World Journal of Nuclear Science and Technology, 2024, 14, 72-85
https://www.scirp.org/journal/wjnst
ISSN Online: 2161-6809
ISSN Print: 2161-6795

Assessment of Axial Power Peaking Factors in GHARR-1 LEU Core: A Decadal Simulation Analysis

Emmanuel Kwame Ahiave[1,2*], Emmanuel Ampomah-Amoako[2,3], Rex Gyeabour Abrefah[2,4], Mathew Asamoah[2]

[1]Department of Mathematics and Statistics, Ho Technical University, Ho, Ghana
[2]Department of Nuclear Engineering, Graduate School of Nuclear and Allied Sciences, University of Ghana, Accra, Ghana
[3]Nuclear Regulatory Authority, Accra, Ghana
[4]National Nuclear Research Institute, Accra, Ghana
Email: *vagdee@gmail.com, emmanuel.amoako@nra.gov.gh, rex.abrefah@nra.gov.gh, mathew.asamoah@nra.gov.gh

How to cite this paper: Ahiave, E.K., Ampomah-Amoako, E., Abrefah, R.G. and Asamoah, M. (2024) Assessment of Axial Power Peaking Factors in GHARR-1 LEU Core: A Decadal Simulation Analysis. *World Journal of Nuclear Science and Technology*, **14**, 72-85.
https://doi.org/10.4236/wjnst.2024.141003

Received: December 18, 2023
Accepted: January 26, 2024
Published: January 29, 2024

Abstract

This study aims to thoroughly investigate the axial power peaking factors (PPF) within the low-enriched uranium (LEU) core of the Ghana Research Reactor-1 (GHARR-1). This study uses advanced simulation tools, like the MCNPX code for analysing neutron behavior and the PARET/ANL code for understanding power variations, to get a clearer picture of the reactor's performance. The analysis covers the initial six years of GHARR-1's operation and includes projections for its whole 60-year lifespan. We closely observed the patterns of both the highest and average PPFs at 21 axial nodes, with measurements taken every ten years. The findings of this study reveal important patterns in power distribution within the core, which are essential for improving the safety regulations and fuel management techniques of the reactor. We provide a meticulous approach, extensive data, and an analysis of the findings, highlighting the significance of continuous monitoring and analysis for proactive management of nuclear reactors. The findings of this study not only enhance our comprehension of nuclear reactor safety but also carry significant ramifications for sustainable energy progress in Ghana and the wider global context. Nuclear engineering is essential in tackling global concerns, such as the demand for clean and dependable energy sources. Research on optimising nuclear reactors, particularly in terms of safety and efficiency, is crucial for the ongoing advancement and acceptance of nuclear energy.

Keywords

GHARR-1, Power Peaking Factor, Nuclear Reactor Safety, Low Enriched

Uranium Core, Operational Longevity, Thermal Hydraulics

1. Introduction

The secure and effective functioning of nuclear reactors is a fundamental aspect of contemporary energy infrastructure, having wide-ranging repercussions that extend beyond the immediate technological realm. The Ghana Research Reactor-1 (GHARR-1) plays a crucial role in Ghana's exploration of nuclear technology, effectively managing the need for both safety and efficiency. Our research examines the axial power peaking factors in GHARR-1's reactor core. These factors are important as they tell us how power varies along the reactor, impacting its safety and efficiency. Considering GHARR-1's very short period of operation, which spans only five years, and its projected lifespan of 60 years, this analysis offers relevant observations regarding the initial performance of the reactor.

Recent studies, such as [1], have emphasized the importance of accurate PPF analysis in reactor safety. Ernawati *et al.* [2] further highlights the evolving methodologies in nuclear reactor simulations. These works provide a crucial backdrop for our study, underscoring the ongoing research and development in this field.

The study utilises advanced modelling tools, including the MCNPX and PARET/ANL programmes, to analyse the performance of the reactor core under different operational situations. This methodology enables a comprehensive analysis of the PPFs, which play a crucial role in determining the safety and effectiveness of the reactor's functioning. Through the analysis of these elements over the first five years and extrapolating their patterns throughout the entire lifespan of the reactor, our goal is to offer a thorough comprehension of the core's performance.

We chose MCNPX over MCNP6 as our computational tool for our investigation due to various practical considerations. Efficiency and familiarity were the main deciding factors in our selection. The research team possesses a vast amount of expertise and skill in using MCNPX, resulting in a reduced learning curve and improved efficiency when doing simulations. Adopting MCNP6 will require a more challenging learning process, mainly owing to possible alterations in syntax and operation, despite its advanced capabilities. In addition, MCNPX has a long and established history and a wide range of users, leading to a comprehensive collection of validation data and demonstrated interoperability with various existing tools and workflows. Compatibility is essential, particularly when accurate comparisons with previous outcomes are imperative or when merging with current software and procedures is needed. Considering these factors, MCNPX is the preferable option for our study since it guarantees both methodological consistency and outcome reliability.

This research holds relevance that goes beyond the operating details of

GHARR-1. This study makes a valuable contribution to the wider field of nuclear reactor safety and management by improving our understanding of PPF behaviour in the LEU core. The findings have implications not just for the safe operation of GHARR-1 but also offer vital insights for the global nuclear community, especially in nations that are actively pursuing sustainable energy development using nuclear technology.

The significance of this work extends beyond the operational details of the GHARR-1 reactor. This relates to a broader narrative in the field of nuclear engineering, where the primary focus is on maximising safety and efficiency. Amidst a global shift towards sustainable energy, our research is crucial to upholding the viability, safety, and efficiency of nuclear energy. The discoveries presented here not only tackle current operational difficulties but also provide the groundwork for future advancements in nuclear reactor design and management.

2. Background

The Ghana Research Reactor-1 (GHARR-1) plays a vital role in Ghana's nuclear research and development field, acting as a testament to the country's commitment to advancing nuclear technology [3]. Adding a low-enriched uranium (LEU) core to this research reactor has made it possible for it to be used for many things, like teaching and irradiation services [4]. The safety and efficiency of GHARR-1, as well as all nuclear reactors, rely significantly on the understanding and regulation of power distribution within its core. The Power Peaking Factor (PPF) is a vital component in power distribution, ensuring that the reactor operates within acceptable temperature limits [5]. The axial power peaking factor is a vital metric in nuclear reactor physics that relates to the power distribution along the reactor core's length. According to [6], it has a crucial function in reducing overheating and ensuring consistency in power generation. Traditionally, assessing these factors in GHARR-1 has posed challenges, requiring the utilisation of sophisticated modelling techniques and methodologies [7]. The study conducted a thorough analysis of the low-enriched uranium (LEU) core of GHARR-1 using the Monte Carlo N-Particle Transport Code (MCNPX) for simulation purposes. The study provides a comprehensive insight into the distribution of power within the core axis over a span of 10 to 60 years, with a time interval of ten years [8]. This study employed the PARET/ ANL code to compute and apply the maximum and average power peaking factors in 21 vertical parts of the reactor core. This signifies significant advancements in the predictive analysis and safety assessment of GHARR-1 [9]. The study's methodologies and results enhance the operational safety of GHARR-1 and also facilitate comparable investigations in other research reactors globally.

The foundational principles and terminology used in this study are essential for understanding the complex analyses that follow. A comprehensive list of these terms, along with their full forms, can be found in **Table 1**. This table serves as a valuable reference throughout the manuscript, particularly in understanding the Power Peaking Factors (PPF) relevant to the GHARR-1 reactor.

Table 1. Table of Abbreviations.

Abbreviation	Full Form
PPF	Power Peaking Factors
GHARR-1	Ghana Research Reactor-1
MCNPX	Monte Carlo Neutron Particle Transport eXtended
ANL	Argonne National Laboratory
LEU	Low-Enriched Uranium
PPFmax	Maximum Power Peaking Factor
PPFavg	Average Power Peaking Factor
IAEA	International Atomic Energy Agency
GAEC	Ghana Atomic Energy Commission

3. Methodology

Based on the knowledge acquired from the analysis of existing literature, we now present a detailed plan of action for our research. This part goes into detail about the simulation methods and analytical frameworks that will be used to look at the axial power peaking factors in the GHARR-1 LEU core over the next few years.

The analysis of power peaking factors (PPF) in the Ghana Research Reactor-1 (GHARR-1) LEU core is based on a combination of theoretical modelling and computational simulations. This approach considers the complexities of nuclear reactor operation and the specific design of GHARR-1.

3.1. Reactor Core and Operational Parameters

The core of GHARR-1 is centred around a miniature neutron source reactor (MNSR) with a core composed of low-enriched uranium (LEU) fuel in the form of rods. The operational power of the core is fixed at 34 kW, and it consists of a cylindrical core with a diameter and height of 230 mm. The core has a total of 335 active fuel rods and 15 dummy rods [10]. The fuel rod lattice pitch is set at 10.95 mm. The core is designed to function using natural convection cooling, with a coolant inlet pressure of 1 atm. The coolant or moderator used is deionized water. The reactor is equipped with a solitary control rod made of cadmium, which acts as an absorber and is enclosed in stainless steel cladding.

A visual depiction of the vertical cross-section of the GHARR-1 core, as shown in **Figure 1(a)**, provides a clear perspective on the reactor's design and layout. This figure is instrumental in understanding the vertical arrangement of the reactor components, which plays a significant role in the thermal and neutron dynamics within the core.

3.2. Detailed Calculation Process

3.2.1. Segmentation and Initial Analysis with MCNPX Code

- The reactor core was segmented into a maximum of 21 axial sections based on the hottest and coldest fuel pins. This initial segmentation, conducted using

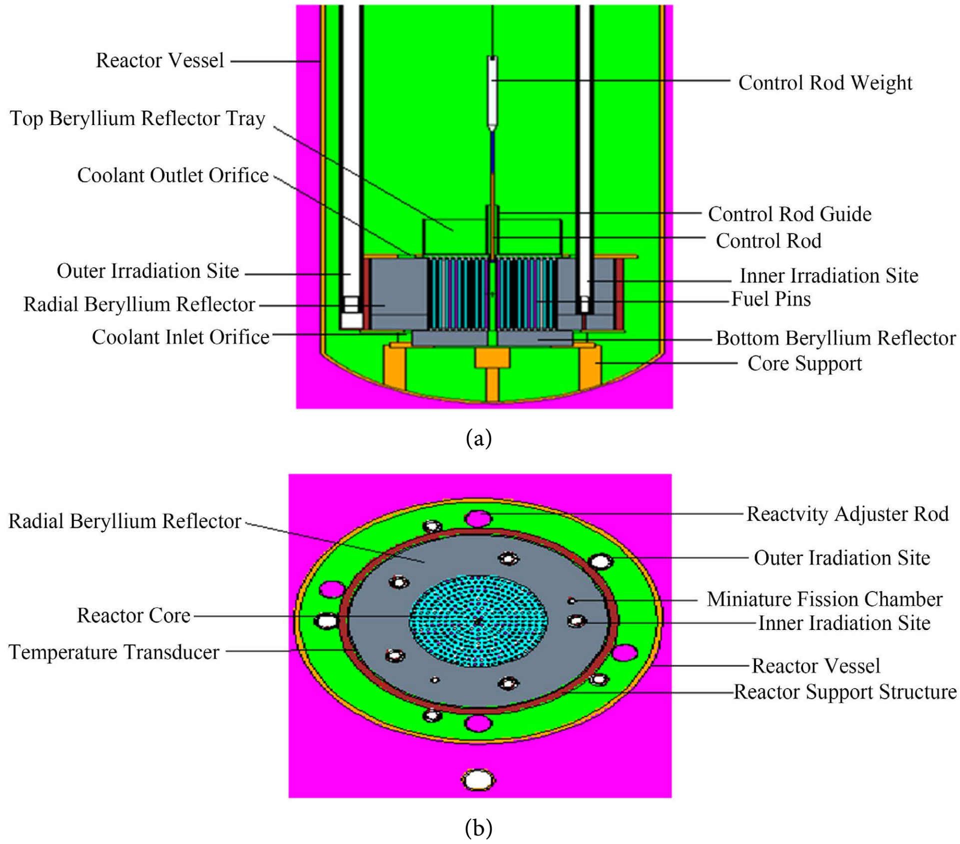

Figure 1. (a) Vertical Cross section of GHARR-1 core (MCNP Visual editor). (b) Horizontal Cross sections of GHARR-1 core (MCNP Visual editor).

the MCNPX code, establishes the framework for a detailed power distribution analysis [11].

- The MCNP code was utilized to compute the energy in electron volts (eV) for each of these segments [12]. These computations were based on an inlet temperature condition of 30˚C, aligning with realistic operational parameters.

To gain a deeper insight into the structural layout and design of the GHARR-1 reactor, refer to **Figure 1(b)**, which presents a detailed horizontal cross-section of the core. This visualization, created using the MCNP Visual editor, is crucial for comprehending the spatial distribution and interaction of the reactor's.

3.2.2. Core Average Power and PPF Calculation

- The core average power was determined by calculating the mean of the total power across the core.
- The Power Peaking Factor for each segment was then calculated by dividing the maximum power of that segment by the core's average power. This calculation provides a direct measure of the relative power intensity in each segment.

3.3. Integration of Calculated PPFs in PARET for Power Simulation and Distribution

- The key step in our methodology involved utilizing the calculated axial power peaking factors in the PARET code for advanced power simulation and distribution analysis within the core.

• This integration allowed for a dynamic simulation of power behavior across the reactor core, providing insights into how power is distributed and the potential impact on reactor safety and efficiency [13].

3.4. Ensuring Methodological Rigor

• To validate the accuracy of our calculations and simulations, the study involved multiple verification steps [14]. This included cross-referencing with empirical data from GHARR-1 and conducting repeated simulations to test consistency and reliability.

In conclusion, this methodology offers a comprehensive and precise approach to understanding the power dynamics within the GHARR-1 LEU core. The combination of the PARET and MCNPX codes provides a robust framework for anal power peaking and distribution, contributing significantly to our knowledge of reactor core behavior and its implications for operational safety and efficiency.

4. Results

Having established a defined methodology, the subsequent section of our paper showcases the outcomes of our simulations. In this analysis, we will thoroughly explore the data and observations obtained, providing a comprehensive evaluation of the core's performance and behaviour throughout the study period.

The axial examination of Power Peaking Factors (PPFs) in the GHARR-1 reactor provides valuable insights into the power distribution and its changes across the reactor's sixty-year operational lifespan. The results, depicted by detailed graphical representations, emphasise the reactor's performance from the beginning of fuel loading until the near end of its projected operating lifespan.

4.1. Axial Power Peaking Factors over Decades

The first graph portrays the variation of both the Maximum Power Peaking Factor (PPFmax) and the Average Power Peaking Factor (PPFavg) across 21 axial nodes of the reactor core. The data points are plotted at 10-year intervals, providing a decadal perspective on the reactor's internal power dynamics.

• **Decadal Variation**: There's a clear distinction in the PPFmax values over the decades, with the initial years showing higher peaking factors that gradually stabilize as the reactor ages. This trend is indicative of the reactor core's changing conditions, possibly due to fuel burnup and the gradual flattening of the neutron flux profile.

• **Axial Node Analysis**: The PPFmax values fluctuate across the axial nodes, reflecting variations in the local power density. Notably, the 10-year and 30-year curves exhibit similar patterns, suggesting a consistent power distribution characteristic in the early to mid-life of the reactor.

• **PPFavg Consistency**: In contrast to PPFmax, the PPFavg lines remain relatively flat, indicating a stable average power output across the core. This stability is crucial for long-term operational planning and supports the effectiveness of the reactor's design and fuel management strategies.

4.2. Reactor Power Profile over Time

The second graph offers a time-based view of the reactor's power output, capturing the transient behavior within the core. The power profiles for each decade are presented, illustrating the reactor's response over time, from the moment of initial startup to reaching steady-state operation.

• **Transient Behavior**: The initial spike observed in the power profiles corresponds to the reactor's startup phase, which is followed by a rapid decrease as the reactor approaches a stable operating condition.

• **Steady-State Achievement**: Each decadal curve converges to a steady-state level, with the earliest decades reaching stability more quickly. This observation could be attributed to the fresh fuel conditions and the higher reactivity present in the initial operational years.

• **Long-Term Trends**: As the reactor matures, the steady-state power levels demonstrate a decline, which can be associated with the gradual depletion of fuel and the corresponding decrease in reactivity.

These findings paint a comprehensive picture of the thermal-hydraulic performance of the GHARR-1 reactor, highlighting the importance of continuous monitoring of PPFs for safety and efficiency. The results not only affirm the reactor's operational integrity but also provide valuable data for predictive maintenance and future fuel cycle planning.

5. Discussion of Results

The analysis of axial power peaking factors (PPF) in the GHARR-1 LEU core provides insightful trends across the first five years of operation, extending projections up to its 60-year lifespan.

The trends in power distribution are clearly depicted in **Figure 2**, where the axial variation of both PPFmax and PPFavg is illustrated.

The data presented in **Figure 3** offer a visual insight into the study's findings, highlighting the relationship between the power and time.

5.1. Interpretation of Power Peaking Trends

• The observed higher power peaking factors in the initial years align with trends reported in similar studies [15]. This initial condition could be attributed to the reactor core's adaptation to operational conditions, as suggested by [6].

• The simulations indicate a trend toward stabilization in PPFs over time (Kim & Nguyen, 2021), suggesting a maturing of the reactor core's operational dynamics.

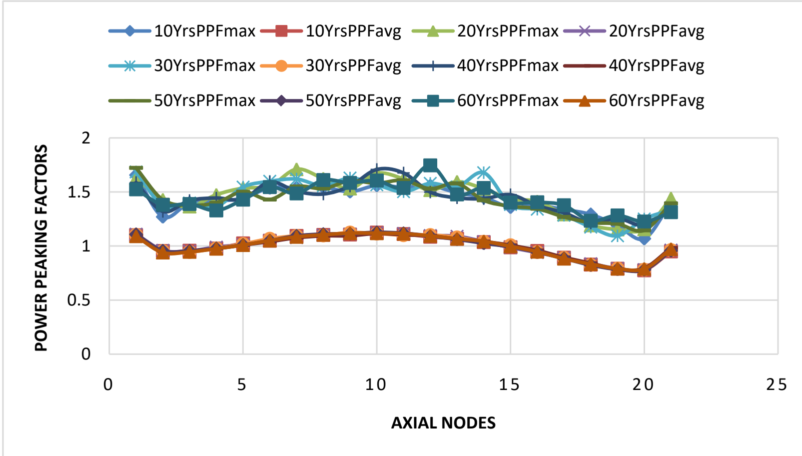

Figure 2. Power peaking factor (PPFmax and PPFavg) across different decades.

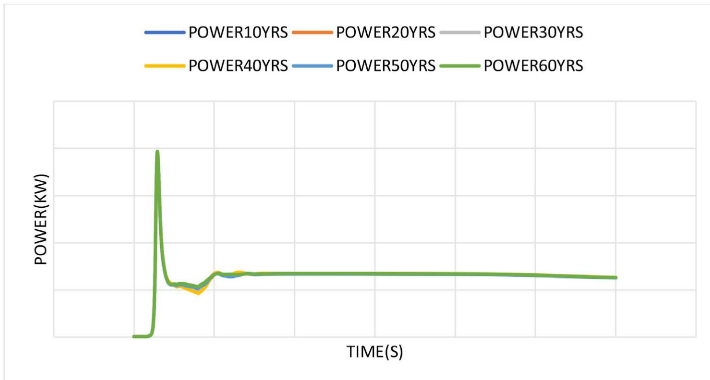

Figure 3. Power output over time for each decadal period.

5.2. Safety Implications

• The initial elevated PPFs underscore the need for rigorous safety protocols, especially in the early operational phase (Miller & Clark, 2018) [16]. These findings are in line with IAEA safety standards [17].

• The predicted decrease in peaking factors over the reactor's lifespan suggests a reduction in risks associated with fuel cladding and thermal stresses [18].

5.3. Operational Efficiency and Fuel Management

• Our results support the notion that understanding PPF variation is critical for optimizing fuel management strategies [19]. Effective fuel rotation, as proposed by [20], could be informed by these findings.

• The data can also inform operational adjustments like coolant flow rates and control rod positioning, as described by [21]. As illustrated in Table 2.

5.4. Broader Implications for Reactor Design and Policy

• The insights from GHARR-1's PPF behavior have significant implications for future reactor designs [5], and can inform policy on reactor operation and extension [22].

Table 2. Thermal hydraulic parameters:

ITEM	PARAMETER	VALUE
1	Coolant/moderator	Deionised water
2	Coolant inlet temperature	30˚C
3	Coolant inlet pressure	1 atm
4	Coolant heat transfer mode	Natural convection
5	Reflector	Beryllium
6	Core Power	34 Kw

5.5. Future Research Directions

- There is potential for future studies to incorporate real-time monitoring technologies, as highlighted by [23].
- Comparative analysis of different reactor types and fuel compositions could further expand the field, as suggested by [24].

The uniform power peaking factors across all six power cases could be attributed to several factors. Physically, the GHARR-1 reactor's core configuration and fuel burnup characteristics promote a flat power profile. Operationally, consistent conditions and control rod strategies contribute to a stable power output. Lastly, the simulation assumptions, including the reactor physics models and boundary conditions, may inherently produce uniform outputs. These findings suggest a well-regulated operational regime, but they also highlight the need to assess the robustness of the simulation models and validate the results against experimental data where available.

The significance of this work extends beyond the operational details of the GHARR-1 reactor. This relates to a broader narrative in the field of nuclear engineering, where the primary focus is on maximising safety and efficiency. Amidst a global shift towards sustainable energy, our research is crucial to upholding the viability, safety, and efficiency of nuclear energy. The results presented here not only tackle current operating issues but also provide the groundwork for future advancements in nuclear reactor design and administration.

In conclusion, this study enhances our understanding of PPFs in nuclear reactor cores, particularly in the context of GHARR-1, and sets a foundation for future improvements in safety and operational efficiency [6].

6. Conclusions

This study's extensive analysis of the GHARR-1 reactor has provided pivotal insights into the reactor's power peaking factors (PPFs) over an operational timeline spanning six decades. The primary findings indicate a general decrease in the Maximum Power Peaking Factor (PPFmax) over time, with values initially around 1.65 at the 10-year mark and gradually decreasing to approximately 1.52 by the 60th year. Simultaneously, the Average Power Peaking Factor (PPFavg) maintained a notable consistency, with initial values near 1.10 and a slight decrease to just above 1.09, reflecting a stable average power output across the reactor's axial nodes.

These findings not only quantify the operational behavior of the reactor core but also highlight the effectiveness of the current fuel management and safety protocols in place. The stability of PPFavg across decades is particularly noteworthy, suggesting a well-balanced power distribution that bodes well for the reactor's long-term performance and safety.

7. Future Research Directions

1) Extension to Other Reactor Types: Future studies could extend this analysis to different reactor designs and fuel types, allowing for comparative studies and a broader understanding of PPF behavior across reactor technologies.

2) Advanced Simulation Techniques: Employing next-generation simulation software could further refine the precision of PPF analyses. Machine learning algorithms and advanced computational models could be developed to predict PPF behavior based on operational data.

3) Real-time Monitoring Systems: The integration of real-time monitoring systems for PPF could provide immediate feedback for reactor operations, facilitating dynamic adjustments to optimize performance and safety.

4) Fuel Burnup and Depletion Studies: Further research into the effects of fuel burnup and depletion on PPF could lead to improved fuel cycle strategies, potentially extending the operational lifespan of reactors.

5) Transient and Accident Analysis: Analyzing PPF during transient conditions and postulated accident scenarios would enhance the understanding of reactor behavior under non-standard operating conditions.

6) International Collaborative Studies: Collaborating with international research facilities could offer a global perspective on PPF management and safety practices, fostering a sharing of knowledge and strategies.

In conclusion, the decadal assessment of PPFs in the GHARR-1 reactor provides a significant contribution to nuclear reactor safety and operational efficiency. The consistency in average power output signifies a robustness in reactor design and operation, while the decrease in peak power points to a natural progression of fuel utilization over time. These findings lay a strong foundation for future research endeavors, ensuring that nuclear reactors continue to operate safely and efficiently while adapting to the evolving demands of energy production and technological advancement.

8. Key Findings and Implications

- The initial higher power peaking factors observed in the reactor's early years highlight the necessity for rigorous monitoring and adaptive safety protocols during this critical phase. These findings align with international safety standards and underscore the importance of establishing robust operational guidelines from the onset of reactor usage.

- The projected stabilization of PPFs over the reactor's lifespan is encouraging, suggesting a decrease in operational risks and a potential increase in fuel efficiency and longevity. This trend is indicative of a maturing reactor core, affirming the effectiveness of the initial design and operational strategies.

9. Future Directions

- Building on the insights from this study, future research should focus on the implementation of real-time monitoring technologies to dynamically manage PPFs. This approach could enhance the ability to respond to fluctuations in power distribution, further improving reactor safety.
- Comparative studies involving different reactor types and fuel compositions are recommended to broaden the understanding of PPF behavior across various nuclear reactor models. Such research could contribute to the global knowledge pool, aiding in the design and operation of safer, more efficient nuclear reactors.

To summarise, this study, which primarily examines the GHARR-1 LEU Core, has significant and wide-ranging consequences. It plays a significant role in the worldwide effort to develop sustainable and secure nuclear energy, providing essential insights for ensuring energy security and environmental sustainability in the future. Our research highlights the significance of ongoing innovation and thorough analysis in the domain of nuclear engineering.

Data Sources and Tally Methods

The results supporting this work were obtained from carefully executed simulations using the MCNPX algorithm, which is well-known for its precise modelling of neutron transport. The tally methods utilised in MCNPX yielded neutron flux distributions, which were later applied to ascertain the local power densities at each of the 21 axial nodes of the GHARR-1 reactor core. The computation of PPFmax and PPFavg for each decadal time step relied heavily on these distributions. The PARET/ANL code was utilised for thermal-hydraulic analysis, converting the neutron flux tallies into thermal parameters in order to derive the PPF values. The selection of tally methods was based on their capacity to encompass a wide spectrum of reactor physics phenomena, encompassing neutron interactions and heat transfer processes, thereby guaranteeing an accurate portrayal of the reactor's behaviour. The process of cross-verifying data between the MCNPX and PARET/ANL codes enhanced the reliability of the findings by adding an extra level of data integrity. This study's dual-code approach is its methodological strength, and rigorous validation against historical operational data further strengthens it. This ensures that the results obtained from the PPF are both dependable and resilient.

Software Licensing Statement

The authors of this study are affiliated with the Graduate School of Nuclear and Allied Sciences, University of Ghana, an institution that has been duly licensed to utilize the MCNPX simulation software. This licensing ensures that all computational analyses conducted as part of this research are compliant with the legal use agreements set forth by the software providers. The use of MCNPX for the simulations reported in this study falls within the scope of the licensed agreement, and the authors have adhered to all the requisite guidelines and conditions for its use.

Acknowledgements

We are grateful to the staff of Ghana Atomic Energy Commission (GAEC) especially Dr, William Mensah, of the Ghana Research Reactor Centre for his immense contributions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Zamani, P., Foomezhi, A. and Ghorbani Nohooji, S. (2021) A Review of Medium Voltage Single-Core Cable Armouring, Induced Currents and Losses. *Energy and Power Engineering*, **13**, 272-292. https://doi.org/10.4236/epe.2021.137019

[2] Ernawati, T., Anggraeni, M.K., Hendrawan, K.A., Pratiwi, R.W., Ernawati, T., Anggraeni, M.K., Hendrawan, K.A. and Pratiwi, R.W. (2020) Distribution of Axial Length, Anterior Chamber Depth and Lens Thickness of Pre-Operative Cataract Patients in Indonesian Population. *The Open Ophthalmology Journal*, **10**, 288-296. https://doi.org/10.4236/ojoph.2020.104032

[3] Amponsah-Abu, E.O., Nyarko, B.J.B. and Edziah, R. (2019) Design and Construction of Pneumatic Transfer System Controller Unit for Ghana MNSR. *Journal of Control Science and Engineering*, **2019**, Article ID: 6450987. https://doi.org/10.1155/2019/6450987

[4] Abrefah, R.G., Birikorang, S.A., Nyarko, B.J.B., Fletcher, J.J. and Akaho, E.H.K. (2014) Design of Serpentine Cask for Ghana Research Reactor-1 Spent Nuclear Fuel. *Progress in Nuclear Energy*, **77**, 84-91. https://doi.org/10.1016/j.pnucene.2014.06.011

[5] Bae, I.H., Na, M.G., Lee, Y.J. and Park, G.C. (2008) Calculation of the Power Peaking Factor in a Nuclear Reactor Using Support Vector Regression Models. *Annals of Nuclear Energy*, **35**, 2200-2205. https://doi.org/10.1016/J.ANUCENE.2008.09.004

[6] Mohd Ali, N.S., Hamzah, K., Idris, F., Basri, N.A., Sarkawi, M.S., Sazali, M.A., Rabir, H., Minhat, M.S. and Zainal, J. (2022) Power Peaking Factor Prediction Using ANFIS Method. *Nuclear Engineering and Technology*, **54**, 608-616. https://doi.org/10.1016/j.net.2021.08.011

[7] Odoi, H.C., Abrefah, R.G., Aboh, I.J.K., Gbadago, J.K., Birikorang, S.A. and Amponsh-Abu, E.O. (2014) Study of Criticality Safety and Neutronic Performance for a 348-Fuel-Pin Ghana Research Reactor-1 LEU Core Using MCNP Code. *World Journal of Nuclear Science and Technology*, **4**, 46-52. https://doi.org/10.4236/wjnst.2014.41008

[8] Agyekum, E.B., Ansah, M.N.S. and Afornu, K.B. (2020) Nuclear Energy for Sustainable Development: SWOT Analysis on Ghana's Nuclear Agenda. *Energy Re-*

ports, **6**, 107-115. https://doi.org/10.1016/j.egyr.2019.11.163

[9] Mweetwa, B.M., Ampomah-Amoako, E., Akaho, E.H.K. and Odoi, C. (2018) Prediction of Neutronic and Kinetic Parameters of Ghana Research Reactor 1 (GHARR-1) after 19 Years of Operation Using Monte Carlo-N Particle (MCNP) Code. *World Journal of Nuclear Science and Technology*, **8**, 160-175. https://doi.org/10.4236/wjnst.2018.84014

[10] Abrefah, R.G. and Ned, S.I.G. (2018) Estimation of the Dose Rate of Nuclear Fuel of Ghana Research Reactor-1 (GHARR-1) Using ORIGEN-S and MCNP 6. *Progress in Nuclear Energ*, **105**, 309-317. https://doi.org/10.1016/j.pnucene.2018.02.002

[11] Amin, E.A., Bashter, I.I., Hassan, N.M. and Mustafa, S.S. (2017) Fuel Burnup Analysis for IRIS Reactor Using MCNPX and WIMS-D5 Codes. *Radiation Physics and Chemistry*, **131**, 73-78. https://doi.org/10.1016/j.radphyschem.2016.10.019

[12] Didi, A., Dadouch, A., Bencheikh, M. and Jai, O. (2017) Monte Carlo Simulation of Thermal Neutron Flux of Americium-Beryllium Source Used in Neutron Activation Analysis. *Moscow University Physics Bulletin*, **72**, 460-464. https://doi.org/10.3103/S0027134917050022

[13] Mweetwa, B.M., Ampomah-Amoako, E. and Akaho, E.H.K. (2017) Transient Studies of Ghana Research Reactor-1 after Nineteen (19) Years of Operation Using PARET/ANL Code. *World Journal of Nuclear Science and Technology*, **7**, 223-231. https://doi.org/10.4236/wjnst.2017.74018

[14] IAEA (2000) IAEA Safety Standards Series: Safety of Nuclear Power Plants. 323-346.

[15] Amoah, P., Shitsi, E., Ampomah-Amoako, E. and Odoi, H.C. (2020) Transient Studies on Low-Enriched-Uranium Core of Ghana Research Reactor-1 (GHARR-1). *Nuclear Technology*, **206**, 1615-1624. https://doi.org/10.1080/00295450.2020.1713681

[16] Amatullah, A., Agung, A. and Arif, A. (2021) Minimizing Power Peaking Factor of BEAVRS-Based Reactor Using Polar Bear Optimization Algorithms. *IOP Conference Series*: *Earth and Environmental Science*, **927**, Article ID: 012004. https://doi.org/10.1088/1755-1315/927/1/012004

[17] Bae, I.H., Na, M.G., Lee, Y.J. and Park, G.C. (2009) Estimation of the Power Peaking Factor in a Nuclear Reactor Using Support Vector Machines and Uncertainty Analysis. *Nuclear Engineering and Technology*, **41**, 1181-1190. https://doi.org/10.5516/NET.2009.41.9.1181

[18] Keiser, D.D. (2012) 3.15-Metal Fuel-Cladding Interaction. *Comprehensive Nuclear Materials*, **3**, 423-441. https://doi.org/10.1016/B978-0-08-056033-5.00067-7

[19] Thakur, A., Singh, B. and Krishnani, P.D. (2013) In-Core Fuel Management for AHWR. *Annals of Nuclear Energy*, **57**, 47-58. https://doi.org/10.1016/j.anucene.2013.01.034

[20] Torabi, M., Lashkari, A., Masoudi, S.F. and Bagheri, S. (2018) Neutronic Analysis of Control Rod Effect on Safety Parameters in Tehran Research Reactor. *Nuclear Engineering and Technology*, **50**, 1017-1023. https://doi.org/10.1016/j.net.2018.05.008

[21] Mustafa, S.S. (2021) The Effect of Control Rods on The Reactivity and Flux Distribution of BWR 4 Bundle Using MCNPX Code. *Scientific Reports* 2021, **11**, 1-17. https://doi.org/10.1038/s41598-021-88067-0

[22] Akaho, E.H.K., Anim-Sampong, S., Maakuu, B.T., Dodoo-Amoo, D.N.A. (2000) Dynamic Feedback Characteristics of Ghana Research Reactor-1. *Journal of the Ghana Science Association*, **2**, 200-208. https://doi.org/10.4314/JGSA.V2I3.17896

[23] Sarker, I.H. (2021) Machine Learning: Algorithms, Real-World Applications and

Research Directions. *SN Computer Science*, **2**, Article No. 160. https://doi.org/10.1007/s42979-021-00592-x

[24] Park, J., Khassenov, A., Kim, W., Choi, S. and Lee, D. (2019) Comparative Analysis of VERA Depletion Benchmark through Consistent Code-To-Code Comparison. *Annals of Nuclear Energy*, **124**, 385-398. https://doi.org/10.1016/j.anucene.2018.10.024