Monte Carlo Simulations of Uncollided Neutron Flux

Brandon Henry, Gabriel Reese, Hunter Spradlin, Tyler Wiggins, Nathaniel Zuraw

Sponsors: Dr. Elliott Biondo, Dr. Mathew Swinney, Loftin Gerberding

Appalachian STEM Academy at Oak Ridge 2024

Introduction

A nuclear reactor's activity is defined by its criticality, where the production of new neutrons determines the rate of the fission reaction. Neutron activity in a reactor can be modeled using a statistical process known as the Monte Carlo method. Programs can model this neutron flux and origin, and are utilized in material analyses of neutron interactions with relevant materials. The purpose of this project was to determine the most effective use of this modeling method to ensure the best possible accuracy.

Important aspects to consider:

- Key events in a nuclear reactor
- Properties of fissile materials
- Neutron behaviors in materials
- Statistical Methodologies
- Computational analysis

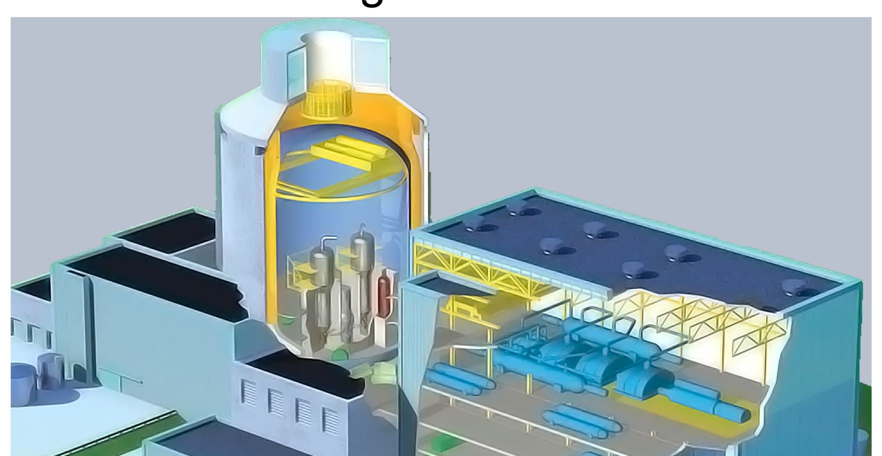

Fig. 1 – A model of Westinghouse's AP1000 Reactor Project

Background

Fission reactions produce neutrons as a byproduct. These neutrons often interact with a nearby atoms' nuclei. Simulating instances of such random neutron behaviors gives useful statistical insights into how fissile materials interact with themselves and their environments.

Nucleus

- Scatters or absorbs neutrons
- Fissile isotopes may fission
- Fission releases more neutrons

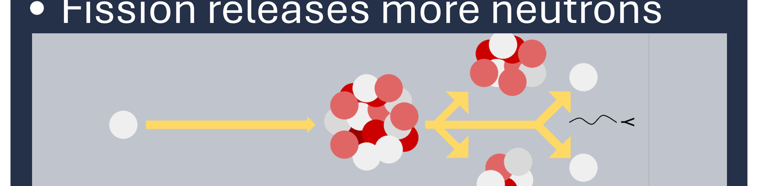

Fig. 2 – A visual model of fission producing fragments and neutrons

Method

This can be modeled with the **Monte Carlo method**. It samples particle behavior over many trials to simulate complex nuclear systems that cannot be simulated by mathematical models alone, offering statistically reliable insights when direct analysis is impossible.

The program references data of a material's **nuclear cross section** in order to make a statistical estimate on how a system will behave.

Altering the number of trials and batches in a Monte Carlo simulation affects behaviors of computational systems and neutron interactions.

This method can predict neutron exposure and emission rates in specific areas such as a nuclear reactor or in radiation shielding.

Monte Carlo Method

- Simulates pseudo-random individual particle behavior
- Synthetic data used to create predictive model

Cross Section (CS)

- Neutron-nuclei interaction relies on a probability
- The likelihood of interaction is defined as its cross section

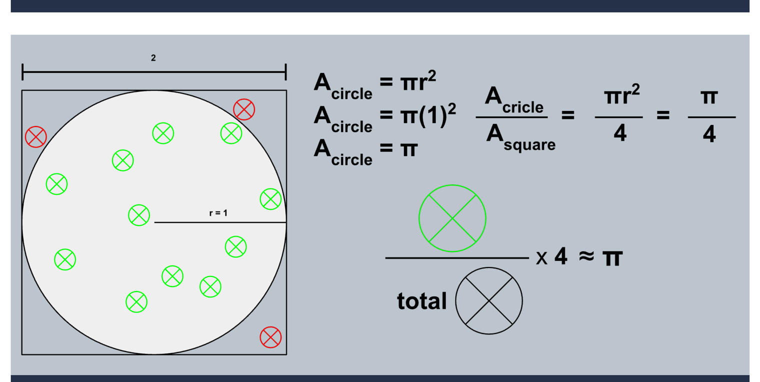

Fig. 3 – A graphic of an estimation of Pi using the Monte Carlo Method

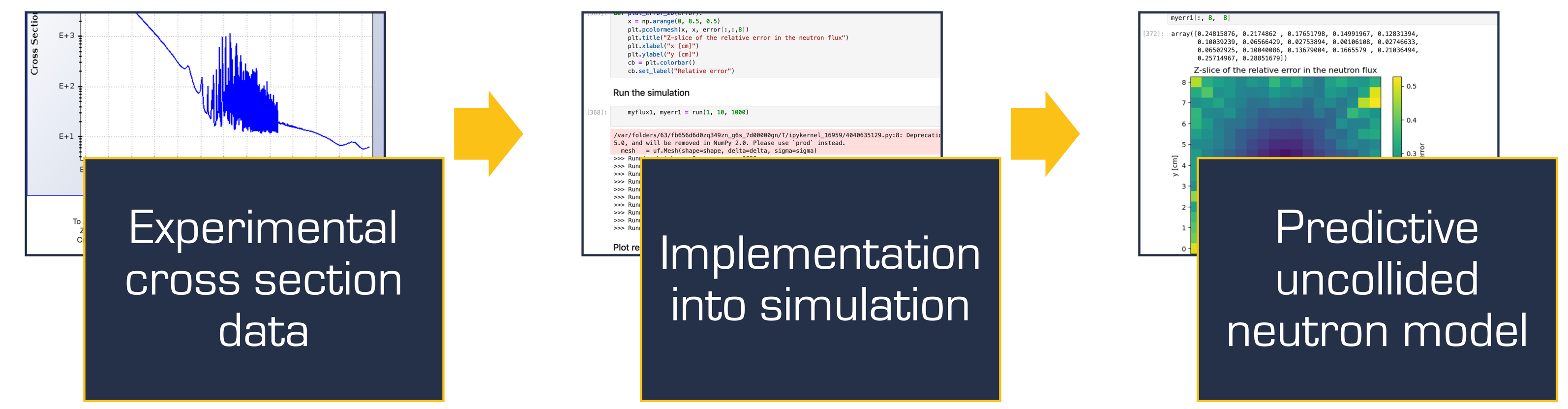

Fig. 4 – A flowchart indicating how a nuclear cross section is analyzed by processing material data

Results

Neutron Flux by Cross Section Value

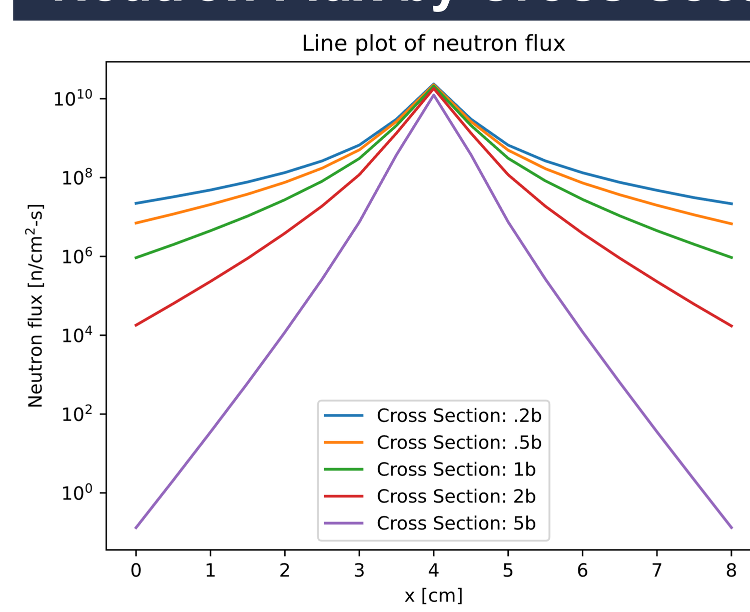

Fig. 5 – The relationship of neutron flux with cross section over a given length of 8 cm.

Result

As shown in Figure 5, increasing the cross section causes the neutron flux to drop off precipitously, whereas lowering the cross section yields the opposite result. Thus a higher cross section value would yield a lower flux as the number of uncollided neutrons present in the system is limited by the magnitude of the cross section value.

Relative Error by Cross Section Value

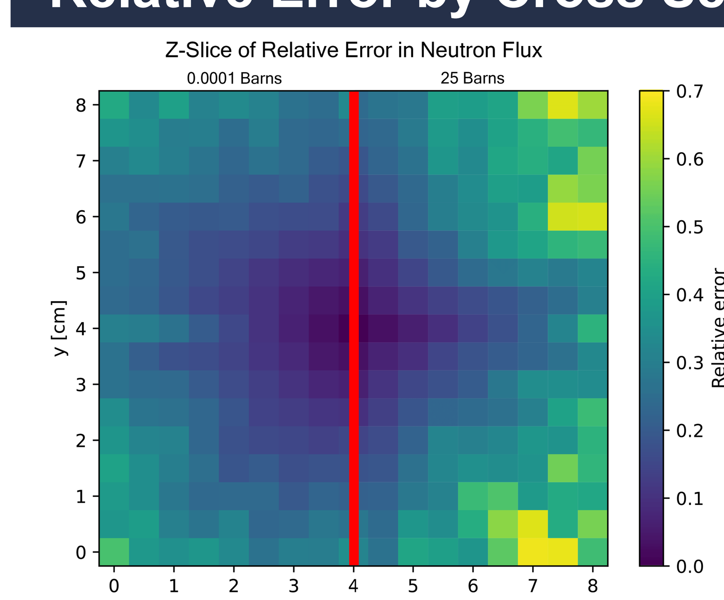

Fig. 6 – The distribution of error in two different cross sections with 10000 histories

Result

The error in neutron flux and cross section are proportional. A higher cross section decreases the probability of uncollided neutrons reaching areas farthest from the source. Therefore, increasing the cross section warrants higher uncertainty in distant areas, as less data can be extrapolated due to the lower probability of neutrons reaching those regions.

Relative Error by Number of Histories

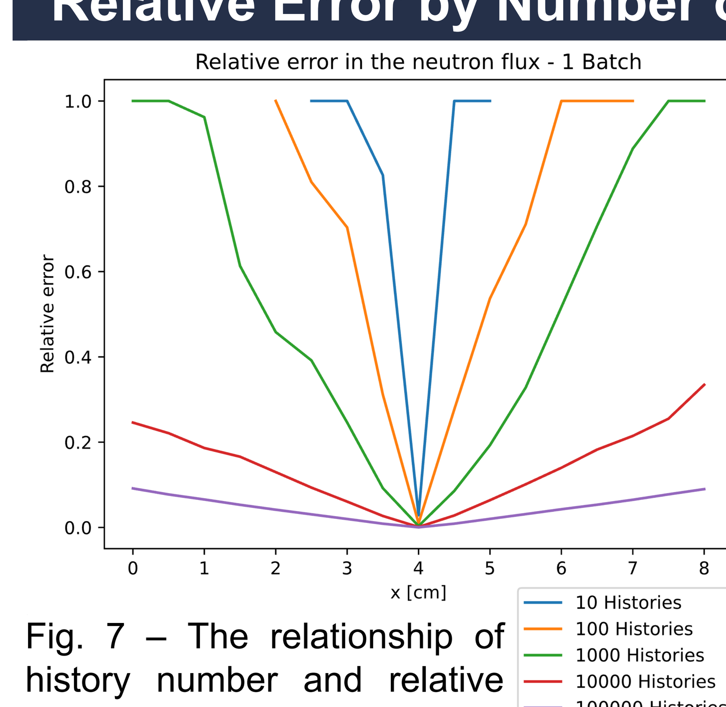

Fig. 7 – The relationship of history number and relative error in a cross section of 1

Result

This data depicts how the number of neutron histories taken affects the degree of error. Only one batch was used for this simulation (fig. 5). As more histories are taken, the relative error decays significantly. Plotting batches in this way warranted a similar result. Hence, an experiments accuracy is dependent on the number of histories or batches taken.

Results Cont.

Error and Run Time by History Ratios

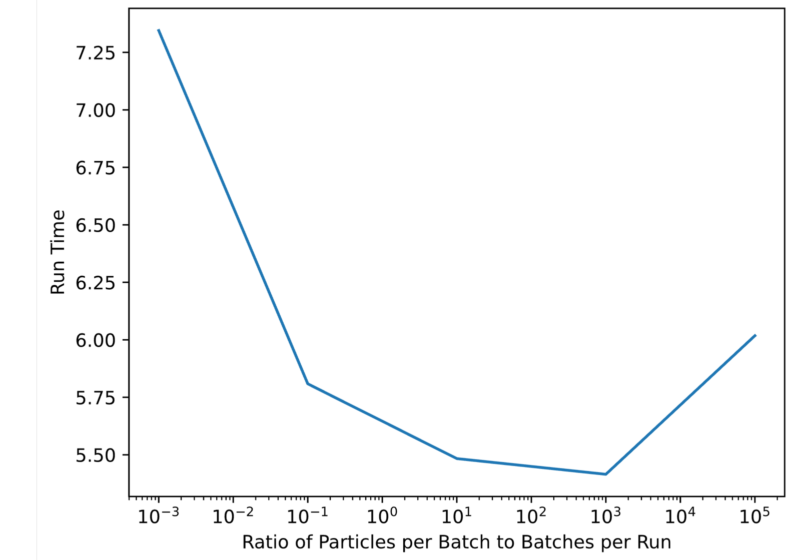

Fig. 8 – The relationship of run time with the ratio of particles per bath to batches per run

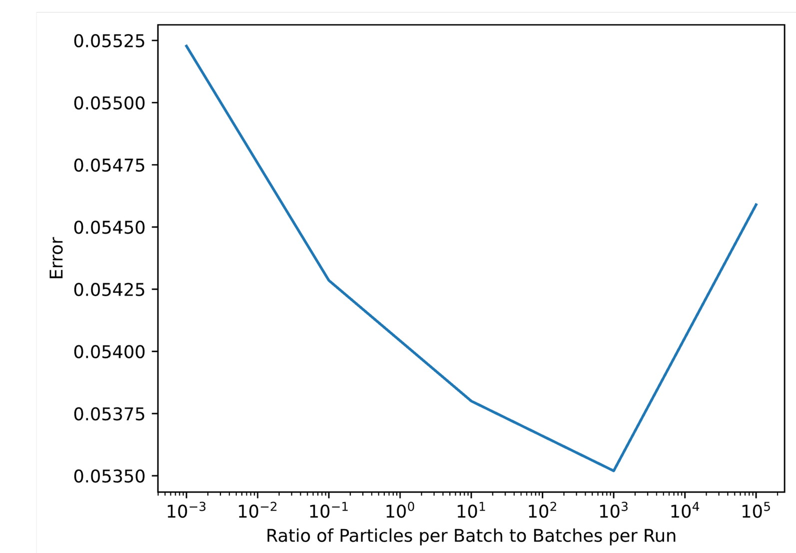

Fig. 9 – The relationship of relative error with the computational ratio

Result

Figure 8 demonstrates that there is a "sweet spot" of runtimes with the computer efficiency and accuracy. (Between ~10x more particles to 1000x more particles than batches). For future modeling, the error of a system does not significantly diminish with a cost-effective run-time to error ratio.

Figure 9 demonstrates an exponential decay in error until a critical point: >1000x more particles than batches. Here the error rises again.

These results, coupled with the "sweet spot" demonstrated in Figure 8, shows a region of accuracy and efficiency between 10x more particles and 1000x more particles that can be used to better and more efficiently model these interactions going forward.

Conclusion

The Monte Carlo method provides a useful means for the predictive modeling of a system of uncollided neutrons. Analysis into the specific parameters of these models allows for more accurate modeling within the methodologies demonstrated in the data. The Experimental data shows that increased histories, certain ratios for batch to history, and different cross section modeling all affect flux patterns and their error through a system. This data can optimize a simulation's efficiency and accuracy, but is limited by only measuring uncollided neutrons.

Acknowledgements

We would like to give special appreciation to Dr. Elliott Biondo, Dr. Matthew Swinney, and Mr. Loftin Gerberding for guiding our research and making this project possible. We are very grateful for the opportunity provided to us by Oak Ridge National Laboratory, Oak Ridge Associated Universities and the Appalachian Regional Commission. This support has been instrumental in advancing our understanding of applied sciences' relevancies in the world.

Citations

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Media X Group. (2023). *AP1000 - Westinghouse*. Nuclear Street. https://nuclearstreet.com/nuclear-power-plants/w/nuclear_power_plants/ap1000-westinghouse