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ASI Advanced Sensors and Instrumentation

Reactor Power Synthesis Studies: FY24 Updates and Findings

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Oak Ridge National Laboratory

Project Overview

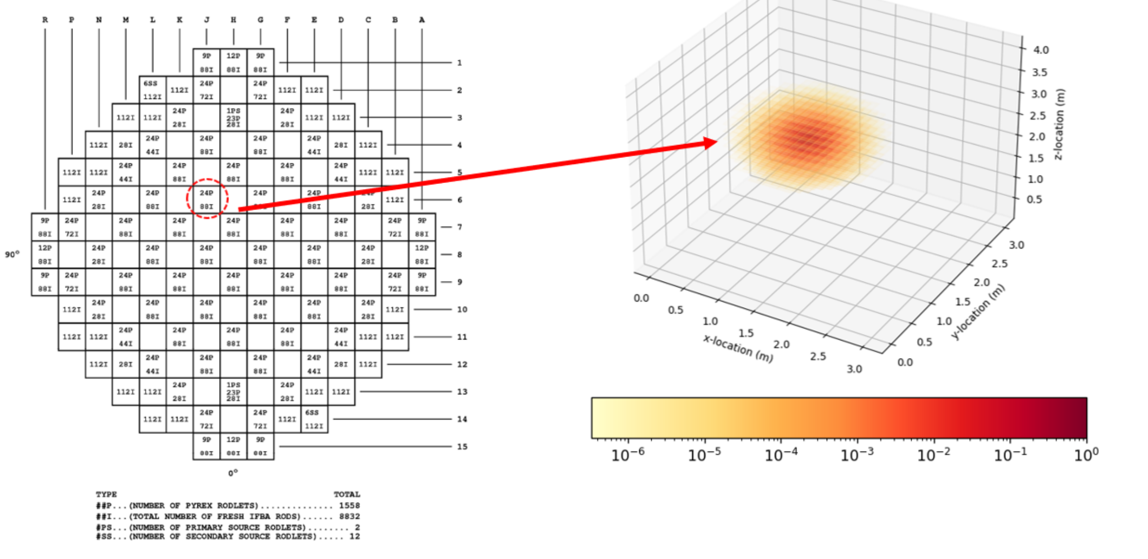
- The goal of this project is to utilize a weighting function based method to synthesize core power based on simulated sensor responses
  - Reactor models come from MCNP, sensor physics can come from Geant4
  - The method we use is called the point-based iterative (PBI) method (fundamentally similar to state-of-the-art methods)
- In FY24, there were to main focuses:
  1. **Assess the impact of realistic sensor physics on synthesis results**
  2. **Determine the extent to which ex-core sensors increase synthesis performance**
- Participants

  ORNL: Anthony Birri (PI), Callie Goetz (Geant4 modeling), Daniel Sweeney (python expertise), N. Dianne Bull Ezell (supervision)

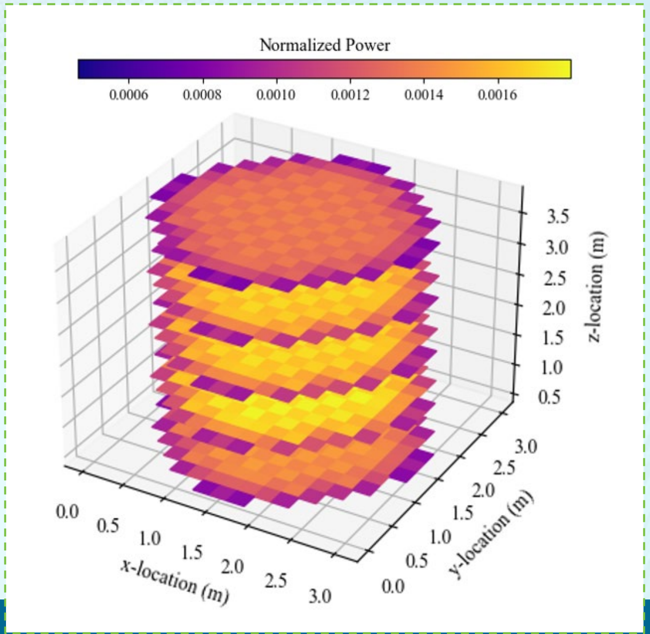
  INL: Kevin Tsai (experimental coordination)

  TAMU: Tyler Gates (MCNP modeling)

Simulate Sensor Responses

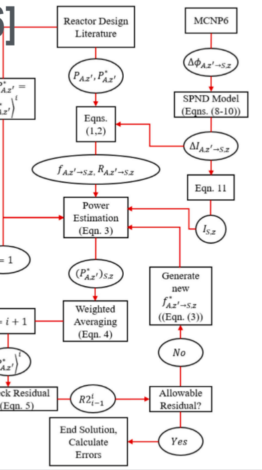


Infer Power Distribution



Developments to Date

[6]



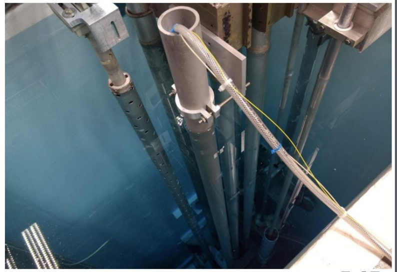


Figure 6.8: OFBGT-OSU-1 inserted into the WIF. [4]

Conceptualization for Gamma Thermometers

2019-2021

[1]

Theoretical basis

[2,3]

Perturbation analysis

[2,4,5]

Experimental integration

Adaptation to SPNDs

2022-2024

[6]

Theoretical modifications

[6,7,8]

Perturbation testing

[7]

Sensor uncertainty analysis

[9]

Realistic physics, sensor placement studies

Future Work

2025--

Additional experimental integration with SPNDs

Inclusion of other sensor types

[3]

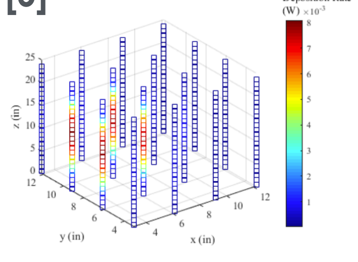
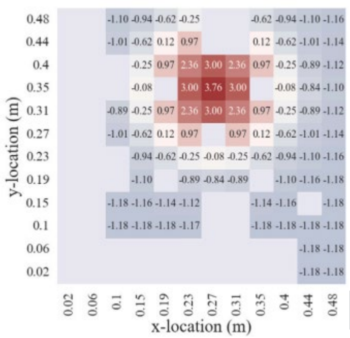
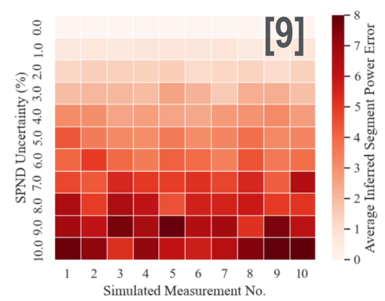


Fig. 7. Difference between the perturbed simulated measured dose rates and the unperturbed simulated dose rates ($\dot{D}^{*} - \dot{D}$).



[8]

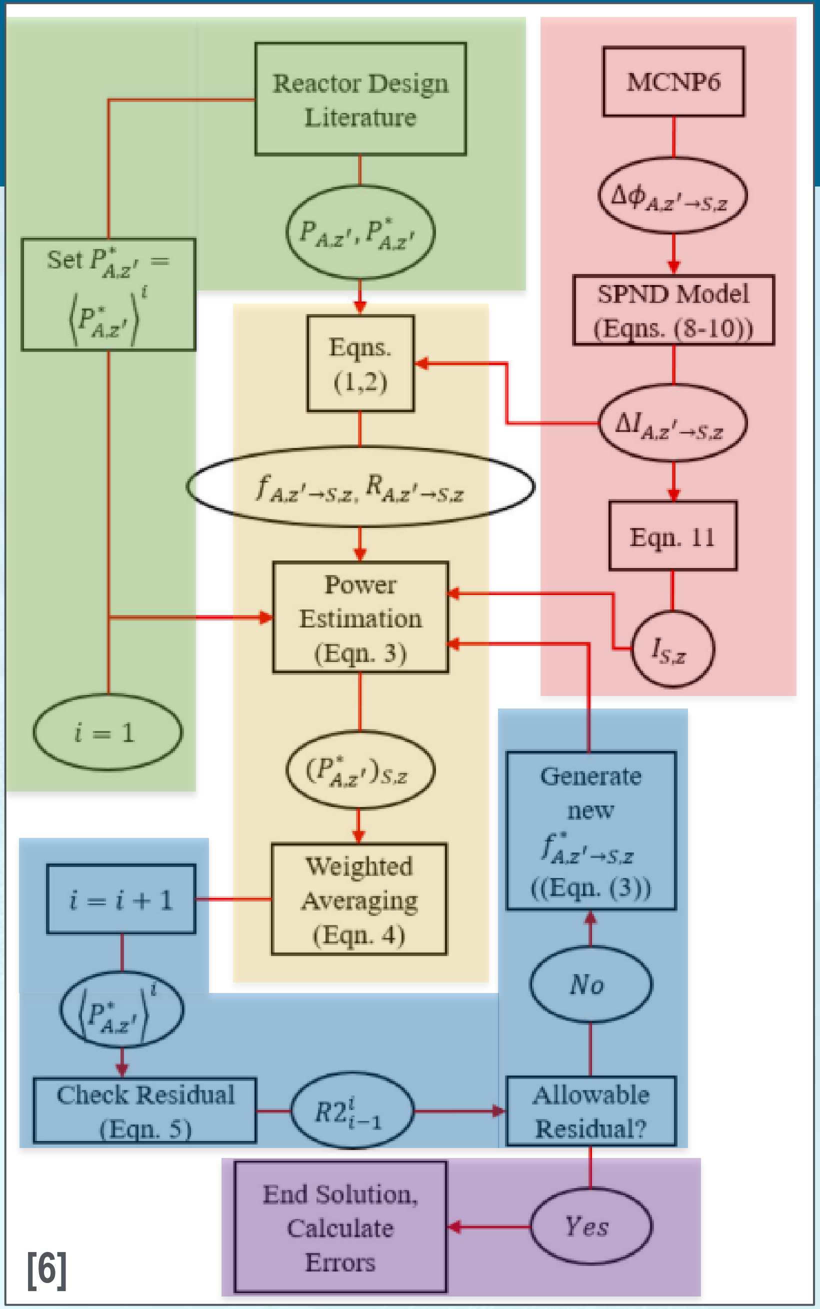


[9]

Methodology Description

An abbreviated description of the PBI method is given as follows:

1. Provide an estimate of the power distribution for some given reactor state
   - Can come from literature or direct Monte-Carlo calculation
   - Should account for physics like depletion, feedback effects, poisoning, etc.
2. Calculate signal contributions from individual fuel chunks to sensors
   - Flux contributions convert to signals from sensor models
   - These dictate response functions, which correlate local power to signal response
3. Use measured (or simulated measured) sensor signals to provide a weighted average which updates the power distribution
4. Perform an iterative process to update terms in the averaging scheme which are susceptible to perturbations
5. Minimize residual, finalize solution

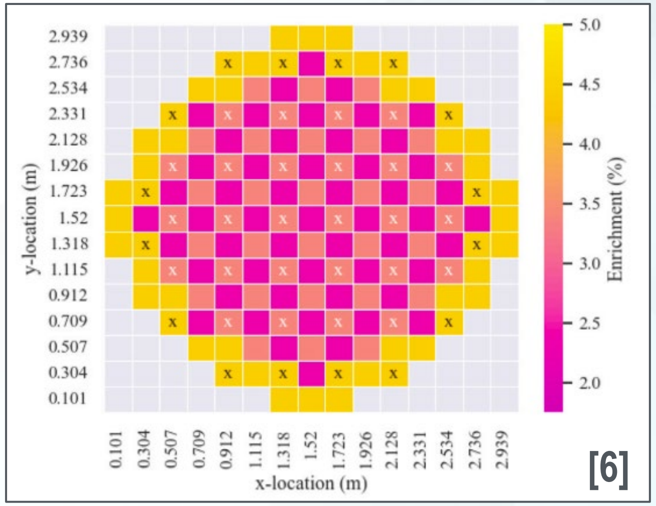


Equations referenced above can be found in [6]

Goal 1: Assess realistic sensor physics impact

- Both analytical models and Geant 4 models compared for AP1000 and NuScale, different burnup levels
- Power distribution data comes from heterogenous models, response functions from homogenous models
- Different power distribution fidelities and sensor string densities tested

AP1000 Fuel Arrangement (BOL)



NuScale SMR Fuel Arrangement (BOL)

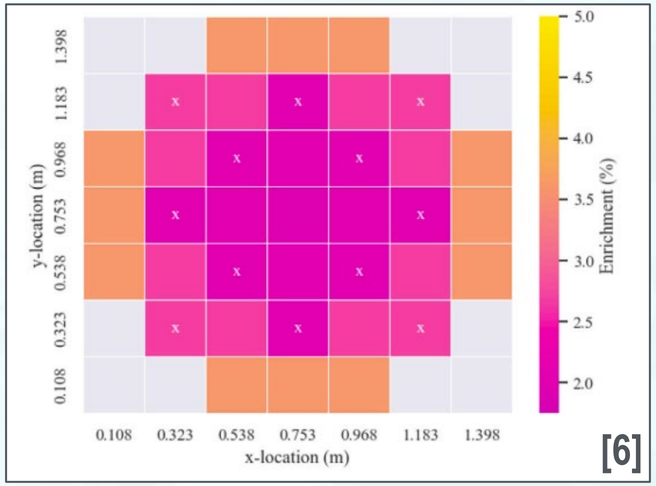
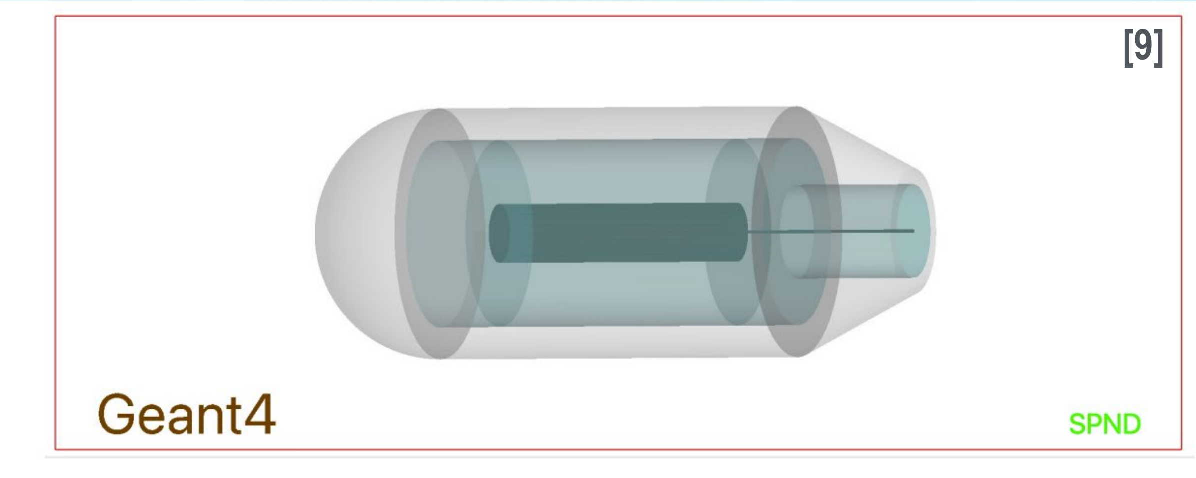


Table 1. Summary of the aspects of the two different goals of this study.

Aspect	Goal 1	Goal 2
Goal description	Assess realistic sensor physics impact	Assess ex-core sensor impact
Reactor model(s)	AP1000 and NuScale SMR	TAMU TRIGA
Response functions	Homogeneous	Heterogeneous
SPND Model	Geant4 and analytical	Analytical
Perturbation type	From fuel burnup	Gaussian-type
Comparisons to perform	Geant4 versus analytical SPNDs	In-core only versus in-core plus ex-core sensors
Metrics of comparison	Error and total iterations	Error and total iterations

[9]

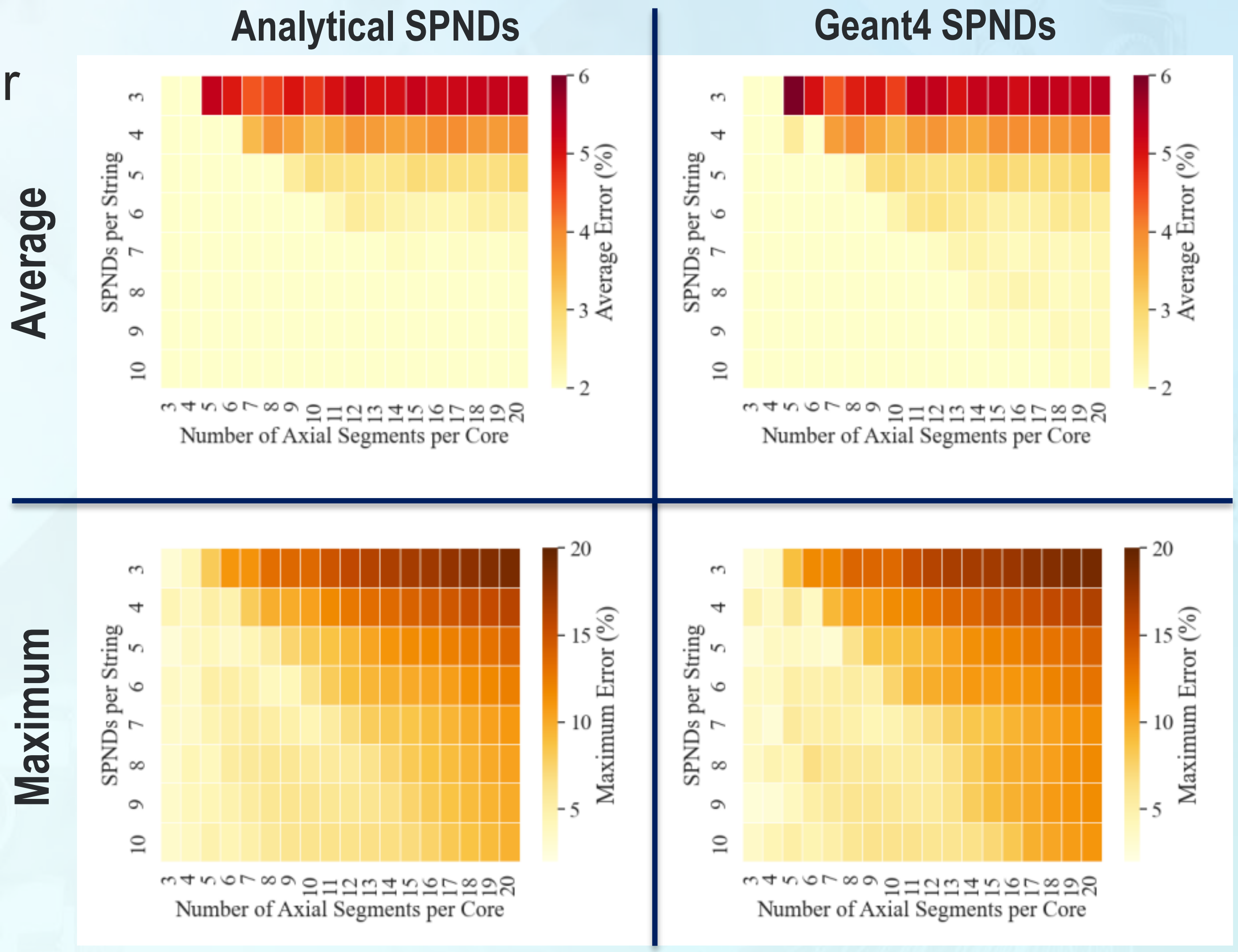
SPND in Geant4



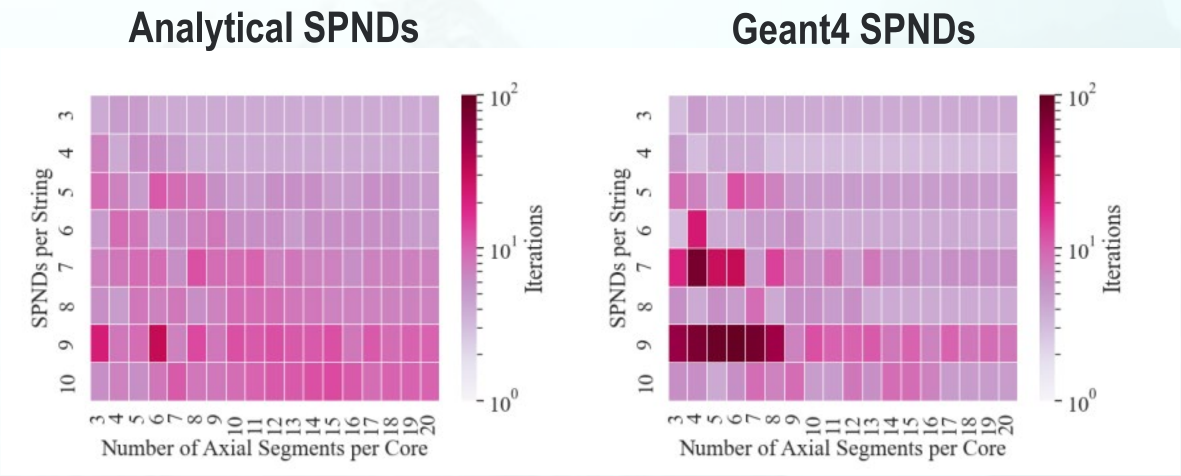
Goal 1 Results

- Results from NuScale MOL burnup condition (BOL a priori assumption) shown here
  - Similar trends observed for AP1000 [9]
- Little difference in average and max synthesis error
  - Note that error is due to the “assumed” distribution being different than the “ground truth” perturbed distribution
- Difference in convergence time results, meaning Geant4 is important for understanding runtime considerations

Error for NuScale MOL Synthesis



Number of Iterations for NuScale MOL Synthesis



Goal 2: Assess ex-core sensor impact

- A fully heterogeneous model was considered for the TAMU TRIGA to test inclusion of ex-core sensors
  - This is relevant for future experimental testing in this reactor with SPNDs
  - Analytical Geant4 models used due to model heterogeneity
- Small perturbations moved to each fuel pin to see how synthesis accuracy changes versus perturbation location

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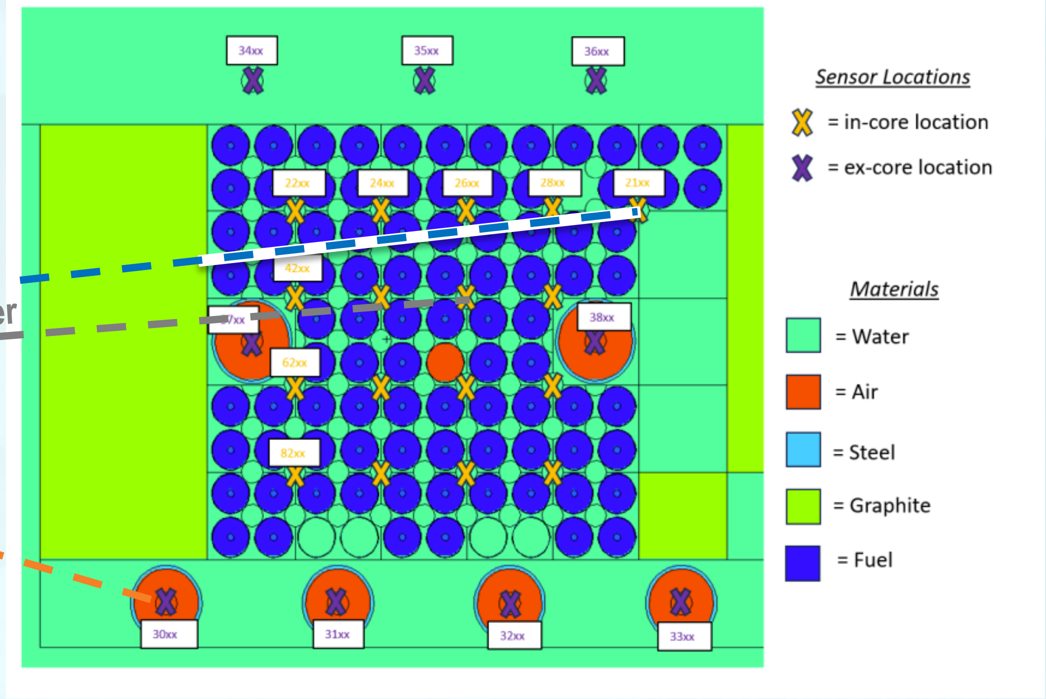
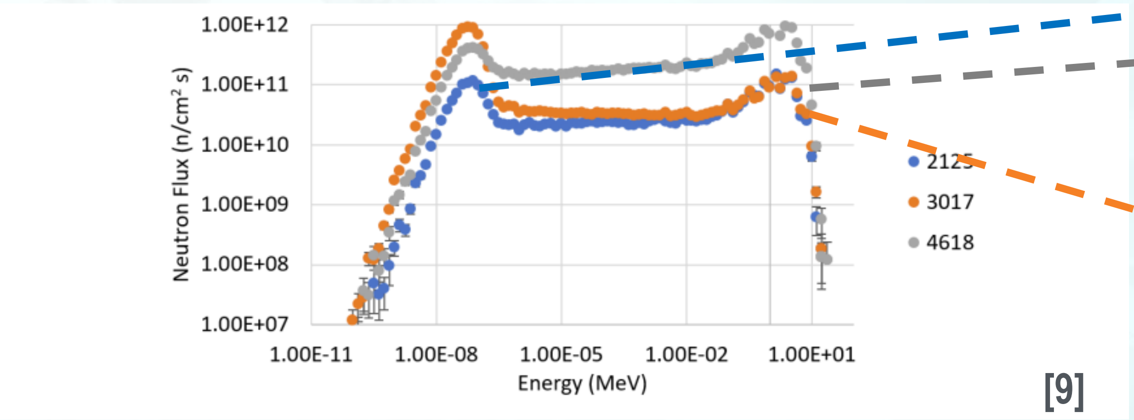
TAMU TRIGA MCNP model



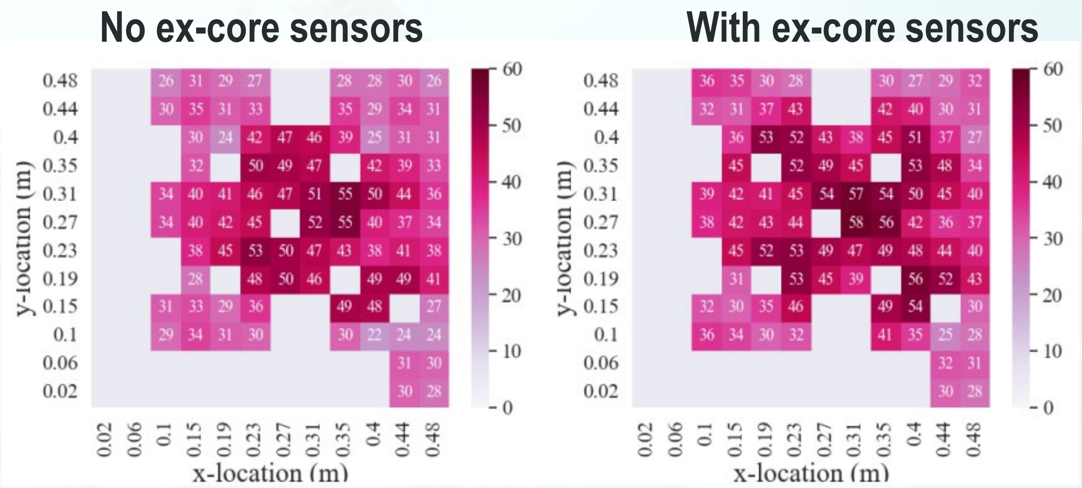
Neutron fluxes for various TAMU TRIGA locations



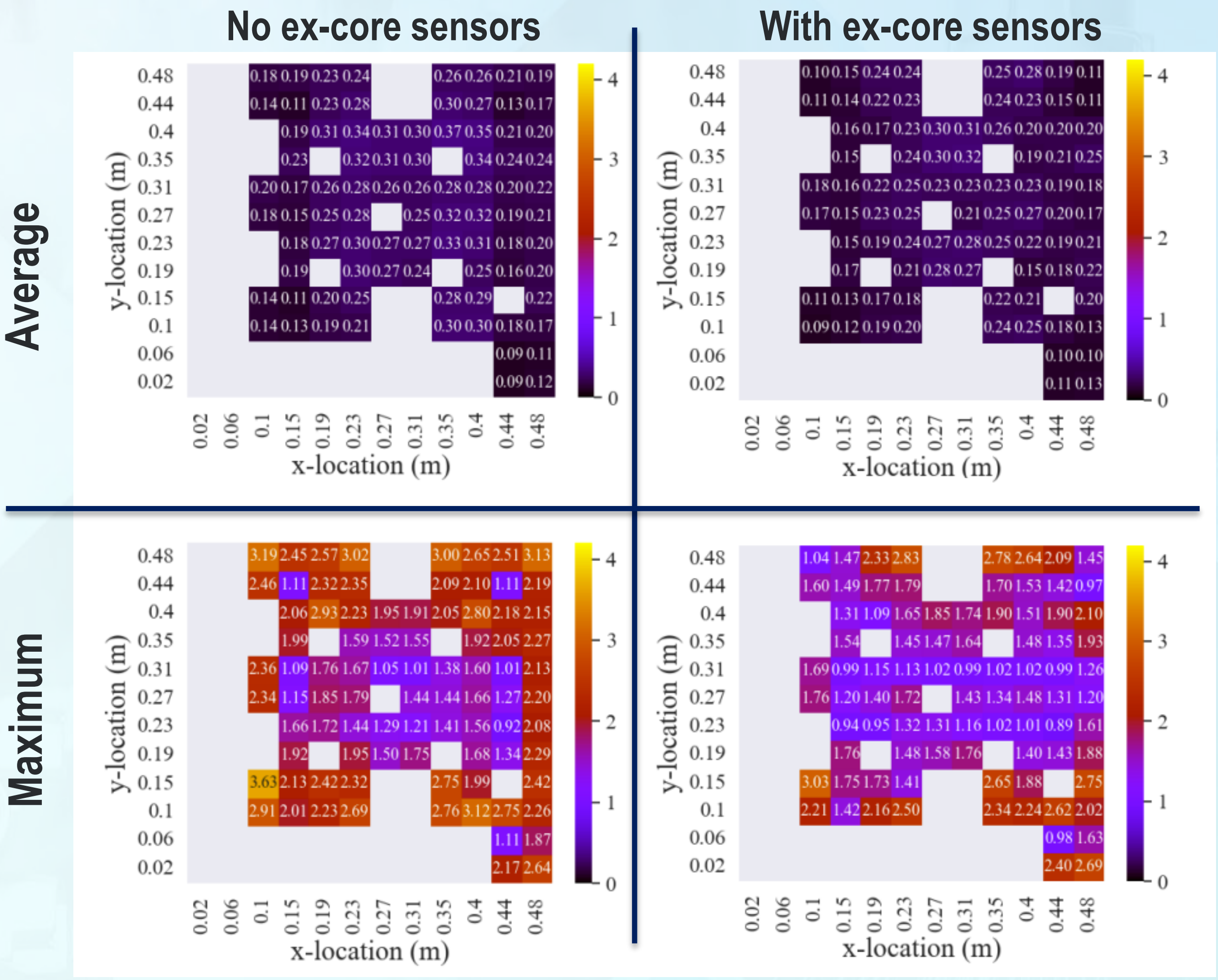
Goal 2: Results

- Results from TAMU TRIGA study show ex-core sensors improve accuracy resolving perturbations
  - Big impact for peripheral locations
  - Small impact for central locations
- Computational cost increase is minimal
- This study shows ex-core sensors assist in power mapping of the full core
  - For power peaking considerations, in-core sensors may be sufficient

Number of Iterations Versus Perturbation Location



% Error for TAMU TRIGA



Conclusion

- The PBI method is principally similar to state-of-the-art methods for power distribution monitoring and provides a tool for simulation studies of power distribution synthesis
- Previous work has shown that this method can be used for multiple sensor types, and has enabled studies of fuel burn-up effects, sensor uncertainty impacts, sensor arrangement considerations, and more
- This study FY24 had two goals:
  1. **Assess the impact of realistic sensor physics on synthesis results**
  2. **Determine the extent to which ex-core sensors increase synthesis performance**
- The primary finding of study 1 is that analytical models may be sufficient for determining method accuracy, but Geant4 should be used for determining real-time capabilities
- The primary finding of study 2 is that ex-core sensors yield significant improvement on synthesizing peripheral power distribution perturbations

References

1) Birri, Anthony, and Thomas E. Blue. "Methodology for inferring reactor core power distribution from an optical fiber based gamma thermometer array." *Progress in Nuclear Energy* 130 (2020): 103552.
2) Birri, Anthony. *The development of an optical fiber based gamma thermometer*. The Ohio State University, 2021.
3) Birri, Anthony, et al. "Data analytic methodology for an optical fiber based gamma thermometer array." *Transactions of the American Nuclear Society* 123.2020 (2020).
4) Birri, A., J. T. Jones, and T. E. Blue. "Testing of an Optical Fiber Based Gamma Thermometer in the Ohio State University Research Reactor." *Transactions of the American Nuclear Society* 125.1 (2021): 982-985.
5) Gates, J. Tyler, and Pavel V. Tsvetkov. "Testing of fiber optic based sensors for advanced reactors in the Texas A&M University TRIGA reactor." *Annals of Nuclear Energy* 196 (2024): 110222.
6) Birri, Anthony, Daniel C. Sweeney, and N. Dianne Bull Ezell. "Simulating self-powered neutron detector responses to infer burnup-induced power distribution perturbations in next-generation light water reactors." *Progress in Nuclear Energy* 153 (2022): 104437.
7) Birri, Anthony, et al. *Towards Realistic and High Fidelity Models for Nuclear Reactor Power Synthesis Simulation with Self-Powered Neutron Detectors*. No. ORNL/TM-2023/3009. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), 2023.
8) Birri, Anthony, et al. "A simulation study of the ability to detect power distribution perturbations in the Texas A&M TRIGA reactor with self-powered neutron detectors." *Progress in Nuclear Energy* 172 (2024): 105200.