PRELIMINARY ANALYSIS OF INITIAL CRITICALITY FOR PELUIT-40 USING HTGR CODE PACKAGE (HCP)

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Abstract

The PeLUIt-40 (*Pembangkit Listrik dan Uap untuk Industri*) reactor, a pebble-bed High-Temperature Gas-Cooled Reactor (HTGR) with a power of 40 MWt designed for electricity and co-generation applications, holds promise as a solution for clean energy. A thorough examination of neutronic and thermal-hydraulic aspects is essential to assess the resilience of the PeLUIt-40 design and ensure compliance with safety standards. The study focuses on the neutronic aspects of the reactor, specifically examining initial criticality and temperature coefficients of reactivity using the HTGR Code Packages (HCP). The HCP is a sophisticated computational tool that facilitates detailed simulations of various reactor phenomena. Key modules used in the analysis include TRISHA for neutron spectrum calculations, TNT for burn-up calculations, and SHUFLE for fuel management. Initial criticality calculations for PeLUIt-40 were obtained with a pebble bed height of 117 cm, achieving the effective multiplication factor (k-eff) value of 1.001693983 under helium and air atmospheres at a core temperature of 20°C, without the insertion of control rods. These conditions simulate the reactor's start-up behavior, providing a critical benchmark for performance and safety validation. The study also investigates the temperature coefficient simulation, involving the calculation of the full core k-eff ($5m^3$) under a helium and air atmosphere with core temperatures of 20°C, 120°C, and 250°C, respectively, without any control rods being inserted. The HCP is being leveraged to optimize PeLUIt-40 operational dynamics, enhancing efficiency and sustainability. The research integrates various simulations enabled by the HCP to provide detailed insights into PeLUIt-40 behavior. Neutronics simulations offer an understanding of neutron flux distributions and criticality. The study will contribute to ongoing discussions on advanced reactor technologies and inform future HTGR design and operation advancements.

1. INTRODUCTION

The PeLUIt-40 is a concept reactor designed based on a high-temperature gas reactor (HTGR) type. The reactor is aimed at developing a nuclear power plant that can generate both electricity and co-generation applications. The reactor's thermal power is 40 MWth, which is significantly smaller than commercial nuclear reactors but still has the potential to make a significant impact on the energy landscape [1–2]. The PeLUIt-40 reactor's unique design utilizes helium gas as a coolant, offering the potential for efficient and sustainable energy generation. The current study seeks to provide a detailed analysis of the PeLUIt-40 reactor's design, performance, and safety features, emphasizing its innovative aspects and contributions to the field of nuclear energy.

Designed for both heat utilization and electricity generation, the PeLUIt-40 reactor incorporates a cogeneration system integrating the reactor with a steam generator. Extensive studies, simulations, and analyses have been conducted to optimize its performance and safety [3–5]. The foremost significance in developing new HTGR concepts is their passive safety features, which lead to a predictable high degree of safety. Consequently, the investigation of HTGR's safety and operational aspects and validation involving various coordinated research efforts are primarily required. The study provides an initial criticality simulation (identified as B1 case), which involves calculating the loading height (measured from the upper surface of the conus region) for achieving the first criticality: the effective multiplication factor (k-eff) = 1.0 under a helium and air atmosphere with a core temperature of 20 °C, without any control rods being inserted. Additionally, the temperature coefficient simulation (B2 case) calculates the k-eff of the full core ($5m^3$) under helium and air atmosphere with core temperature variations of 20°C, 120°C, and 250°C (identified as B21, B22, and B23 case, respectively), without any control rods being inserted.

2. CALCULATION METHODS

The HTR Code Package (HCP) is a comprehensive computer code system designed to simulate various aspects of HTGRs in an integrated manner. This powerful tool aids in the design, safety assessment, and operation of HTGRs, which utilize gas coolant to remove heat from the reactor core. The HCP is modular, consisting of several interworking modules that simulate different aspects of an HTGR as shown in Fig. 1. These modules include TRISHA for neutron spectrum calculations, which determine the reactor's power distribution and overall performance; a fluid dynamics module that simulates the flow of coolant gas and calculates heat transfer between the fuel and the coolant; SHUFLE for fuel management, which simulates the movement of fuel elements within the reactor core; STAR for dust production and transport, assessing potential environmental impacts; STACY for fission product release calculations, crucial for safety and environmental performance; and TNT for burn-up calculations, simulating fuel element depletion over time. Written in C++ and employing object-oriented programming, the HCP simplifies data management and exchange among modules, making it highly flexible and adaptable for various HTGR designs and applications. Its advanced capabilities make the HCP an essential tool for the future of nuclear power generation, offering valuable insights into the performance, safety, and environmental impacts of HTGRs [6–7]. The study utilized TRISHA, TNT, and SHUFLE modules of HCP to simulate the initial criticality for PeLUIt-40.

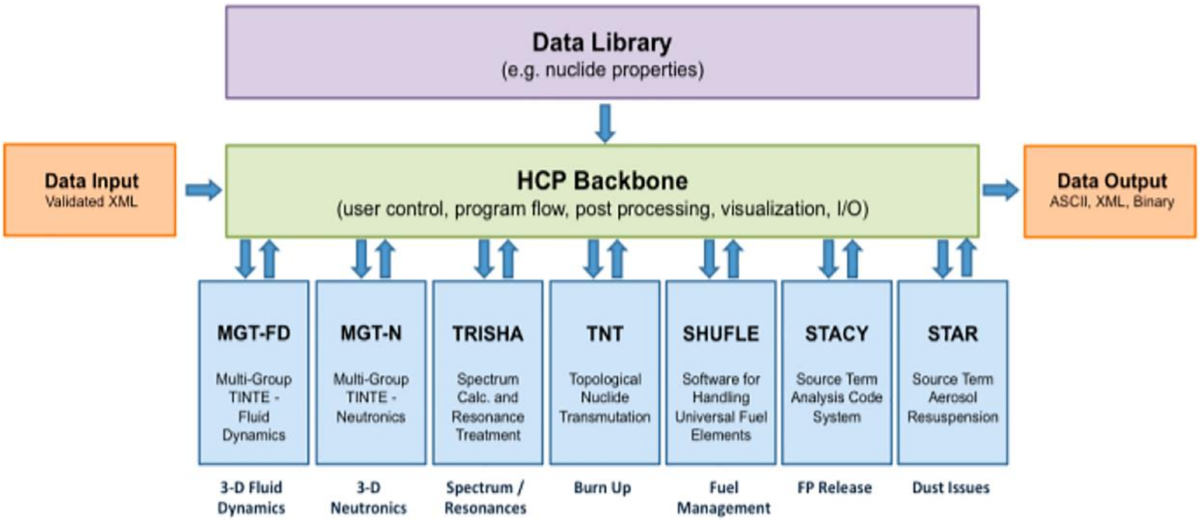

FIG. 1. Architecture of the HTR Code Package (HCP) [6–7].

3. REACTOR DESIGN

The PeLUIt-40 reactor is an HTGR utilizing pebble bed fuel elements that consist of ceramic-coated fuel particles. The reactor core has a diameter, a mean height, and a volume of 1.8 m, 1.97 m, and 5.0 m^3, respectively, and is surrounded by graphite reflectors. The reactor core is composed of 27,000 fuel elements in which the fuel elements use low-enriched uranium with a designed mean burnup of 80,000 MWd/t. Further, the pebble contains approximately 8335 coating particles dispersed in the fuel zone, has a heavy metal content of 5 g, and an enrichment of 17%.

In the general reactor design, graphite serves as the primary core structural material, primarily in the top, bottom, and side reflectors. A steel pressure vessel supports the metallic core vessel, which contains the ceramic core structures. The side reflector is 100 cm thick, with a layer of carbon bricks included. The primary coolant, helium, can flow upward from the annular area between the connecting vessel and the hot gas duct after entering the reactor pressure vessel thanks to the design of the cold helium channels in the side reflector. At the top of the reactor core, the helium flow reverses to enter the pebble bed, creating a downward flow pattern. The helium travels down the hot gas duct, into the hot gas chamber in the bottom reflector, and then onto the heat exchange components after being heated in the pebble bed. TRISO-coated fuel particles form a spherical fuel element with a diameter of 6 cm and fill the reactor core. The zone identification numbers for the two-dimensional reactor physics calculation model are shown in Fig. 2.

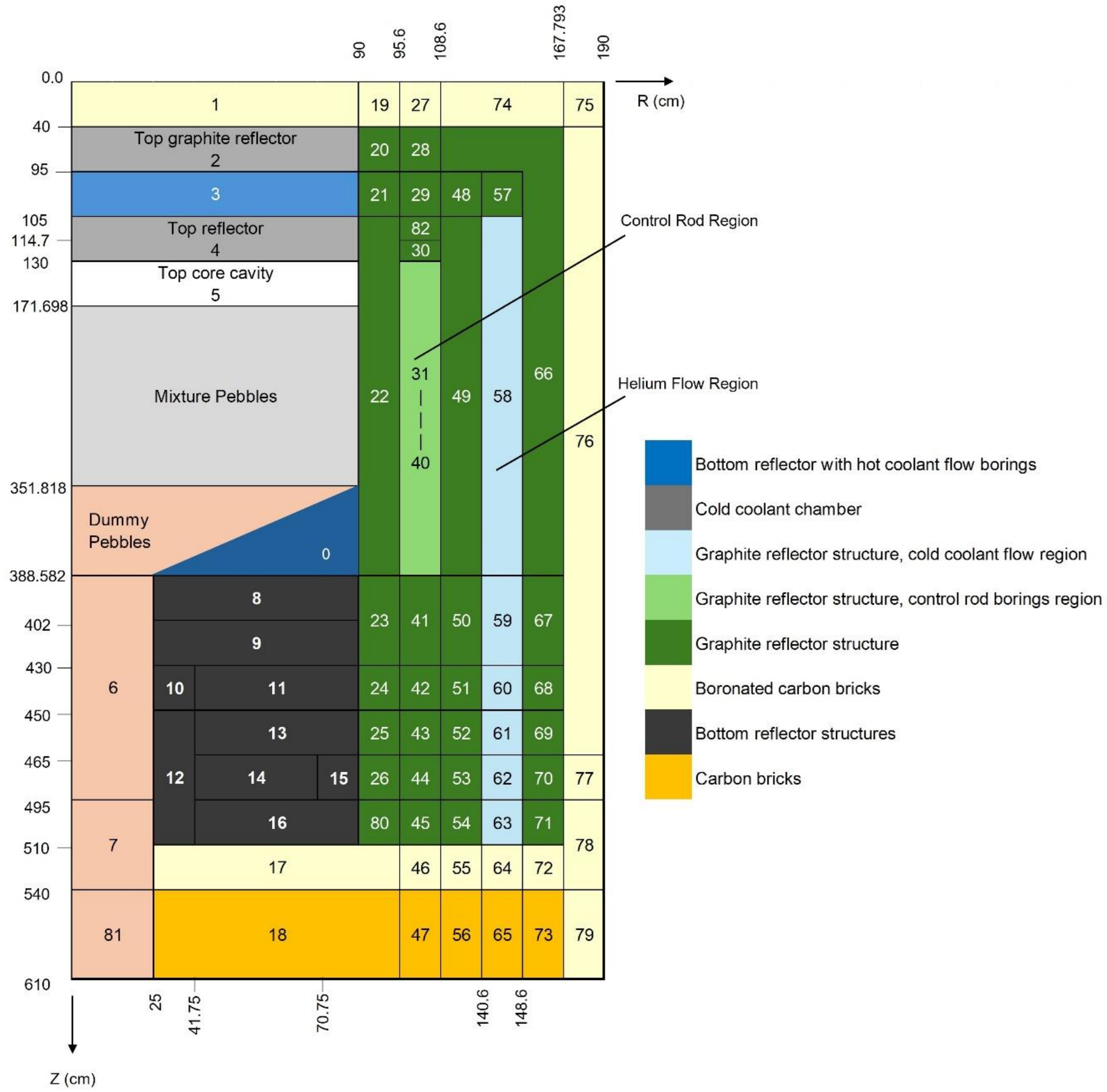

FIG. 2. Reactor pressure vessel model of PeLUIt-40 [6–7].

The extrapolation approach was employed for the first criticality experiment on the HTR-10, back in December 2000. With 16,890 pebbles put into the reactor core, criticality was reached, resulting in an estimated critical height of 123.06 cm from the top of the cone region. [7].

A validation calculation was conducted for the PeLUIt reactor with power variations starting from 10 – 40 MW. The validation involves calculating the amount of loading for the first criticality. The measured experimental critical height was 123.06 cm from the conus area's top. [7]. In order to obtain a rigorous comparison among different powers for 10 MW and 40 MW, the critical height is fixed for every code model, and the k-effectives are then compared with the reference.

To ascertain the quantity of loading (provided in loading height, starting from the upper surface of the conus region) for the first criticality, initial criticality in pebble height variations of PeLUIt-40 is conducted. The calculation of the k-eff for different core loading heights was performed using the HCP for PeLUIt-40 geometry with a power of 40 MW.

Two requirements concerning the initial core loading and the initial criticality calculation were changed from the benchmark definition after the core physics benchmark problems were defined and prior to the initial core loading. Firstly, the benchmark's definition of dummy pebbles was not followed by those meant for the first core loading. Instead, graphite pebbles of a different type were prepared. The variations in the prepared graphite pebbles compared to the defined ones pertain to two aspects of physics calculation: density and impurity. The density of the prepared graphite pebbles is 1.84 g/cm3, contrasting with the defined value of 1.73 g/cm^3. The manufactured dummy pebbles have impurities with a boron equivalent of 0.125 ppm, which is different from the specified value of 1.3 ppm. Second, contrary to the benchmark specification [8], ambient air was used for the first criticality calculation rather than helium. Table 1 summarizes the deviations mentioned above.

TABLE 1. SUMMARY OF THE SCENARIO INVOLVED IN THE STUDY

B1 Case	**Original**	**Deviated**
Density of dummy pebbles	1.73 g/cm^3	1.84 g/cm^3
Boron equivalent of impurities in dummy pebble	1.3 ppm	0.125 ppm
Core atmosphere at initial criticality	Helium	Air

Additionally, the temperature coefficient simulation (B2 case) calculates the k-eff of the full core (5m^3) under helium and air atmosphere with core temperatures of 20°C (B21), 120°C (B22), and 250°C (B23), respectively, without any control rods being inserted for the original and deviated scenario.

4. RESULTS AND DISCUSSION

4.1. Validation of the Simulation

The power modified starting from 10 MW is intended to validate the input file against the reference that uses HTR-10. The results indicate that the k-eff for all power levels is approximately 1.014 for the original case, consistent with the reference [6], and 1.024 for the deviated case. Table 2 illustrates the k-eff for varying power levels (10 MW, 20 MW, 30 MW, and 40 MW) under both original and deviated conditions. For the original condition, the k-eff values remain relatively consistent across the power levels, with only minor variations. These values indicate a stable reactor state with a slight decrease as power increases, suggesting a slight reactivity drop due to increased fuel consumption or temperature effects. In the deviated condition, the k-eff values are higher for all power levels than in the original condition, indicating a deviation that likely introduces additional reactivity. These findings align with the understanding that operational deviations can significantly impact reactor reactivity and stability. The slight decrease in k-eff with increasing power in both conditions suggests a predictable behavior.

The k-eff value is lower when air is used as a coolant compared to that of helium. This phenomenon occurs since neutron absorption in air is relatively high compared to helium, and neutron moderation in helium is slightly higher than in air [9]. However, in this case, there are differences in the boron concentration parameters that employed in the study. The boron concentration in the original case was about 10 times greater. As a result, the condition lowers the k-eff value of the helium coolant due to neutron capture from boron.

TABLE 2. K-EFF IN POWER VARIATIONS FOR ORIGINAL AND DEVIATED B1 CASE

Power (MW)	**k-eff**	
	Original	**Deviated**
10	1.01438534137	1.02426113628
20	1.01438534120	1.02426113724
30	1.01438534111	1.02426113749
40	1.01438534083	1.02426113761

Fig. 3 and 4 show the axial fast and thermal neutron flux profiles, respectively, at several power levels for both original and deviated scenarios. Deviated cases exhibited relatively lower axial fast neutron flux profiles compared to those of original cases. Meanwhile, there are no significant differences between the original and deviated scenarios for the axial thermal neutron flux profile.

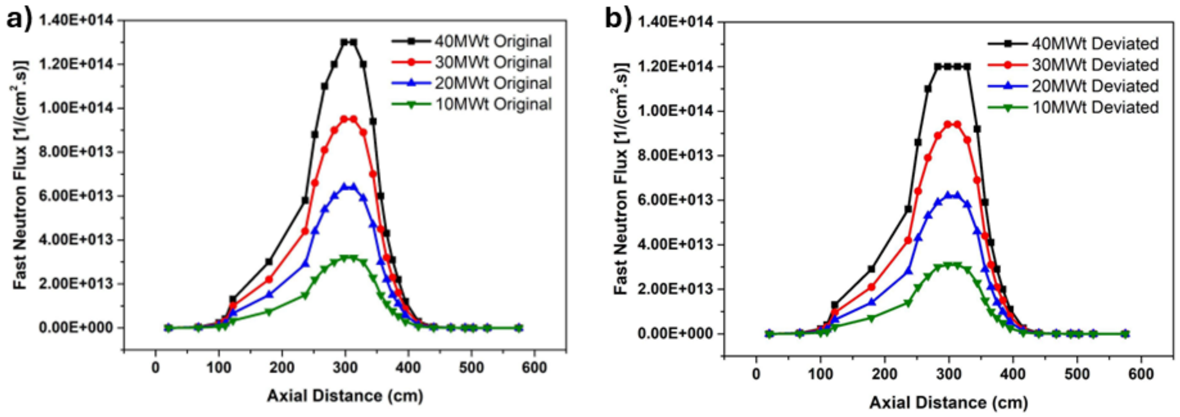

FIG. 3. Axial fast neutron flux profile (a) original and (b) deviated scheme

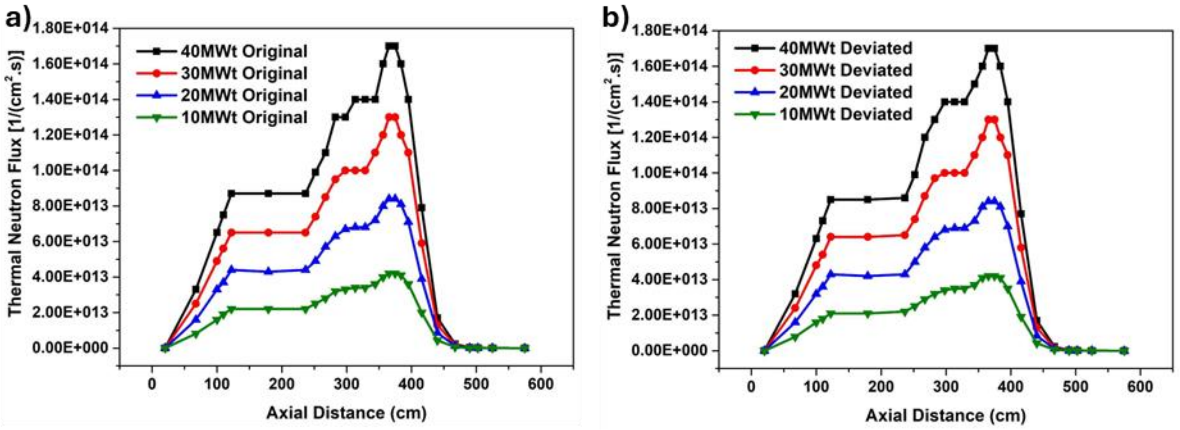

FIG. 4. Axial thermal neutron flux profile (a) original and (b) deviated scheme

4.2. Pebble Height Determination for Initial Criticality of PeLUIt-40

Calculation of the k-eff for different core loading heights was performed using the HCP code for PeLUIt-40 geometry with a power of 40 MW. The calculation is aimed to find the loading amount (provided in loading height) for the first criticality, k-eff = 1.0, under a helium atmosphere and core temperature of 20°C, starting from the upper surface of the conus region or 90 to 180 cm, with no control rod inserted. The results of the calculation are presented in Table 3, which shows the k-eff values for different core loading heights. The data shown in Table 3 indicates that the k-eff value increases with increasing core loading height, but the increase is not linear. Further, based on the data in Table 2, achieving an effective multiplication factor (k-eff) of 1 for PeLUIt-40 under 20ºC helium should be possible with a loading height of 117 cm with the amount of pebble fuel ball and graphite moderator balls around 9162 dan 6911, respectively, resulting in a k-eff of 1.001693983.

Fig. 5 shows the change in neutron flux for each variation of core loading height. The distribution of neutron flux for each core loading height indicates that both fast and thermal neutron fluxes generally decrease as the core loading height increases. This decrease in neutron flux is a critical parameter in nuclear reactor design because it influences the reactor power distribution and overall performance.

The neutron flux distribution is a key parameter in determining the reactor power distribution and overall performance. The neutron flux is influenced by various factors such as the core loading height, fuel composition, and reactor design. In the context of pebble-bed reactors, the neutron flux distribution is particularly important because it affects the burnup profile of the pebbles and the overall reactor performance.

The decrease in neutron flux with increasing core loading height is a common trend observed in nuclear reactors. This decrease is primarily due to the increased distance between the core and the reactor vessel, which leads to a reduction in neutron moderation and absorption. The neutron flux is highest near the core center and decreases as the distance from the core center increases. In addition, the decrease in neutron flux with increasing fuel height, despite the presence of more fissile material, can be influenced by several factors such as neutron leakage and changes in neutron moderation efficiency due to the reactor geometry. As the fuel height increases, there might be more opportunities for neutrons to escape, especially in taller, narrow reactors, and the moderation might not be as effective, leading to a reduced reaction rate.

Understanding the neutron flux distribution is crucial for optimizing reactor design and operation. Analyzing the neutron flux distribution allows for identifying the optimal core loading height and fuel composition to achieve the desired reactor performance. Additionally, the neutron flux distribution can be used to predict reactor power distribution and identify potential issues related to neutron flux variations.

TABLE 3. PEBBLE HEIGHT VARIATIONS FOR PELUIT-40 FOR INITIAL CRITICALITY

Pebble Height (cm)	Number of fuel balls	Number of graphite moderator balls	k-eff
90	7047	5316	0.907602
100	7830	5907	0.946276
110	8613	6498	0.980246
115	9005	6793	0.995747
117	9162	6911	1.001694
120	9396	7089	1.010363
123	9631	7266	1.014385
130	10179	7679	1.034291
140	10963	8270	1.060151
150	11746	8861	1.083375
160	12529	9451	1.10434
170	13312	10042	1.123369
180	14095	10633	1.140748

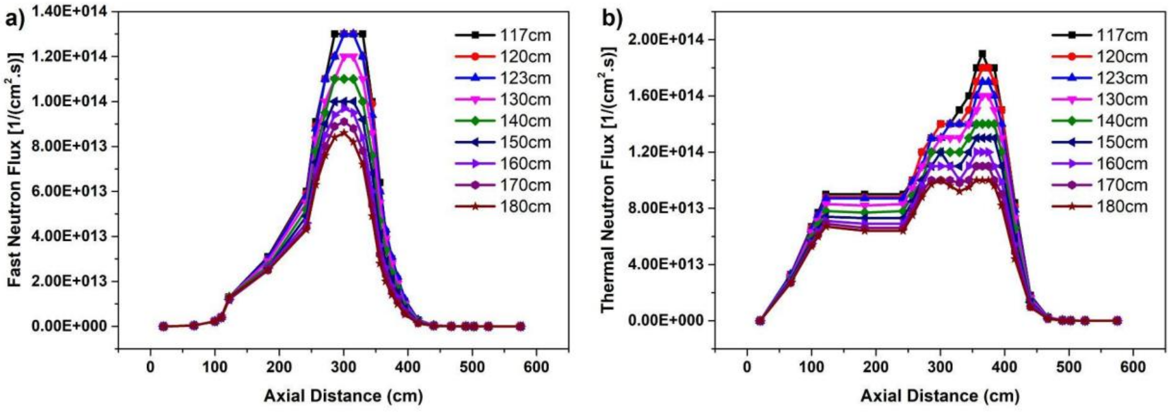

FIG. 5. Axial (a) fast and (b) thermal neutron flux profile with the variation of pebble heights.

4.3. Calculation Analysis for B1 Case with Determined Pebble Height

The calculations on B1 case employ a pebble height of 117 cm for the first criticality k-eff = 1.0 under the atmosphere of helium and air, with a core temperature of 20°C, without the insertion of control rods, for the original and deviated scenario. Table 4 provides critical data comparing the original and deviated scenarios for the benchmark problem B1 in a nuclear reactor setting. Specifically, it details the k-eff and the maximum neutron flux for both fast and thermal neutrons. The k-eff value, which indicates the reactor's ability to sustain a nuclear chain reaction, shows a slight increase from 1.001693983 in the original scenario to 1.011804662 in the deviated scenario. This increase suggests a marginally higher reactivity in the deviated scenario. Additionally, the maximum fast neutron flux decreases from 1.4E+14 [1/(cm²·s)] in the original scenario to 1.3E+14 [1/(cm²·s)] in the deviated scenario, indicating a reduction in the intensity of fast neutrons. Interestingly, the maximum thermal neutron flux remains constant at 1.9E+14 [1/(cm²·s)] for both scenarios. This consistency suggests that the changes leading to the deviated scenario predominantly affect the fast neutron population while leaving the thermal neutron flux unchanged.

TABLE 4. K-EFF VALUES AND MAXIMUM FAST AND THERMAL NEUTRON FLUX OF BENCHMARK PROBLEM B1 WITH ORIGINAL AND DEVIATED SCENARIOS

Scenario	k-eff	Max. Fast Neutron Flux [1/(cm^2.s)]	Max. Thermal Neutron Flux [1/(cm^2.s)]
B1 Original	1.001693983	1.4E+14	1.9E+14
B1 Deviated	1.011804662	1.3E+14	1.9E+14

Figure 6 illustrates the axial profiles of fast and thermal neutron fluxes for benchmark problem B1, comparing the original and deviated scenarios. In Fig. 6a, the fast neutron flux peaks at around 300 cm axial distance for both scenarios, with the original scenario showing a slightly higher peak flux, consistent with the table's data indicating a higher maximum fast neutron flux in the original scenario. The flux increases rapidly to this peak and then decreases sharply. Fig. 6b shows the thermal neutron flux peaks around the same axial distance. However, the maximum flux values are nearly identical for both scenarios, which aligns with the table's data showing constant maximum thermal neutron flux. This suggests that while the deviation affects the fast neutron population, the thermal neutron population remains relatively unchanged along the reactor's axial length.

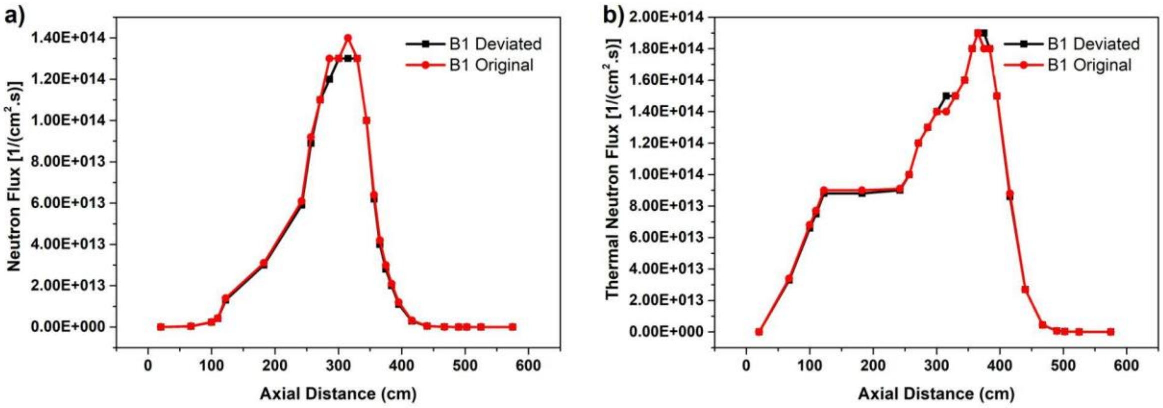

FIG. 6. Axial (a) fast and (b) thermal neutron flux profile for benchmark problem B1 with the variation of scenarios (original and deviated).

4.4. Calculation Analysis with the Variation of Temperature Levels (B2 Case)

The calculation of temperature coefficient (B2 case) simulation involves the calculation of the k-eff of the full core (5m³) under helium and air atmosphere with core temperatures as follows: 20°C (B21 case), 120°C (B22) and 250°C (B23) respectively, without the insertion of control rods. Table 5 shows k-eff variations across different temperatures and scenarios. For B21 at 20°C, the k-eff slightly increases from 1.148216985 in the original scenario to 1.156694957 in the deviated scenario. This pattern of a slight increase in k-eff from the original to the deviated scenario is consistent across all temperature settings: 1.133615587 to 1.141703808 at 120°C (B22) and 1.116852855 to 1.124676976 at 250°C (B23). These increases suggest a marginally higher reactivity in the deviated scenarios across different temperatures. The maximum fast neutron flux shows minor variations between the original and deviated scenarios at each temperature. The thermal neutron flux, however, demonstrates a slight increase in the deviated scenarios. These patterns suggest that while the fast neutron flux generally decreases slightly in deviated scenarios, the thermal neutron flux tends to increase, indicating a shift in neutron population dynamics with temperature changes in the reactor core.

Fig. 7 shows the axial fast and thermal neutron flux profile for benchmark problem B2 with the original and deviated scenarios. The presence of boron impurities in the coolant influences the k-eff and reactor core neutron flux values. The large absorption cross-section value in the thermal neutron spectrum has a significant effect on the thermal neutron flux. Therefore, the thermal neutron flux in the original conditions with higher boron impurities tends to be lower due to boron absorption (Fig. 7b). The increase in boron concentration will not be directly proportional to neutron flux, since boron plays a role as a thermal neutron absorber.

TABLE 5. K-EFF VALUES AND MAXIMUM FAST AND THERMAL NEUTRON FLUX OF BENCHMARK PROBLEM B2 WITH ORIGINAL AND DEVIATED SCENARIOS

Scenario	**Temperature (°C)**	**k-eff**	**Max. Fast Neutron Flux [1/(cm^2.s)]**	**Max. Thermal Neutron Flux [1/(cm^2.s)]**
B21 Original	20	1.148216985	8.50E+13	9.90E+13
B21 Deviated		1.156694957	8.30E+13	1.00E+14
B22 Original	120	1.133615587	8.60E+13	9.80E+13
B22 Deviated		1.141703808	8.40E+13	1.00E+14
B23 Original	250	1.116852855	8.70E+13	9.30E+13
B23 Deviated		1.124676976	8.60E+13	9.50E+13

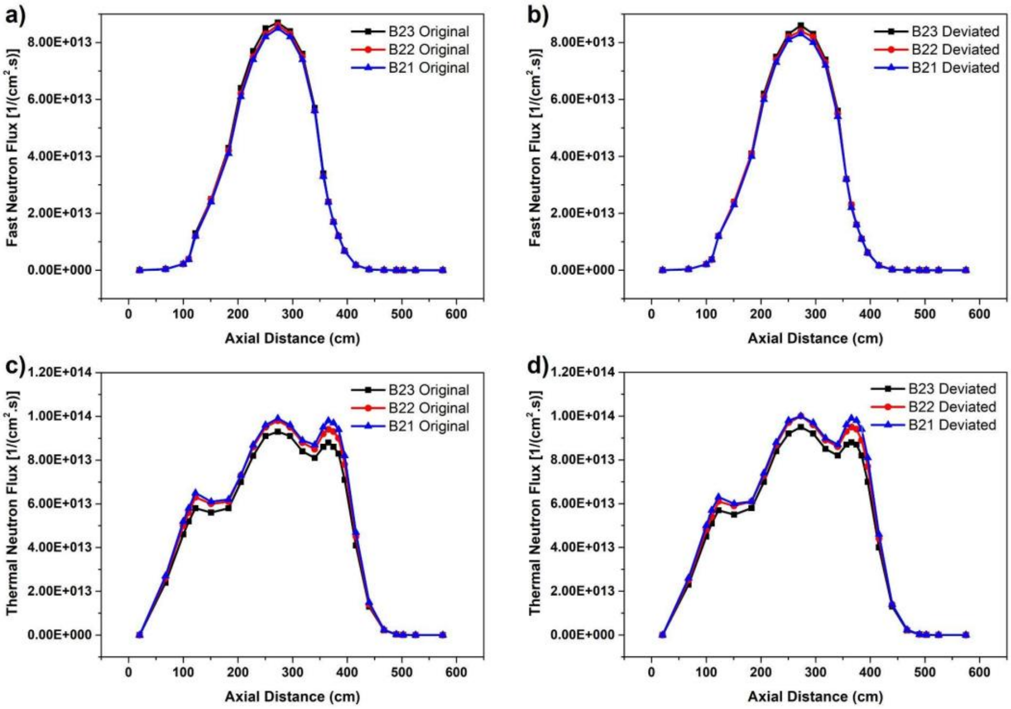

FIG. 7. Axial (a, b) fast and (c, d) thermal neutron flux profile for benchmark problem B2 with the variation of scenarios: (a,c) original and (b,d) deviated.

5. CONCLUSIONS

The analysis of initial criticality for PeLUIt-40 utilizing the HTGR Code Package (HCP) has provided valuable insights into the reactor's behavior under various conditions. Through simulations and calculations, critical loading heights and effective multiplication factors (k-eff) were determined, as crucial parameters in assessing the reactor's performance and safety. Initial criticality calculations for PeLUIt-40 were obtained with a pebble bed height of 117 cm, achieving the k-eff value of 1.001693983 under helium atmospheres at a core temperature of 20°C, without the insertion of control rods. In the deviated case, the k-eff value is slightly higher than the original case, even though the neutron capture with air cooling is greater than helium, but the presence of boron impurities in the coolant has a significant influence on the calculation results. This is caused by the cross-section of boron absorption which is quite high.

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