# Core Geometry and Reflector Optimization of 10 MWt Micro-PeLUIt Pebble Bed HTGR

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**Abstract**

The microreactor technology can address the energy requirements of Indonesia's less developed, remote, and frontier regions. Previous studies focused on optimizing the size of nuclear reactor cores for remote areas in Indonesia by maintaining the height-to-diameter ratio at 1.1, similar to the HTR-10 model. The findings suggested that the optimized reactor volume is 4.4 m³, with dimensions of 172 cm in diameter and 189.2 cm in height, aiming for a minimum burnup of 60 MWD/kg-HM. The study compares the neutronic and thermal-hydraulic performance of 5 m³ and 4.4 m³ reactor volumes. It also analyzes the impact of reflector size modifications on the new geometry with variations in size from 70-130 cm. The research utilized the Pebble Bed Reactor Neutron Diffusion (PEBBED) Code, a computational tool for analyzing High-Temperature Gas-cooled Reactor (HTGR) physics, specifically Pebble Bed Reactors. It examined neutronic parameters such as total fuel flow, burnup, power peaking factors, and power density distribution. Furthermore, the study examines thermal-hydraulic and safety parameters, including steady-state and transient fuel temperatures, focusing on scenarios involving Depressurized Loss of Forced Cooling (DLOFC) accidents. The comparison results show that the reactor with a volume of 4.4 m³ exhibits comparable neutronic and thermal-hydraulic performance to that of the 5 m³ volume. The results also indicate that reducing the reflector size to 90 cm still meets the burnup target of 60 MWD/kg-HM.

## INTRODUCTION

It has undergone significant advancements since the 1940s, when the High-Temperature Gas-cooled Reactor (HTGR) concept was introduced. Initial research focused on developing helium-cooled reactors operating at high temperatures using spherical graphite fuel. In 1962, the world's first HTGR, Dragon, with a capacity of 20 MWt, was constructed through collaboration between European and British communities. The United States pioneered commercial HTGR operations with the Peach Bottom Atomic Power Station, which served as a prototype for further HTGR development. Germany developed the AVR (Arbeitsgemeinschaft Versuchsreaktor) in 1967, achieving operational temperatures up to 950°C. By 1983, Germany launched THTR-300, the first commercial HTGR with a power capacity of 300 MW and operating temperatures also reaching 950°C [1]. China joined these developments by introducing the HTR-10 in 2000 and constructing the HTR-PM in 2012 [1]. The HTR-10 demonstrated superior thermal efficiency over Pressurized Water Reactors (PWR) and Sodium-cooled Fast Reactors (SFR), achieving an efficiency rate of 50%. The high exit temperatures of the coolant allowed HTGRs to be utilized in various industrial applications such as efficient power generation, hydrogen production, and other industrial heat uses [2]. The HTR-PM represents an advancement from the HTR-10, aiming to produce inherently safe, economical modular reactors with high potential in energy efficiency and hydrogen production [3], [4]. This project has facilitated experience integration and laid a crucial foundation for developing the HTR-PM600 reactor in China [5].

Indonesia has initiated the introduction of nuclear technology by developing a HTGR type called PeLUIt (*Pembangkit Listrik dan Uap untuk Industri*). PeLUIt continues the development of the Experimental Power Reactor (RDE) as a non-commercial prototype reactor with a 10 MWt capacity [6]. Designed in 2014, the RDE is engineered for high safety and efficiency in producing electricity and heat. This reactor has passive safety features that ensure the core's safety, even in accident conditions such as loss of coolant [7]. The program aims to enhance energy security and national sovereignty by reducing dependence on fossil fuels and increasing the use of clean energy as a medium-term strategy. In the long term, this initiative is expected to enhance Indonesia's competitiveness on the global stage and strengthen its national industrial capacity.

Indonesia has many large islands that require electricity, yet integrating a centralized electrical grid is impractical. Additionally, remote islands in Indonesia face transportation and electricity management challenges, which incur high costs [8]. Therefore, the concept of downsizing HTGR (High-Temperature Gas-Cooled Reactor) is well-suited for application in Indonesia.

Previous studies indicate that reducing the reactor's volume while maintaining the constant height-to-diameter (H/D) ratio did not enhance performance relative to the PeLUIt-10 design [9]. However, it was shown that a smaller core volume of 4.4 m³ could still achieve the minimum burnup target of 60 MWD/kg-HM, with maximum fuel temperatures remaining within safe limits. This research will optimize the reactor volume of 4.4 m³, comparing its performance in greater detail against the initial design volume of 5 m³ for the PeLUIt-10. The default side reflector size for the PeLUIt-10 is 100 cm. This size is further optimized to determine the smallest reflector size that still meets the 60 MWD/kg-HM burnup target. This study analyzes the neutronic and thermal-hydraulic aspects of various reflector size variations.

## Methodology

### Reactor Models

#### General Model

PeLUIt is a pebble bed HTGR (High-Temperature Gas-cooled Reactor) that utilizes helium as a coolant and graphite as a moderator. The reactor operates under a forced circulation primary system with primary system pressure at 3 MPa and secondary system pressure at 6 MPa. PeLUIt functions within a thermal power range of 10 MWt to 40 MWt. It contains 27,000 pebble beds arranged randomly within a core with a nominal volume of 5 m³, with specifications of 197 cm in height and 180 cm in diameter. There is a void of about 40 cm at the top and a packing fraction of 0.61. The helium inlet temperature is around 250°C, and the outlet temperature is designed to reach 750°C. The fuel elements contain 17% enriched uranium, designed to meet a burnup target of 80 GWd/MTU. PeLUIt employs a once-through-then-out (OTTO) refuelling cycle [9].

Diagram of a machine with text and words

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*FIG. 1. Vertical cross-section of PeLUIt.*

Figure 1 shows the vertical cross-section of PeLUIt, while Table 1 presents the geometry parameters of PeLUIt with different volumes. In this phase of the study, precise design with neutronic and thermal-hydraulic analysis of both volumes is required to ensure that the smaller-sized PeLUIt has good neutronic conditions, meets burnup targets, and satisfies the inherent safety requirements characteristic of HTGR. This phase is the first step in the further downsizing process of the reactor with a smaller burnup target.

TABLE 1. GEOMETRY PARAMETERS

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Unit | PeLUIt-10 (5 m3) | PeLUIt-10 (4.4 m3) |
| Thermal power | MWt | 10 | 10 |
| Average power density | W/cm3 | 2 | 2.27 |
| Reactor core diameter | cm | 180 | 172 |
| Average core height | cm | 197 | 189 |
| Burnup Target | MWd/tHM | 80 000 | 60 000 |
| Side Reflector | cm | 100 | optimized |

#### Reflector

The top, side, and bottom graphite reflectors surround the reactor core, working to maintain thermal stability and reactor safety, as shown in Figure 1. Each layer of the side reflector consists of 20 segmental graphite bricks that have ten channels for control rods, three experimental channels, seven absorber ball channels, and twenty cold helium channels, which help regulate the graphite temperature and prevent the fuel element temperature from rising during an accident. The bottom reflector structure is designed in a conical shape to facilitate the free movement of fuel elements by gravity. The inner surface of the side reflector has indentations to ensure smooth pebble flow. Boronated carbon bricks surround the graphite reflector, serving as thermal insulation and neutron shielding, as well as ensuring the stability and integrity of the core structure. The entire reflector system is connected with dowels and keys made of graphite material to prevent helium gas leakage and support the reactor's internal structure [10], [11].

The size of the reflector at a volume of 4.4 m³ is varied between 70 and 130 cm to observe the neutronic and thermal-hydraulic performance of the reactor when the reflector size is changed. Additionally, this analysis will determine the optimal smallest reflector size that meets the burnup target and safety requirements.

### Calculation and simulation

The research employs the PEBBED (Pebble Bed Reactor Neutron Diffusion Code) to perform neutronic calculations and predict peak fuel temperatures in High-Temperature Gas-Cooled Reactors (HTGRs), particularly Pebble Bed Reactors (PBRs). PEBBED is used to model complex fluid dynamics, heat transfer processes, and the movement of pebbles within the reactor core. It uses a finite-difference algorithm to solve the neutron diffusion equation in multiple dimensions. The accuracy of these simulations hinges on local material temperatures affecting neutron absorption and scattering cross-sections [12].

PEBBED incorporates a convection module for thermal power distribution, which, while efficient, simplifies the radial coolant flow. Enhanced accuracy is achieved by coupling PEBBED with THERMIX-KONVEK for two-dimensional heat transfer and gas dynamics equations. Cross-section generation is managed by COMBINE-7, using ENDF/B-VII data libraries processed with NJOY9. This method addresses fuel double heterogeneity with specific Dancoff factors [13], [14].

PEBBED requires dividing the reactor core into spectral zones for neutronic modeling, with refined accuracy through collaborative efforts. The mesh size for diffusion and depletion equations ranges from 5 to 10 cm. The PEBBED-THERMIX code suite is utilized for steady-state and transient calculations, including Depressurized Loss of Forced Cooling (DLOFC) scenarios, fuel management, and uncertainty analysis. Heat transfer modules in PEBBED compute fuel temperature distribution and peak temperatures during depressurized conduction cooldown (DCC).

The DLOFC scenarios are validated with experimental data, such as those from the Pebble Bed Modular Reactor (PBMR) 400MW. Maintaining fuel temperatures below specified limits during normal and severe conditions is crucial, with heat removal achieved by primary coolant during normal operations and by conduction and radiation during extreme events.

## Result and discussion

### Neutronic and Thermal Hydraulic Comparison of Reactor Volumes for PeLUIt-10

#### General Neutronic

The comparison of neutronic performance for the two-volume types, 5 m³ and 4.4 m³, is presented in Table 2. Several parameters analyzed include fuel flow rate measured in the number of pebble beds inserted per day, helium flow rate, maximum fuel temperature, power density, maximum power density, maximum pebble temperature in steady-state conditions, and power peaking factor, which is the ratio of maximum power density to average power density. Maximum burnup in each channel and average maximum burnup are shown in Table 3.

Based on Table 2, there is an increase in the number of pebbles processed per day as the core volume decreases from 5 m³ to 4.4 m³. In the design with a volume of 5 m³, the number of pebbles processed per day is 25, whereas, in the design with a volume of 4.4 m³, this number increases to 30 pebbles per day. This indicates that the number of pebbles required to maintain reactor reactivity increases with a reduction in volume. A larger volume allows for higher utilization of fissile fuel and increased burnup. Consequently, the reactor core can be maintained in a critical state for longer, thereby extending the fuel discharge time. As a result, the fuel pebble flow rate can be reduced.

The table observed an increase in peak fuel temperature when the reactor volume decreased. This higher temperature can be explained by increased power density and the surface area-to-volume ratio in smaller volumes. In the smaller volume reactor (4.4 m³), the power density is higher (2.27 W/cc) compared to the larger volume reactor (2 W/cc), which means more energy is produced per unit volume, leading to greater localized heating. Additionally, smaller reactors have a higher surface area-to-volume ratio, which can affect heat removal efficiency. If heat removal mechanisms, such as coolant flow, are not proportionally adjusted with the volume reduction, the system may struggle to dissipate heat effectively, resulting in higher internal temperatures. In smaller reactors, there are shorter paths for heat conduction from the fuel, which increases peak temperature. However, the observed temperature difference is insignificant and remains below safety limits.

TABLE 2. NEUTRONIC COMPARISON OF DIFFERENT REACTOR VOLUME

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Design** | **Pebble/day** | **He flowrate** | **Peak Fuel Temp (C)** | **Power Density (w/cc)** | **Max. Power Density [W/cc]** | **Max. Pebble Temp. Steady-State [℃]** | **Peak to avg. power density** |
| PeLUIt-10 (5 m3) | 25 | 4.3 | 1014.5 | 2 | 2.9 | 978 | 1.45 |
| PeLUIt-10 (4.4 m3) | 30 | 4.3 | 1031.9 | 2.27 | 3.26 | 986.5 | 1.44 |

Table 3 shows the maximum burnup values with a consistent trend for reactor volumes of 5 m³ and 4.4 m³. The average burnup for the larger volume reactor is significantly higher at 78.828 MWD/kgHM compared to 64.097 MWD/kgHM for the smaller reactor. Burnup in the 5 m³ reactor ranges from 70.242 to 88.598 MWD/kgHM, while in the 4.4 m³ reactor, it ranges from 59.015 to 73.522 MWD/kgHM. This indicates that the larger volume reactor achieves higher fuel utilization, leading to greater energy extraction from the driver pebbles.

The primary factor contributing to the difference in maximum burnup values is the higher power density in the smaller reactor, which correlates with higher fuel temperatures and potentially less efficient fuel utilization. Additionally, the larger reactor's design may facilitate a more uniform neutron flux distribution and more effective heat removal, enhancing fuel burnup efficiency. The variation in burnup across different flow channels also suggests differences in local flow dynamics and neutron flux, affecting fuel exposure and utilization.

TABLE 3 MAXIMUM BURNUP OF DRIVER PEBBLES BY FLOW CHANNEL

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Design** | **Burnup (MWD/kghm) of Driver pebbles by Flow Channel** | | | | | | |
| **Average** | **Channel 1** | **Channel 2** | **Channel 3** | **Channel 4** | **Channel 5** | **Channel 6** |
| PeLUIt-10 (5 m3) | 78.828 | 88.598 | 85.615 | 79.903 | 73.624 | 70.242 | 74.985 |
| PeLUIt-10 (4.4 m3) | 64.097 | 73.522 | 70.173 | 64.282 | 60.284 | 59.015 | 63.595 |

#### Power Density

The power density distribution and maximum fuel temperature profiles for two reactor designs, PeLUIt-10, with volumes of 4.4 m³ and 5 m³, are illustrated in Figure 2. The power density in the smaller volume reactor (4.4 m³) exhibits higher peak values, reaching up to 3.23 W/cc, as depicted by the red regions in the left plot. This indicates a more concentrated energy production per unit volume. Conversely, the larger volume reactor (5 m³) has a lower maximum power density of 2.88 W/cc, with lower peak values and a broader spread of intermediate power densities, as indicated by the gradient from red to blue in the right plot. This suggests the larger reactor design facilitates a more even power distribution, potentially reducing localized hotspots and improving overall thermal management.

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*FIG. 2. Comparison of Power Density Distribution.*

#### Maximum Fuel Temperature

As shown in Figure 3, the maximum fuel temperature profiles show that the smaller volume reactor (4.4 m³) exhibits higher peak temperatures, reaching up to 1032°C. This is consistent with the higher power density observed in the smaller reactor, where the energy production per unit volume is more concentrated, leading to elevated temperatures. The temperature distribution in the 4.4 m³ reactor shows a steeper gradient, with the highest temperatures concentrated in the bottom and center regions, gradually decreasing towards the periphery and top.

In contrast, the larger volume reactor (5 m³) shows a lower peak temperature of 1016°C, which aligns with its lower maximum power density of 2.88 W/cc. The temperature distribution in the 5 m³ reactor is more uniform, indicating better thermal management and fewer localized hotspots. The broader spread of intermediate power densities in the larger reactor facilitates this even temperature distribution, reducing the risk of thermal stress and potentially enhancing the reactor's safety and efficiency.

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*FIG. 3. Comparison of Maximum Fuel Temperature.*

#### DLOFC

The temperature profiles indicate that both reactors experience a rise in temperature after the onset of the DLOFC event, reaching their respective peak temperatures before gradually cooling down. The smaller volume reactor (4.4 m³) exhibits a higher peak temperature, slightly above 900°C, and reaches this peak faster than the larger volume reactor (5 m³), which peaks at a temperature slightly below 900°C.

The cooling phase for both reactors shows a similar trend, with temperatures decreasing over time. However, the larger volume reactor (5 m³) maintains a lower temperature throughout the entire period after the initial peak. This suggests that the larger reactor design has a better thermal response to the DLOFC event, likely due to its more uniform power density distribution and improved thermal management, as previously discussed.

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*FIG. 4. Comparison of Temperature at DLOFC.*

### Optimizing Side Reflector Size for Burnup Targets in PeLUIt-10

#### Burnup

Table 3 and Figure 5 illustrate the relationship between the size of the side reflector and the maximum burnup of driver pebbles by the flow channel. The table compares burnup targets across different flow channels for reflector sizes ranging from 70 cm to 130 cm, showing a clear trend of increasing average burnup with larger reflector sizes. For instance, the average burnup rises from 53.75 MWD/kgHM with a 70 cm reflector to 69.814 MWD/kgHM with a 130 cm reflector. Reducing the reflector size to 90 cm still meets the burnup target of 60 MWD/kg-HM. The thicker the reflector, the more neutrons are reflected into the reactor core, and fewer neutrons leak from the core. As a result, the neutron flux increases, allowing more neutrons to initiate fission reactions, thereby increasing the burnup level.

Channel 1 consistently exhibits the highest burnup, while Channel 6 shows lower burnup values, albeit with a similar upward trend as reflector size increases. This data highlights the enhanced neutron economy and more efficient fuel utilization achieved with larger reflectors.

TABLE 3 MAXIMUM BURNUP OF DRIVER PEBBLES BY FLOW CHANNEL FOR ALL REFLECTOR SIZE

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Design** | **Burnup (MWD/kghm) of Driver pebbles by Flow Channel** | | | | | | |
| **Average** | **Channel 1** | **Channel 2** | **Channel 3** | **Channel 4** | **Channel 5** | **Channel 6** |
| Reflector 70 cm | 53.75 | 62.023 | 58.869 | 53.295 | 49.323 | 47.827 | 51.163 |
| Reflector 80 cm | 58.798 | 67.173 | 63.915 | 58.17 | 54.157 | 52.746 | 56.625 |
| Reflector 90 cm | 62.497 | 70.893 | 67.576 | 61.734 | 57.72 | 56.386 | 60.672 |
| Reflector 100 cm | 64.097 | 73.522 | 70.173 | 64.282 | 60.284 | 59.015 | 63.595 |
| Reflector 110 cm | 67.187 | 75.539 | 72.168 | 66.246 | 62.265 | 61.049 | 65.857 |
| Reflector 120 cm | 68.746 | 77.077 | 73.691 | 67.746 | 63.779 | 62.601 | 67.578 |
| Reflector 130 cm | 69.814 | 78.114 | 74.722 | 68.771 | 64.823 | 63.677 | 68.777 |

Figure 5 further supports this trend by plotting the maximum burnup against reflector size. This upward curve indicates that larger reflector sizes significantly boost burnup efficiency in the reactor.

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*FIG. 5. Maximum Burnup for All Reflector Size*

#### Pebble per Day

Figure 6 illustrates the relationship between the side reflector size and the pebble flow rate per day. The graph shows a downward trend, indicating that as the size of the side reflector increases, the number of pebbles processed per day decreases. For instance, with a 70 cm reflector, the pebble flow rate is approximately 36 pebbles per day, while with a 130 cm reflector, it is about 28 pebbles per day. The larger reflector sizes improve neutron economy, allowing the reactor to achieve higher burnup rates with fewer fuel pebbles, thus reducing the overall pebble flow rate.

As the previous explanation, the decrease in pebble flow rate with increasing reflector size can be attributed to the enhanced neutron reflection back into the reactor core, resulting in more efficient fuel utilization. With fewer neutrons escaping the core, the reactor can sustain the fission process with fewer pebbles. This optimization improves the reactor's fuel efficiency and extends the fuel pebbles' operational life.

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*FIG. 6. Pebble flow per day for all reflector size.*

#### Peak to Average Power Density

Figure 7 shows the relationship between the side reflector size and the peak-to-average power density ratio for all reflector sizes. The graph indicates that the peak-to-average power density ratio decreases as the side reflector size increases from 70 cm to 130 cm. The decreasing trend suggests that the larger reflectors contribute to a more uniform power distribution within the reactor core.

A lower peak-to-average power density ratio is desirable as it indicates a more even power distribution throughout the reactor core, which also reduces the hot spots.

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*FIG. 7. Peak to average power density for all reflector size.*

#### Power Density

Figure 8 shows the relationship between the side reflector size and the maximum power density. The maximum power density decreases as the side reflector size increases from 70 cm to 130 cm. This trend indicates that larger reflectors help moderate the peak power density. Lower maximum power densities reduce the risk of localized overheating and improve the thermal management of the reactor core.

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*FIG. 8. Maximum power density for all reflector size.*

Figure 9 illustrates the power density distribution along the axial position of the reactor core for various reflector sizes. The curves show that as the reflector size increases, the peak of the power density distribution becomes lower and shifts slightly along the axial position. Reflectors with larger sizes (120 cm and 130 cm) display more uniform power density distributions than smaller reflectors (70 cm and 80 cm).

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*FIG. 9. Power density for all reflector size.*

#### Maximum Fuel Temperature

Figure 10 shows that increasing the size of the side reflector in a Pebble Bed Reactor can lead to a modest reduction in the maximum fuel temperature. This reduction is beneficial for reactor safety and efficiency, as lower maximum fuel temperatures reduce the risk of fuel damage. Larger reflectors show a more uniform temperature distribution along the axial length of the core, contributing to better thermal performance and reactor stability.

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*FIG. 10. Maximum power density for all reflector size.*

#### DLOFC

Figure 11 illustrates the temperature profiles of PeLUIt during a Depressurized Loss of Forced Cooling (DLOFC) event for various reflector sizes. Following the DLOFC event, all reflector sizes exhibit an immediate spike in temperature, reaching peak values within the first few hours. The peak temperatures are just under 900°C for the smallest reflector size (70 cm) and are slightly lower for the larger reflector sizes. This indicates that larger reflectors help moderate the initial temperature rise during a DLOFC event.

After the initial peak, the temperature gradually declines over 100 hours for all reflector sizes. Larger reflector sizes, such as 120 cm and 130 cm, show a more gradual temperature decline than smaller sizes, suggesting better thermal stability and management. By the end of the 100 hours, temperatures for all reflector sizes converge to similar values, around 750°C to 800°C.

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*FIG. 11. Comparison of Temperature at DLOFC for all reflector size.*

## conclusions

The neutronic and thermal-hydraulic performance of the PeLUIt-10 reactor with volumes of 5 m³ and 4.4 m³ has been analyzed, along with the impact of modifications in the reflector size, which varied from 70 to 130 cm. The results of the comparison indicate that the reactor with a volume of 4.4 m³ exhibits performance comparable to the 5 m³ volume in both neutronic and thermal-hydraulic aspects. Additionally, reducing the reflector size to 90 cm still meets the burnup target of 60 MWD/kg-HM.

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