Visualization of Neutron Flux Distribution in the PUR-1 Nuclear Reactor

Problem Statement

The primary goal of this visualization project was to provide a clear and accurate representation of the neutron flux distributions within the PUR-1 research reactor. Specifically, the project aimed to visually map the spatial and energy-dependent variations of neutron flux across different sections of the reactor core, encompassing thermal, epithermal, and fast neutron ranges. The challenge was to transform complex nuclear data, which typically exists in abstract numerical forms and requires specialized knowledge to interpret, into a series of intuitive visual models accessible to a broader audience including engineering students and faculty members.

The need for such visualizations is twofold. First, they are essential for operational support, offering a visual tool to help monitor and analyze the reactor's performance. Effective visualizations can aid in identifying zones of high neutron activity, potential inefficiencies, and areas that may require maintenance or adjustment, thereby contributing to the reactor's safety and efficiency. Second, these visualizations serve an educational purpose, providing a tangible representation of reactor physics that can enhance teaching and learning outcomes in nuclear engineering education.

This project was driven by the hypothesis that improved visual understanding of neutron flux distributions would not only facilitate more effective reactor management but also enhance educational outcomes by providing more engaging and comprehensible learning materials. The ultimate success of the project would be measured by the ability of the visualizations to accurately convey complex data in a manner that is easily understandable and by their adoption as a standard tool in both operational and educational settings.

PUR-1

PUR-1 is a vital component of Purdue university's nuclear engineering program and serves multiple purposes including education, research, and public engagement. This reactor is a Materials Test Reactor (MTR) pool-type reactor, initially built by Lockheed Nuclear Products and currently featuring fuel provided by BWXT Technologies. Initially licensed at 1 kW in 1962, PUR-1 was designed with a 10 kW capacity, emphasizing a robust, yet educational-friendly design that allows for extensive direct interaction with the reactor operations by students and faculty.

PUR-1 uses flat plate type fuel consisting of low-enriched uranium, which aligns with modern safety and non-proliferation standards following its conversion from high-enriched uranium in 2007. The reactor’s core is designed to accommodate up to 16 total assemblies, each capable of housing up to 14 fuel elements. Its unique design features include three drop tubes and four power channels, which facilitate various experiments and tests. The neutron flux in the reactor, essential for numerous nuclear reactions and experiments, peaks at significant levels, offering a robust platform for advanced research and educational purposes.

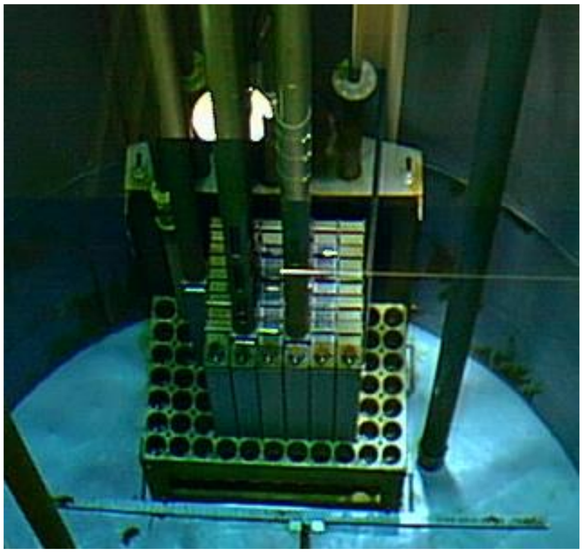

Fig 1: Core layout

Fig 2: Core schematic

Dataset Description

The dataset utilized in this project was derived from detailed Monte Carlo N-Particle (MCNP) simulations of the PUR-1 research reactor. The flux values were generated using the Monte Carlo based neutronics code MCNP6. MCNP, which stands for Monte Carlo Neutron Particle, is a computer software used for simulating nuclear processes. MCNP does something similar to predict the outcome of thousands of dice rolls but for particles in a nuclear reactor or other environments where radiation is present. It simulates how these particles move, interact, and change as they encounter different materials.

The MCNP output file presents a structured array of data indicative of neutron flux across various spatial and energy domains within a reactor simulation. Each line represents a tally, which is a count of neutrons events, corresponding to a specific location, energy bin, or other parameter set within the model. The data is in columns, with each column header denoting a specific variable, such as energy level, spatial coordinates, or tally number. The values are in scientific notation, reflecting the precision required for nuclear simulations. These results give insights into the neutron behavior—where they are most likely to be found, their energy distribution, and the potential for interaction with reactor materials.

To do this for our case, the geometry and corresponding materials of PUR-1 were modeled as an input deck for the code. Then 115 runs were performed modeling the interactions of two million neutrons for each run using random numbers to model the probability of different interactions the neutrons may have within the core. During these runs a mesh grid was applied over the entirety of the core dividing it into 0.5 cm cubes. Lastly, using MCNP6's built in tally feature, the number of neutrons entering and leaving each cell were recorded using the F4 tally input. It encompassed a comprehensive set of neutron flux readings across three distinct energy spectrums: thermal, intermediate, and fast neutrons. These energy ranges of interest were selected: thermal energy range 0 – 0.625 eV, intermediate 0.625 eV – 100 KeV, and fast 100 KeV to 10 MeV.

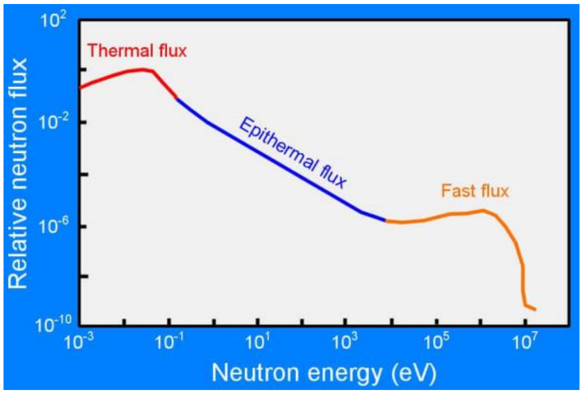

Fig 3: Spectrum of Neutron energy vs Flux

The spectrum displayed above represents the relative neutron flux across different energy levels in a nuclear reactor. It's divided into three principal regions: thermal, epithermal (intermediate), and fast. The thermal region, shown in red, indicates lower-energy neutrons, typically less than 1 electronvolt (eV), which is where neutrons have been moderated, losing their energy through collisions and are at a temperature equilibrium with the surrounding material. This part of the spectrum is crucial for reactors that rely on thermal neutrons for sustaining the chain reaction, as these neutrons are more likely to cause fission when they interact with fuel nuclei.

The epithermal region bridges the thermal and fast regions, featuring neutrons with intermediate energy levels, between about 1 eV and 0.1 megaelectronvolts (MeV). This zone is not as prominent in thermal reactors but can be significant in reactors designed to utilize neutrons in this energy range.

The fast flux, depicted in orange, represents high-energy neutrons, generally above 0.1 MeV. These neutrons have not yet undergone significant moderation and are fast-moving. They play a vital role in fast breeder reactors, which are designed to use this high-energy neutron flux to convert fertile materials into fissile fuel, effectively generating more fuel than they consume.

The graph captures the essence of neutron behavior within a reactor, illustrating that most neutrons are born fast from fission events and then slow down, populating the thermal region where they have the highest probability of causing further fissions. The shape of the spectrum is indicative of the reactor's moderation and its efficiency in creating a sustained chain reaction. Understanding and controlling this spectrum is central to reactor design, safety, and operation.

Each record in the dataset delineated the flux intensity captured at three-dimensional coordinates within the reactor core, alongside relative error estimates, providing a quantitative map of neutron behavior throughout the core. The granularity of the data, with measurements spaced closely together, allowed for a high-fidelity representation of the reactor's operational dynamics. Moreover, the inclusion of temporal data points afforded the ability to assess changes over operational cycles, key for monitoring reactor stability and lifecycle.

Challenges

One of the formidable challenges faced during this project was navigating the bureaucratic and logistical complexities inherent in obtaining critical data. Procuring the necessary simulation outputs required permission from the department head of the school of Nuclear Engineering, given the sensitive nature of the information and the stringent protocols surrounding its dissemination.

Once acquired, the sheer magnitude of the data presented a daunting analytical task. The MCNP output file contained nearly 20 million rows. Handling such a voluminous dataset was not only computationally intensive but also posed significant risks of data corruption or loss during processing. The size of the file far exceeded the standard capacity for many data analysis tools, necessitating the exploration and implementation of more robust data manipulation techniques. Even simple operations, like opening or converting the file to a more accessible format, such as an Excel spreadsheet, were fraught with difficulties, with error messages that indicated potential data truncation.

The data's granularity required fine-tuning the approach to ensure no critical information was overlooked. Processing times were extensive, with MCNP6 often running for hours or even days. This not only tested the limits of available hardware but also demanded a heightened level of scrutiny to ensure that the integrity of the data was maintained throughout the analytical process. The challenge was not merely in managing large quantities of data but in distilling it into coherent, actionable insights that could be understood and utilized effectively, for which only a fraction was possibly explored.

There is also the fact that MCNP is export-controlled, meaning the only person in possession of it was the SRO (senior reactor operator), True Miller. This led to a communication gap and thus not having full freedom in dealing with the data at hand.

Methodology

The visualization process commenced with the preprocessing of MCNP simulation outputs, transforming raw data into a format amenable to graphical representation. Python served as the primary tool for this task. Explorations utilized Matplotlib for generating 2D heatmaps, which quickly communicated the general flux trends across the midplane of the core.

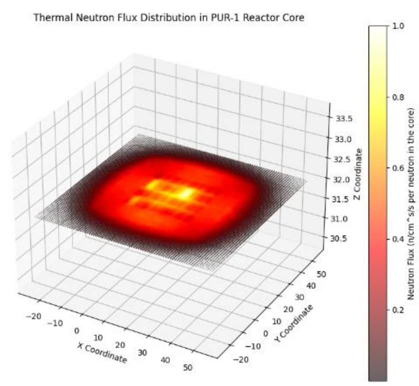

Fig 4: Flux distribution at core midplane

However, the limitations of 2D representations in conveying the three-dimensional nature of the data soon became apparent. As a result, the transition to 3D visualization was explored. These models allowed for a more nuanced view of the data, showing gradients and providing insight into the geometric distribution of flux intensities.

Alternative visualization methods, including direct volume rendering and isosurfacing, were evaluated for their potential to convey additional layers of detail but were not pursued to their computational intensity and the challenges associated with accurately interpreting such representations, but serve as important aspects to consider for improvements to the current code.

Results

The culmination of this project was a series of visualizations that depicted neutron flux distributions with unprecedented clarity. The heatmaps served as an effective tool for rapidly communicating the distribution of neutron flux across various reactor slices, proving particularly useful for instructional purposes. These maps, color-coded for intensity, made it straightforward to identify regions of high and low neutron activity.

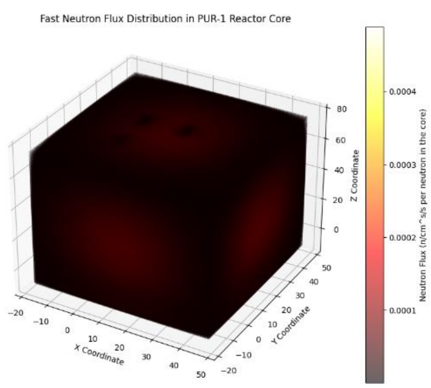

Fig 5: Fast neutron flux distribution for full core

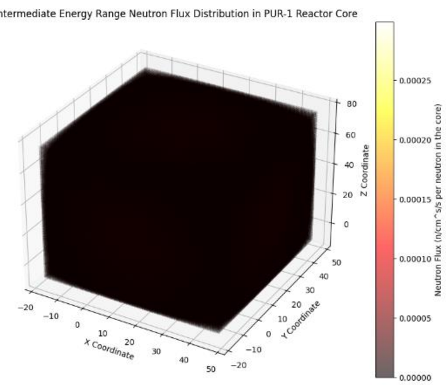

Fig 6: Epithermal neutron flux distribution for full core

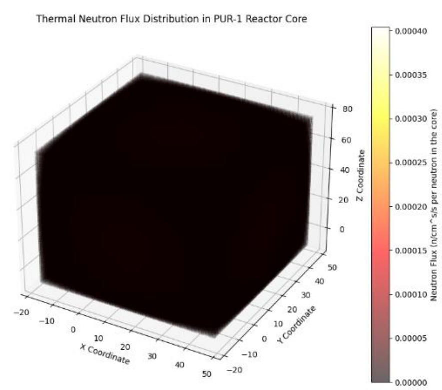

Fig 7: Thermal neutron flux distribution for full core

Fig 5 shows areas with higher neutron flux, as indicated by the brighter colors. The distribution is not uniform, with some regions having a significantly higher flux. These areas could correspond to the active regions of the reactor where fission reactions are more intense.

Fig 6 appears more homogeneous compared to the fast neutron distribution. The intermediate energy range might have a more even distribution throughout the reactor core, with lower overall flux intensity compared to the fast neutrons, suggested by the darker colors.

Fig 7 shows the distribution of thermal neutrons, which are slower than fast and intermediate neutrons. The thermal flux is critical for sustaining the nuclear chain reactions. The visualization suggests a homogeneous distribution, but it's generally darker, which might imply a lower intensity of thermal neutrons compared to fast neutrons within the core.

Across the images, it appears that fast neutrons are more likely to be present in specific regions, possibly near fuel assemblies, while thermal and intermediate neutrons are more evenly distributed. This is a typical pattern as fast neutrons are slowed down (moderated) to become thermal neutrons, which then contribute to sustaining the nuclear chain reactions.

However, it was believed that these images were not showing the flux distribution to the full extent desired. To be able to see into the cube that was being generated, the code was modified to implement a quarter chunk of it to be removed from the x-y plane so that the inner flux could be observed.

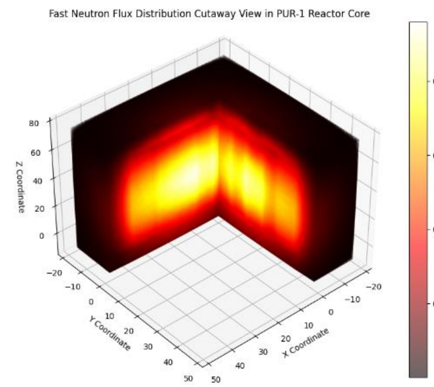

Fig 8: Fast neutron flux distribution with chunk removed

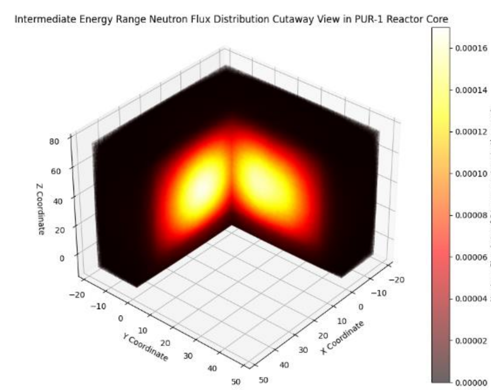

Fig 9: Epithermal neutron flux distribution with chunk removed

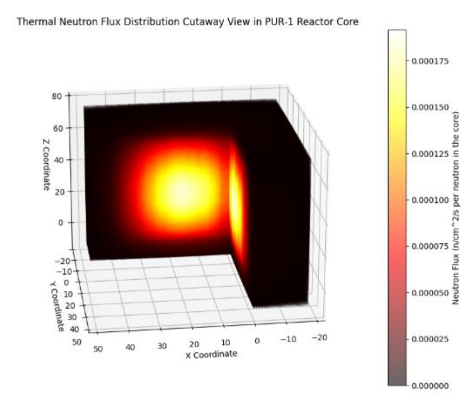

Fig 10: Thermal neutron flux distribution with chunk removed

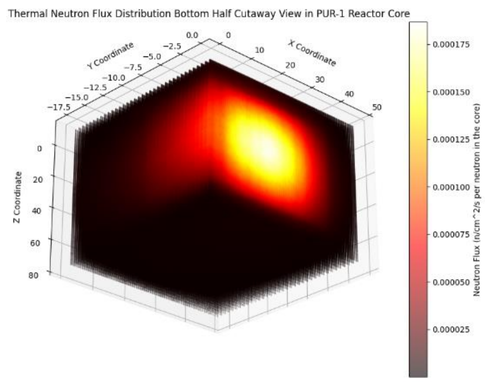

Fig 11: Removed core chunk from thermal neutron flux distribution.

Fig 8 represents fast neutrons, which are produced during fission reactions and have high energy. The bright areas indicate regions with high neutron activity, likely where the fission fuel is located. The gradient from bright to dark suggests that neutron flux decreases with distance from these regions, which is consistent with the behavior of neutrons as they scatter and are absorbed by the reactor material.

Fig 9 shows a similar pattern for intermediate-energy neutrons. These neutrons have lost some energy due to scattering but have not yet slowed down to thermal energies. The distribution seems slightly more uniform than the fast neutrons, possibly indicating that the neutrons have spread out more evenly across the core.

Fig 10, representing thermal neutrons, shows the neutrons that have been moderated to low energies, which are critical for sustaining the nuclear chain reaction. The bright center suggests a high concentration of thermal neutrons in the core, likely where the reactor moderator is most effective at slowing down neutrons.

Through these models, it was possible to illustrate the multi-dimensional nature of neutron flux within the core, highlighting areas of peak activity and providing a visual reference for the theoretical models of reactor physics. The visualizations were rendered with attention to detail, ensuring that each model was both accurate and intuitive to interpret.

Discussion and Future

Reflecting upon the project, the extent to which the objectives were met is satisfactory. The visualizations not only aligned with the project's goals but also provided insights that exceeded initial expectations. Adjustments made along the way, such as the incorporation of cutaway views in the 3D models, were driven by the need for clearer insights into the core's inner workings. These changes stemmed from both the feedback received from the senior reactor operator and the iterative nature of the design process. The results, while in line with theoretical predictions, were revelatory in their visual affirmation of the reactor's operational patterns. However, there were lessons learned throughout the journey, particularly the importance of an adaptable workflow capable of incorporating new techniques and methodologies. Future directions for this work involve the usage of isosurface visualization to render 3D surfaces within a volume of space that represent the flux points of a constant value, as well as the creation of a GUI to help move between energy ranges seamlessly. The MCNP data needs to be processed further to allow for these improvements to be implemented. Improvements for the distant future include integration of real-time data feeds to create dynamic visualizations, the inclusion of interactive elements for educational purposes, and the expansion of the visualization toolkit to support augmented and virtual reality experiences.

References

- Lamarsh, J. R., & Baratta, A. J. (2018). Introduction to Nuclear Engineering. Pearson Education, Inc.
- Currie, K. L., & Rising, M. E. (2020, February 7). MCNP6 source primer: Release 1.0. MCNP6 Source Primer: Release 1.0 (Technical Report) | OSTI.GOV. https://www.osti.gov/biblio/1599011