig. 2.

4. Results and discussion

Steady state

The application of Bernath, Mirshak, and Tong correlation for DNBR analysis during the steady-state operation of a reactor at BOC, 75 MWD, 150 MWD, 700 MWD, and 1000 MWD has been investigated. The findings are depicted in Figure 3 to Figure 7. It is apparent from the visual representations that across all burned core stages, Tong's correlation yields the highest DNBR values, whereas Bernath's correlation yields the lowest. Furthermore, based on simulation data, it is observed that the DNBR is at its lowest during BOC whereas the highest burned core

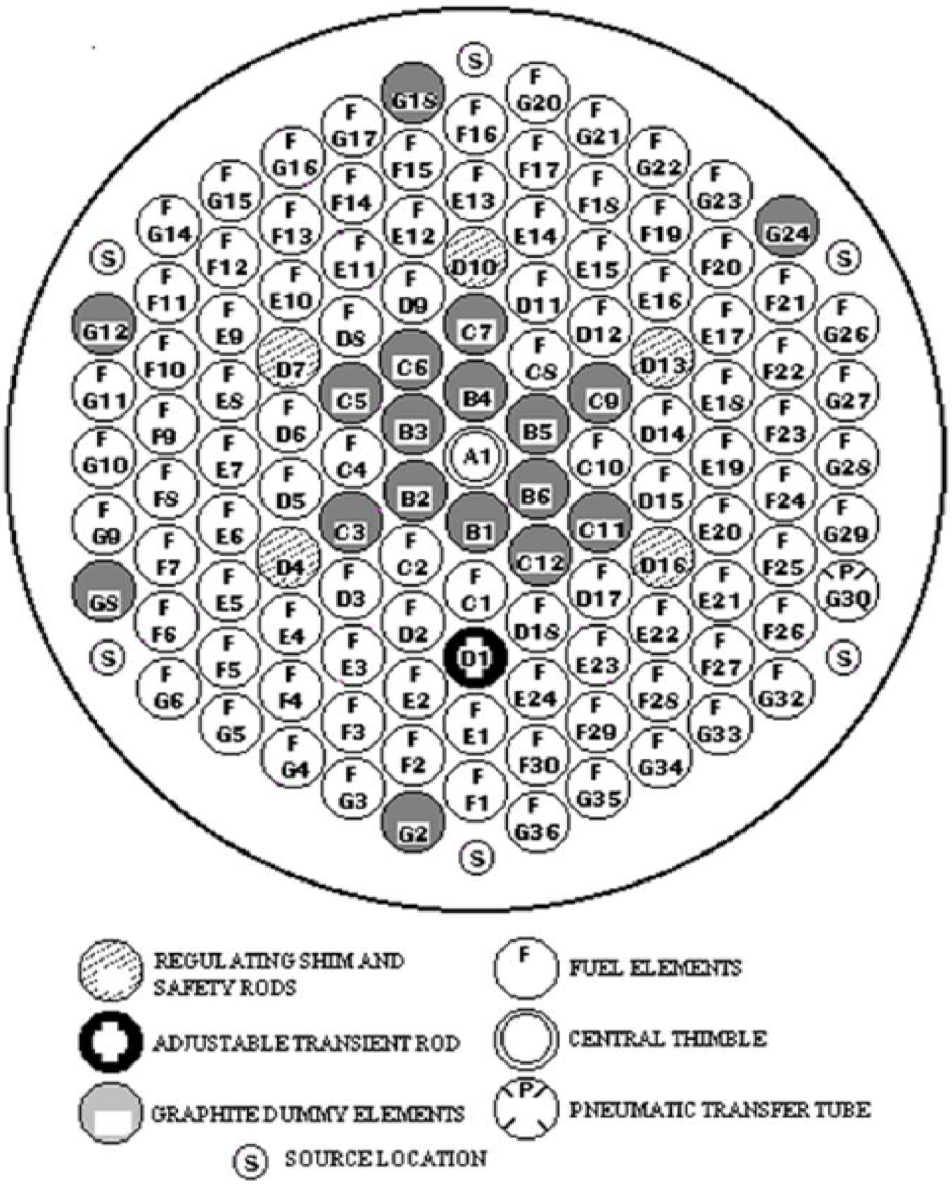

Fig. 2. Present core arrangement of TRIGA mark II research reactor.

stage exhibits the highest minimum DNBR, for all three correlations. The minimum DNBR was determined to be 2.54, 3.17, and 8.04 for BOC, 2.56, 3.20 and 8.11 for the 75 MWD core, 2.58, 3.23 and 8.18 for the 150 MWD core, 2.61, 3.27 and 8.29 for the 700 MWD core, and 2.62, 3.29 and 8.34 for the 1000 MWD core for the Bernath, Mirshak, and Tong correlations, respectively. The lowest DNBR among all operations is 2.54 which was found for Bernath correlation. This

Table 2. TRIGA Mark II operating conditions.

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	3.2089×10^3
Coolant velocity (cm/sec)	287.58

value is much bigger than unity, the safety margin. Also, it is comparable to the minimum DNBR in SAR.

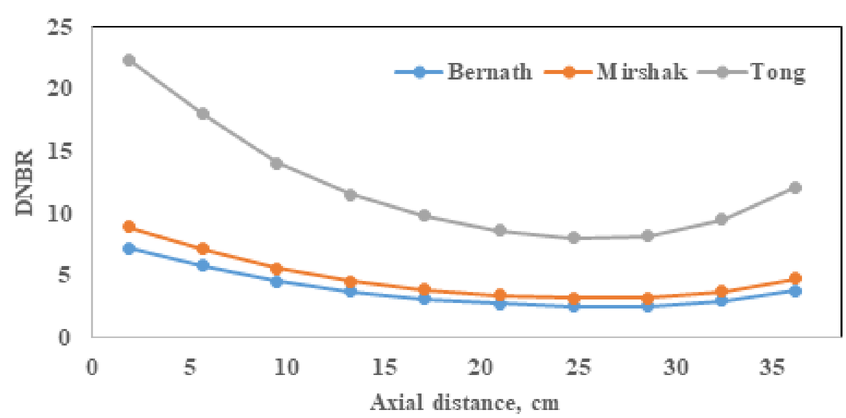

Fig. 3. DNBR distribution for Bernath, Mirshak and Tong correlation of at BOC core.

For every phase of the burned core, the upper segment of the fuel exhibits a higher Departure from Nucleate Boiling Ratio (DNBR) due to its lower heat flux in that area. This trend decreases until it reaches its minimum just below the center of the fuel, and then ascends towards the end of

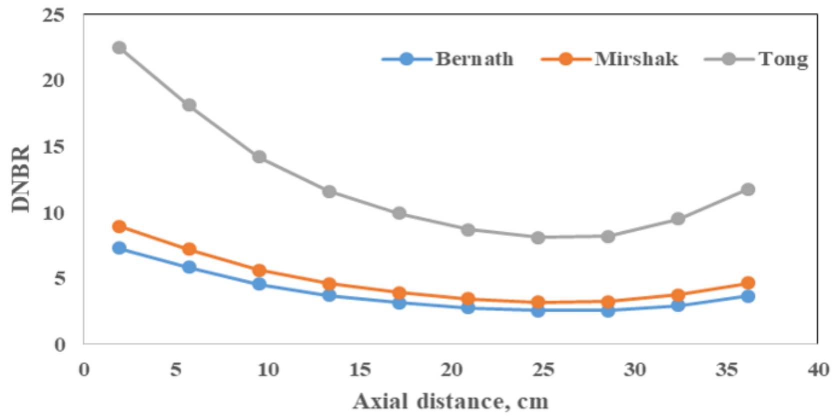

Fig. 4. DNBR distribution for Bernath, Mirshak and Tong correlation at 75 MWD burned core.

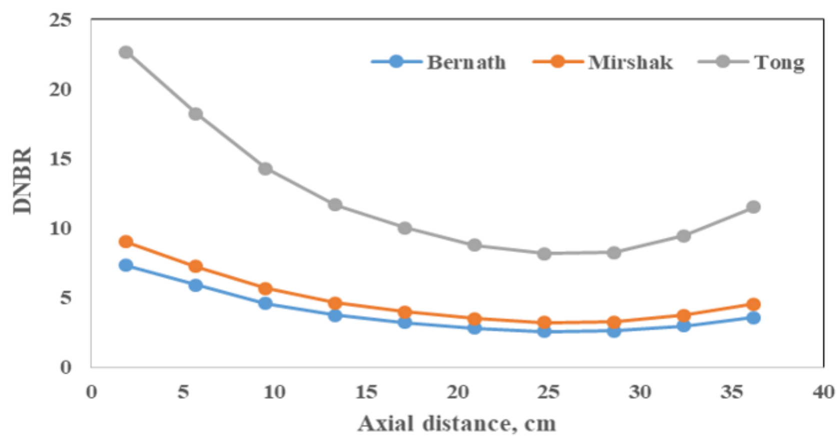

Fig. 5. DNBR distribution for Bernath, Mirshak and Tong correlation at 150 MWD burned core.

the rod. Additionally, the comparison between the Misrack correlation and the Bernath correlation shows that their DNBR outputs are similar.

Transient state

Application of Bernath, Mirshak, and Tong correlation for DNBR analysis and Power transient during the transient state operation with 2$ of reactivity insertion on a 100 watt operating reactor. This large amount of reactivity has been chosen to depict the pulsing operation of the TRIGA. Same operation at the BOC, 75 MWD, 150 MWD, 700 MWD, and 1000 MWD burned core has been conducted. Peak DNBR transition with time at the hottest point of the hottest rod and peak power of the core have been calculated. The findings are depicted in Figure 7 to Figure 16, where Figure 8-9, Figure 10-11, Figure 12-13, Figure 14-15, and Figure 16-17 represent the power and DNBR transient status of BOC, 75, 150, 750 and 1000 MWD respectively for 0.14 second

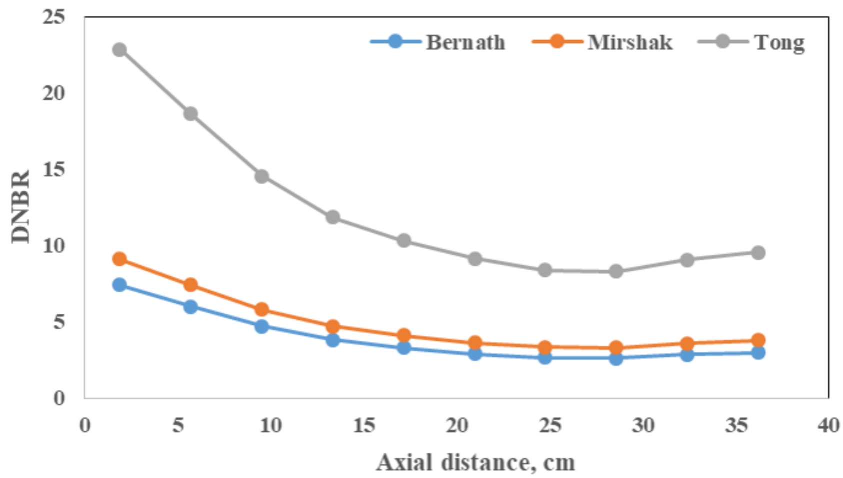

Fig. 6. DNBR distribution for Bernath, Mirshak and Tong correlation at 700 MWD burned core.

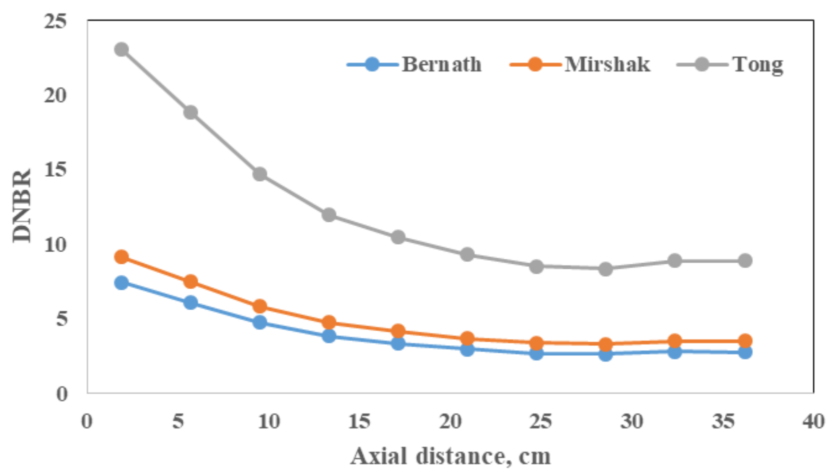

Fig. 7. DNBR distribution for Bernath, Mirshak and Tong correlation at 1000 MWD burned core.

from arbitrary zero sec. It is found from the simulation that there is no change in core power with time for any correlation and the peak power of 877 MW is consistent with SAR report of 852 MW. DNBR correlation functions out of neutronics & thermal-hydraulics iteration loops in PARET. The iteration determines the dynamics of power. Hence the power is the same for all, but the DNBR varies for others. It is apparent from the visual representations that across all burned core states, Tong's correlation yields the highest DNBR values, whereas Bernath's correlation yields the lowest. Furthermore, based on calculated data, it is observed that the DNBR is at its lowest during BOC for all correlations, whereas the highest burned core state exhibits the highest minimum DNBR, for transient operation. The minimum DNBR was determined to be 1.56, 1.96 and

5.08 for BOC, 1.57, 1.99 and 5.04 for the 75 MWD core, 1.59, 2.01 and 5.10 for the 150 MWD core, 1.61, 2.04 and 5.18 for the 700 MWD core, and 1.62, 2.05 and 5.22 for the 1000 MWD core for the Bernath, Mirshak, and Tong correlations, respectively. List of nomenclature and their abbreviation are given in Table 2.

It is evident from the simulation that for the transient state operation of the BOC and and burned cores, at the beginning the fuel exhibits a very large DNBR due to its lower operating power of 100 watts. This trend decreases until it reaches its minimum value when the core produces maximum power. It then ascends towards the end of the rod due to the imposition of negative reactivity inherently. Additionally, the comparison between the Misrack correlation and the Bernath correlation shows that their DNBR outputs are comparable. Bernath shows the lowest minimum DNBR here among all. Most importantly, the pressure of 0.160654 MPa of TRIGA fits in between the range of 0.10 to 20.60 MPa pressure for Bernath Correlation as suggested in Table 1. Hence Bernath Correlation is appropriate for using TRIGA among three Correlations, as suggested by GA.

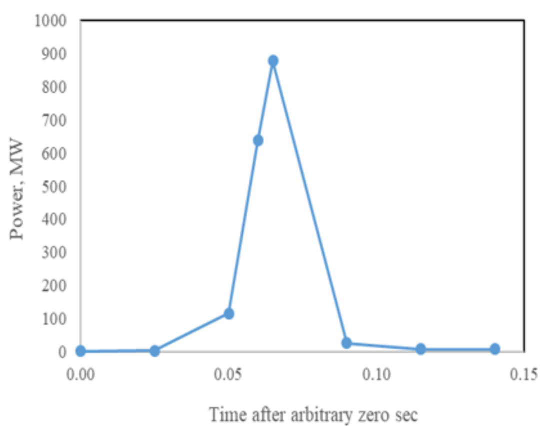

Fig. 8. Power transient at BOC core.

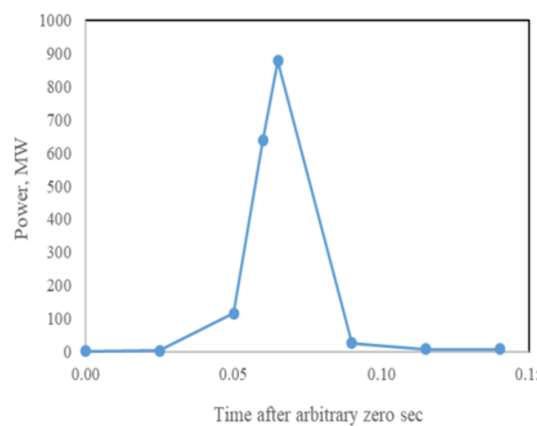

Fig. 9. DNBR transient at BOC core

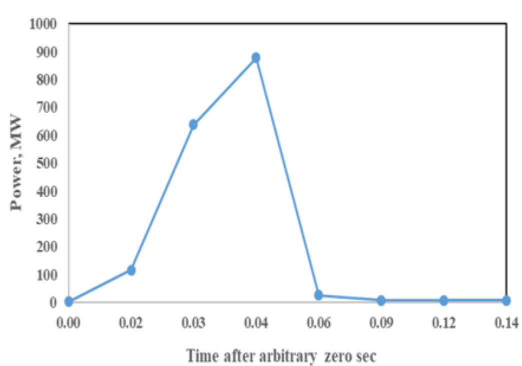

Fig. 10. Power transient at 75 MWD burned core.

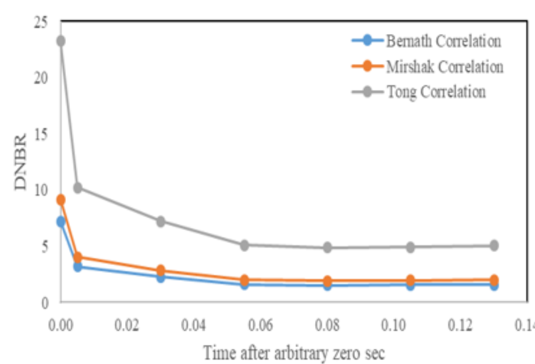

Fig. 11. DNBR transient at 75 MWD burned core.

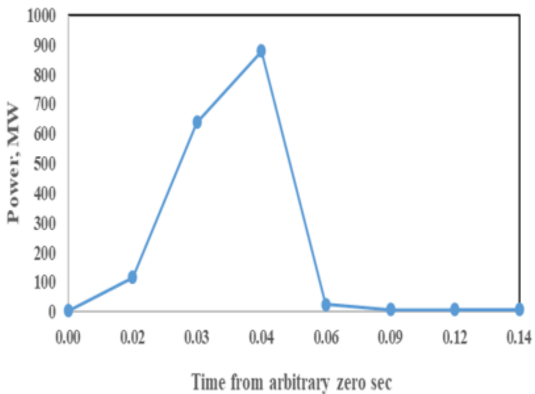

Fig. 12. Power transient at 150 MWD burned core.

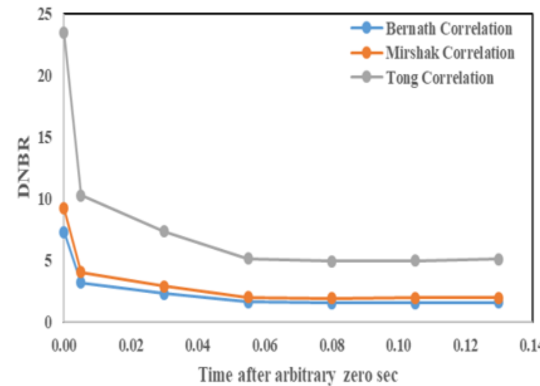

Fig. 13. DNBR transient at 150 MWD burned core.

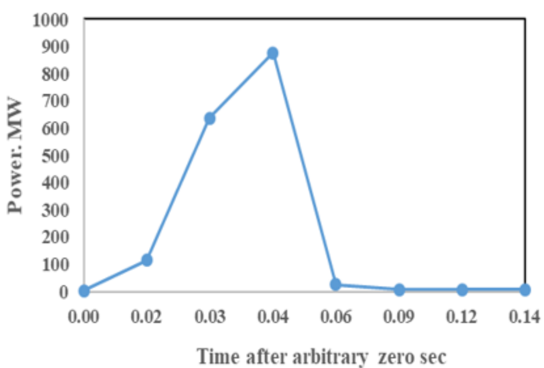

Fig. 14. Power transient at 700 MWD burned core.

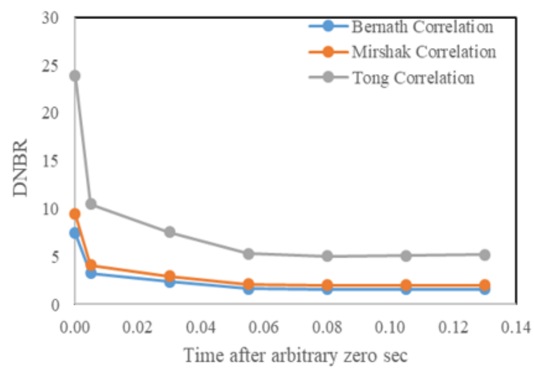

Fig. 15. DNBR transient at 700 MWD burned core.

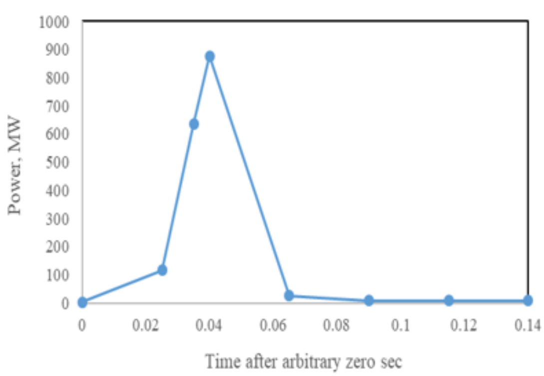

Fig. 16. Power transition at 1000 MWD burned core.

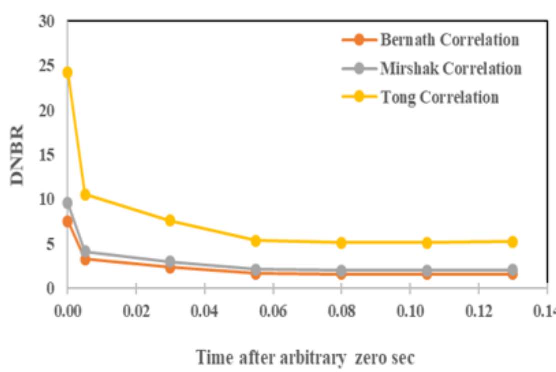

Fig. 17. DNBR transition at 1000 MWD burned core.

5. Conclusion

DNBR and power calculation under various operational modes and burnup conditions have been systematically calculated. The simulations indicate that the minimum DNBR escalates with increasing burnup, whether in steady or transient conditions. Notably, among the three correlations examined, the Bernath correlation emerges as the most conservative, whereas the Tong correlation exhibits a relatively lower degree of conservatism across all scenarios. Also, results derived from the Mirshak followed that of the Bernath correlation. Most importantly, Peak Power in the transient state aligns well with SAR, and the lowest minimum DNBR across all operational states, i.e. for the Bernath correlation, significantly surpasses the safety margins.

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