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Designing a Deimos-based Microreactor Criticality Experiment with MCNP and Whisper

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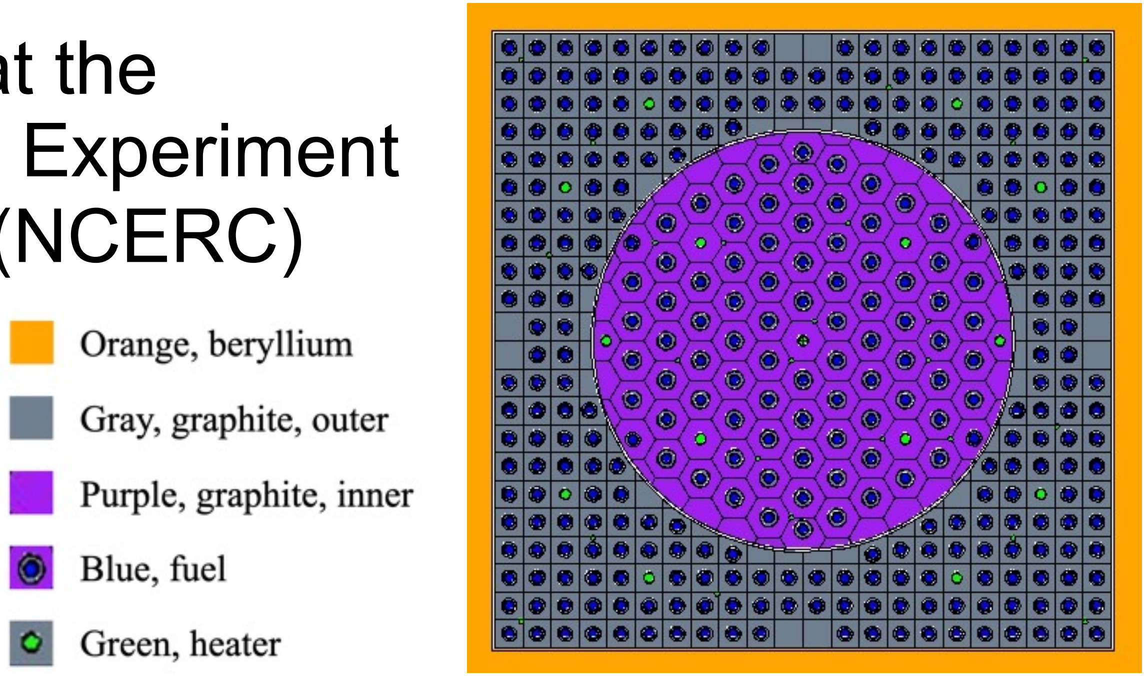
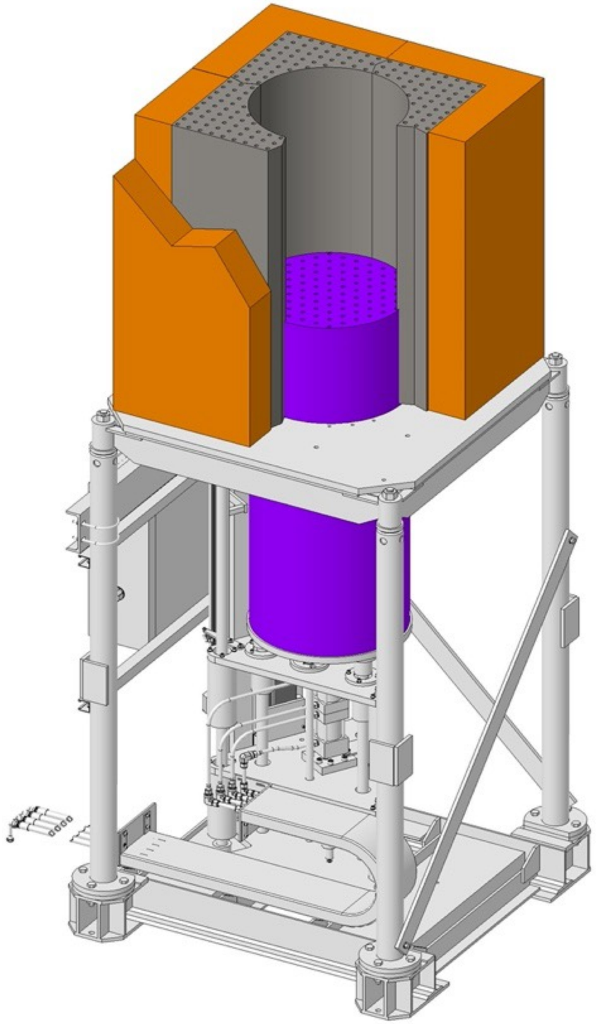
Introduction

- Experiments needed to better understand materials, reactivity, system behavior for advanced reactor concepts
  - Benchmark physics codes
  - Stepping-stone to full-scale prototype
    - Affordable and easier to execute
- **How do we know an experiment is representative of the full-scale system?**
  - For steady-state criticality simulations, correlation coefficients (C_k) are used
  - For transient simulations, work is underway to expand similarity coefficient framework with coupled multiphysics sensitivities

Deimos Experiment

- Graphite-moderated, beryllium-reflected, high assay low-enriched uranium (HALEU) tri-structural isotropic (TRISO) fueled experiment planned for summer 2024
- Will be executed at the National Criticality Experiment Research Center (NCERC)





Deimos Experiment

- Will be heated to 150℃ to validate nuclear data at various temperatures
- Testbed for future advanced reactor experiments targeting +800 ℃ temperatures
- Potential benchmark for the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhE)

Theory - C_k Similarity Parameter

$$C_k(A,B) = \frac{S_A C_{xx} S_B^T}{\sqrt{S_A C_{xx} S_A^T}\,\sqrt{S_B C_{xx} S_B^T}}$$

Where:

- S_A and S_B^T are the sensitivity row vectors of systems A and B respectively
- C_{xx} is the nuclear data relative covariance matrix
- T is the transpose operator
- $C_k(A,B)$ is the correlation coefficient

Sensitivity coefficients are produced via Adjoint-based First-Order Perturbation Theory.

Theory - E_k Similarity Parameters

$$E_k(A,B) = \frac{S_A I_{xx} S_B^T}{\sqrt{S_A I_{xx} S_A^T}\sqrt{S_B I_{xx} S_B^T}}$$

Where:

- I_{xx} is the identity matrix in the same shape as the nuclear data covariance matrix

Unlike C_k, E_k does not fold in the nuclear data uncertainty, meaning it represents only the overlap between each system's sensitivity coefficients with respect to k for all nuclear data available

Methodology

- Monte Carlo N-Particle (MCNP6) code
  - Radiation Transport Code
  - Can generate sensitivity coefficients
- Whisper statistical code
  - Generates correlation coefficients, upper subcritical limits, and more with sensitivity coefficients
  - Whisper-tk is a Python version of Whisper that can be used to generate E_k similarity parameters and percentage of contributions to uncertainty

Similarity Coefficients for Deimos - ICSBEP

Table I. Top 10 C_k Benchmarks for the Deimos experiment and ICSBEP benchmarks

Benchmark	C_k	E_k
leu-comp-therm-028-017.i	69.06%	81.73%
ieu-comp-therm-002-003.i	69.06%	83.46%
leu-comp-therm-028-020.i	68.55%	81.54%
leu-comp-therm-028-018.i	68.40%	81.62%
leu-comp-therm-028-014.i	67.63%	83.28%
leu-comp-therm-028-019.i	67.59%	81.21%
leu-comp-therm-028-012.i	67.53%	83.27%
leu-comp-therm-028-016.i	67.32%	81.06%
leu-comp-therm-060-005.i	67.11%	87.22%
leu-comp-therm-060-006.i	66.88%	94.40%

Similarity Coefficients for Deimos – IRPhE and Others

Table II. Top C_k Benchmarks for the Deimos experiment and IRPhE benchmarks and select advanced reactor concepts

System	C_k	E_k
cnps_v58.i	84.42%	96.22%
snowflake_beo_300k_v0.i	78.83%	94.47%
htr10_gcr_resr_001_001.i	78.79%	92.68%
proteus_gcr_exp_001_001.i	77.58%	93.69%
vhtr_v0.i	76.34%	93.06%
snowflake_yh_300k_v0.i	72.94%	93.85%
rbmk_exp_001_001.i	63.23%	85.02%
agr_v0.i	57.43%	90.01%

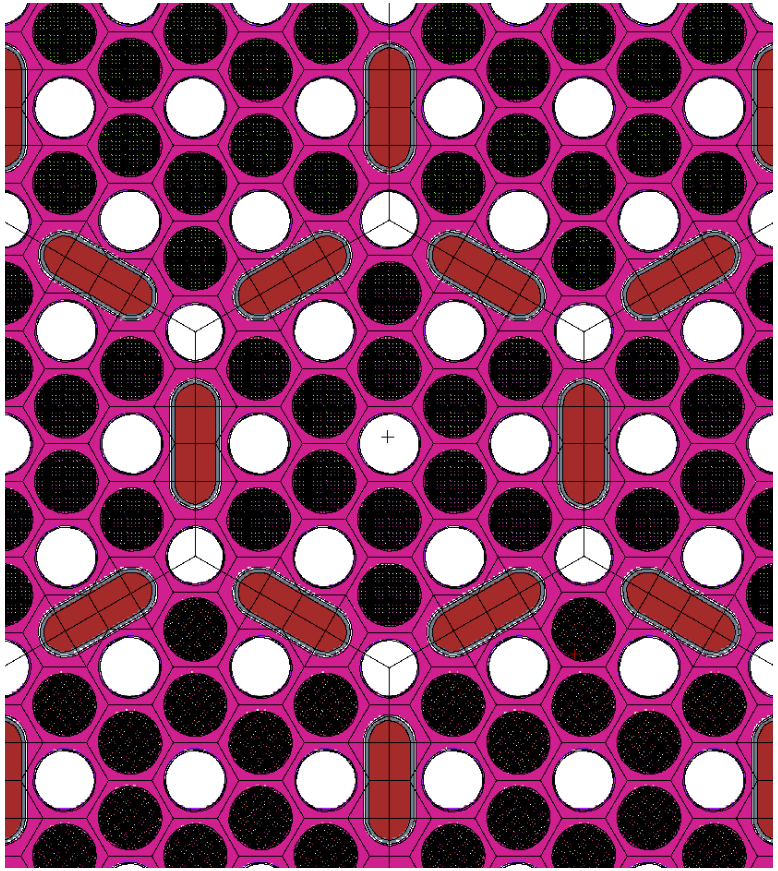
Takeaways

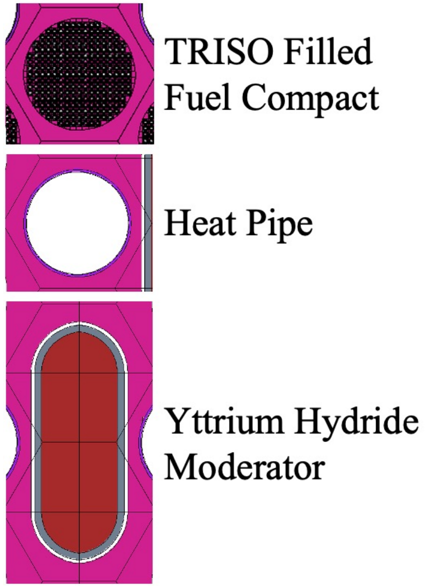
- Deimos is a unique experiment for both the ICSBEP and IRPhE benchmark suites
- Highest correlation coefficient is to the Compact Nuclear Power Source (CNPS) experiment, which uses the same fuel

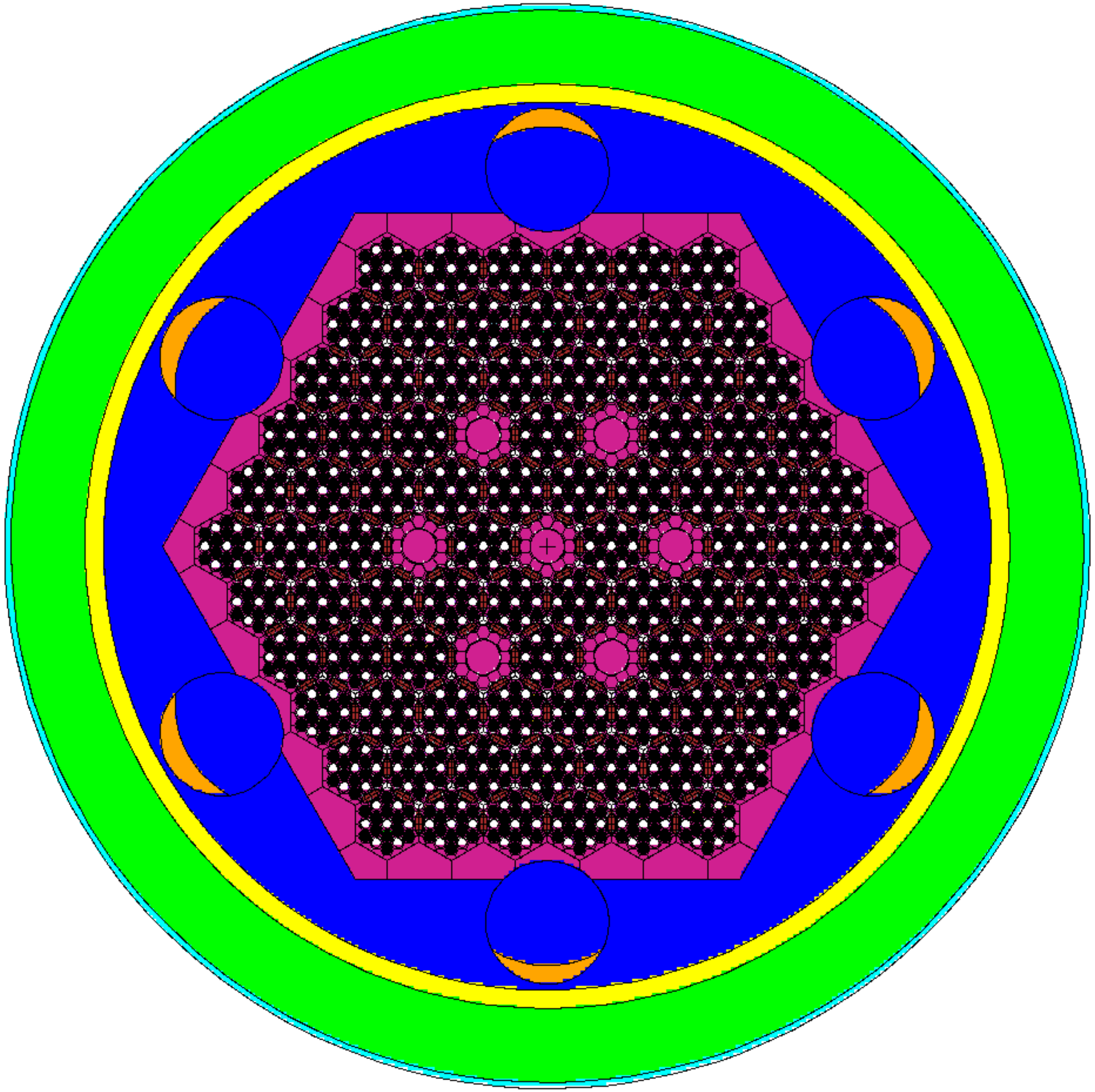
Designing a Microreactor Criticality Experiment with over 95% C_k

- The Nuclear Regulatory Commission (NRC) recommends a correlation coefficient of at least 90% for a demonstration of similarity for Nuclear Criticality Safety applications
- Designing such an experiment for an advanced reactor concept greatly improves confidence in nuclear data for conceptual design
- Experiments ($10M) can act as a stepping-stone to a full-scale proptotype ($100M+)

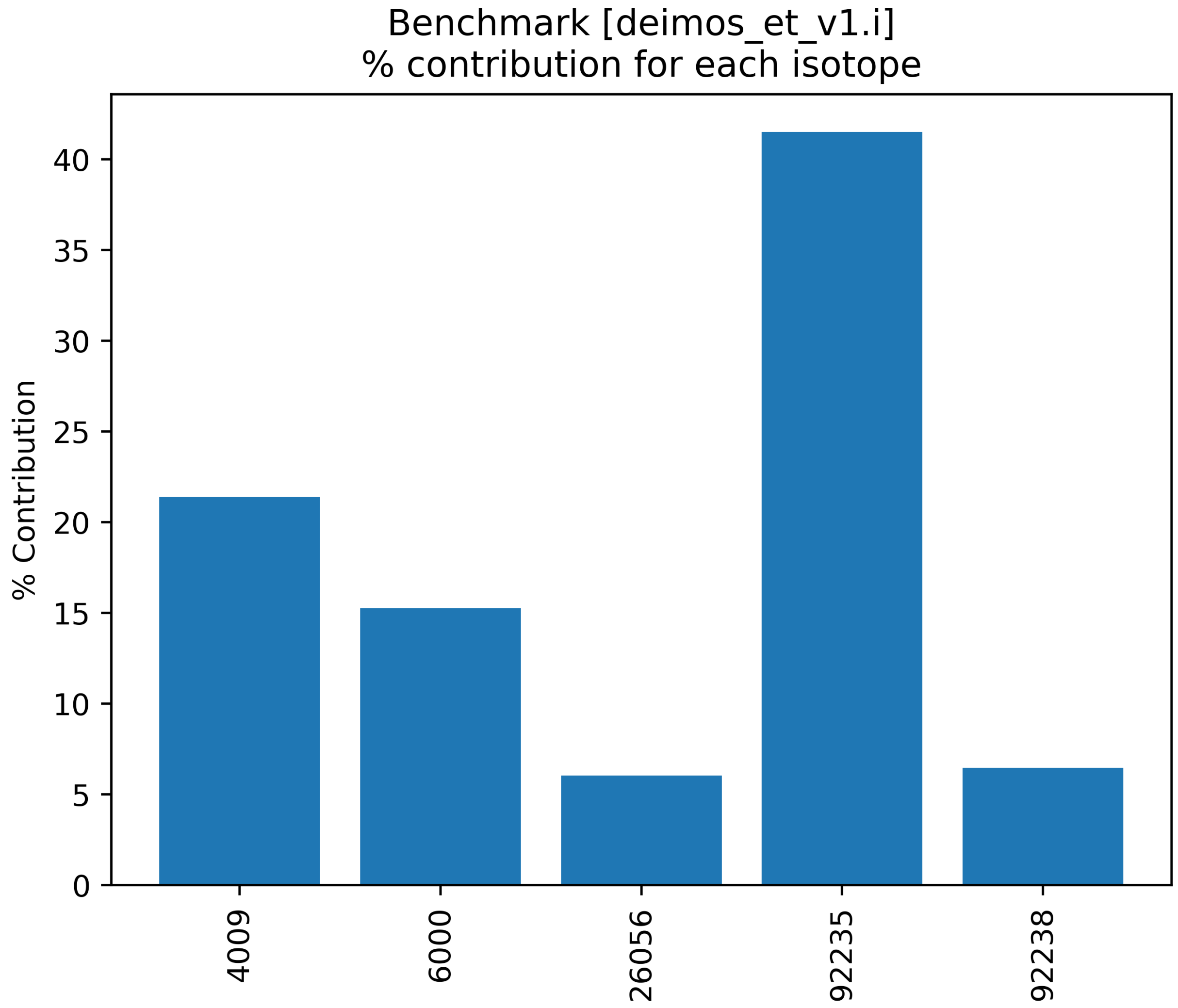
Snowflake Microreactor

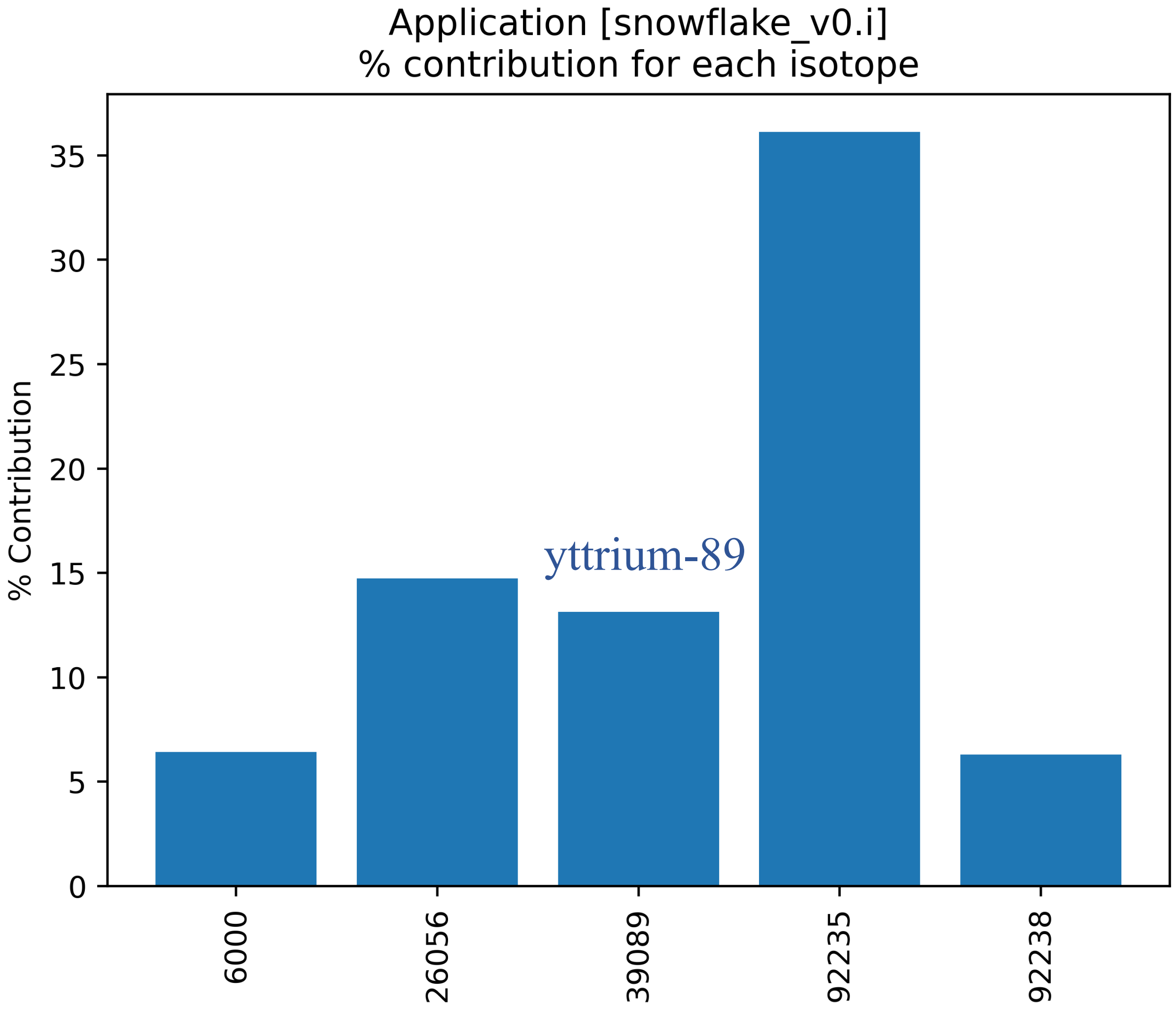




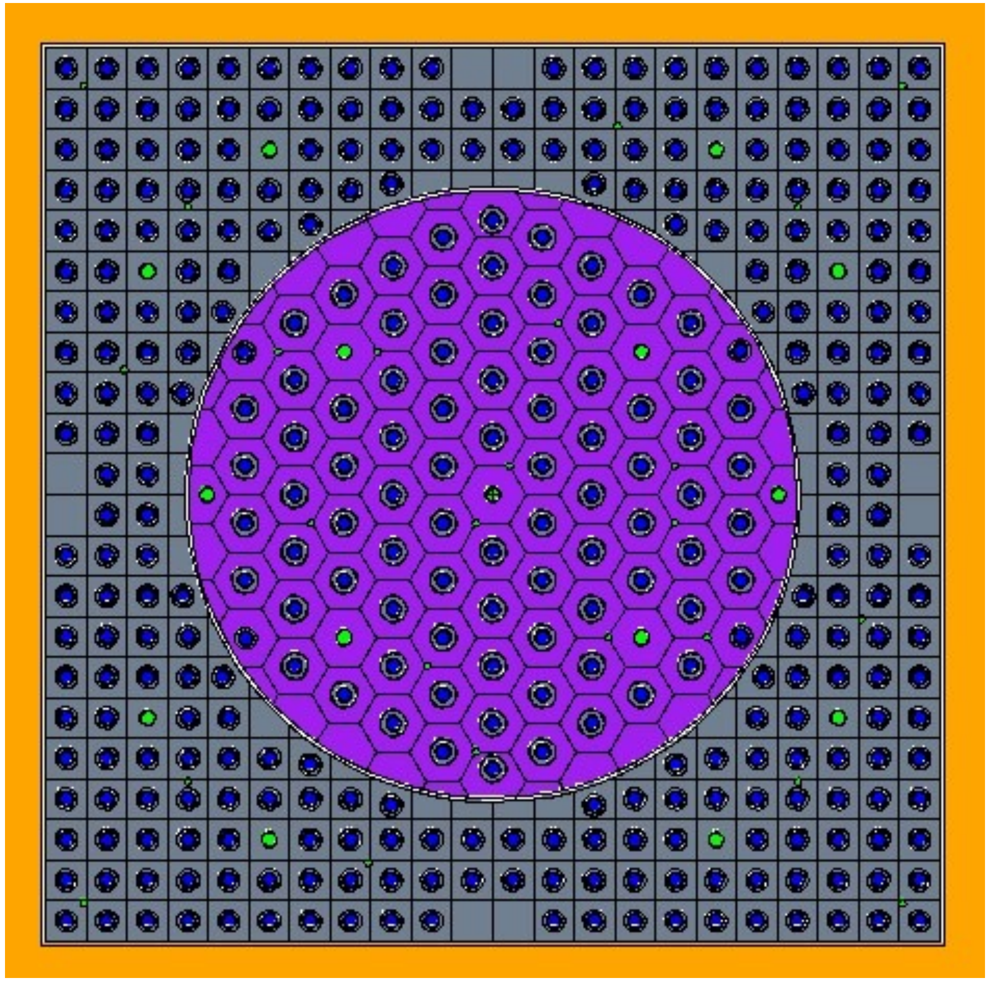


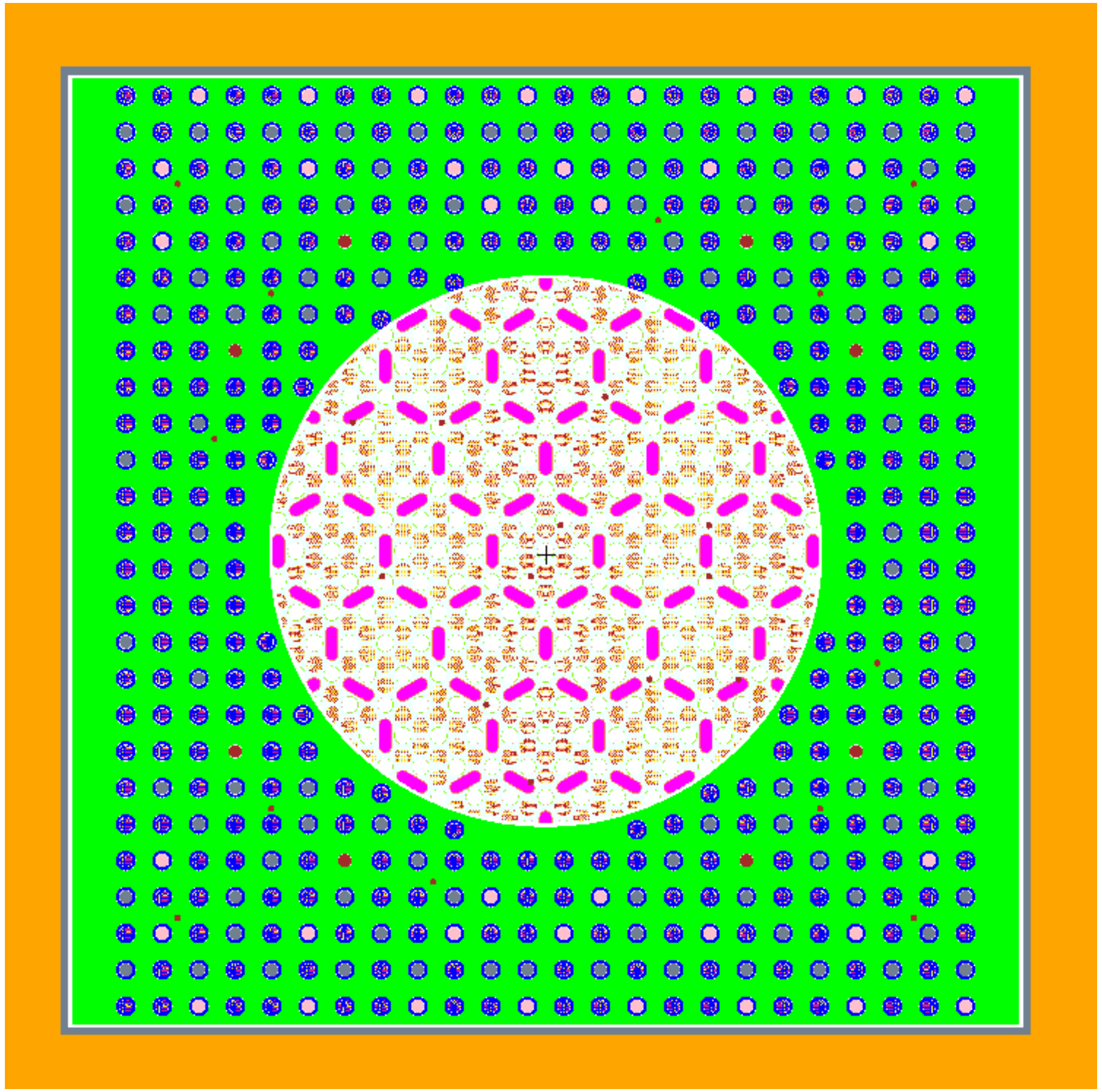
Nuclear Data Uncertainty Contributors





Deimos V0 and V32





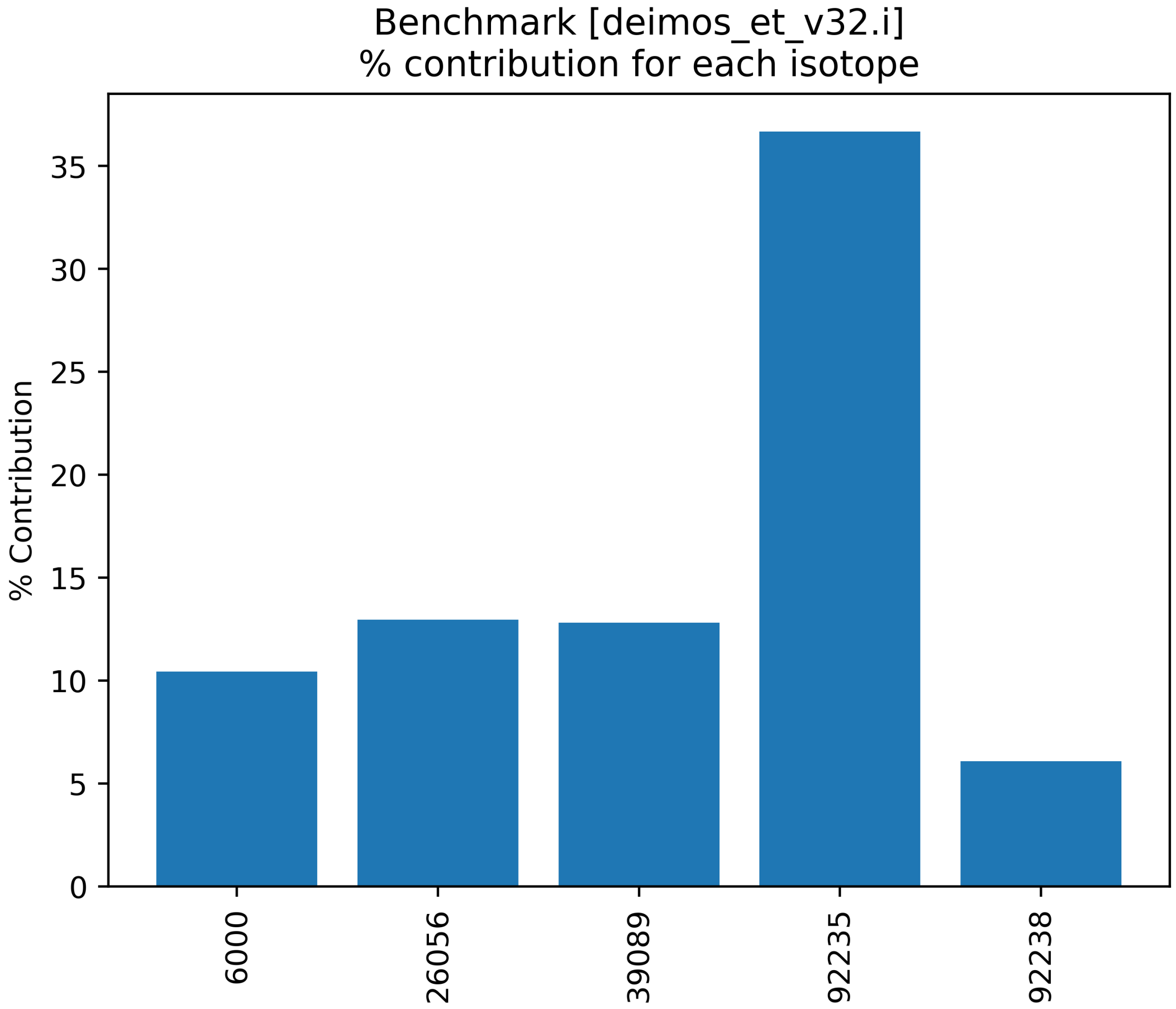
Deimos Iterations

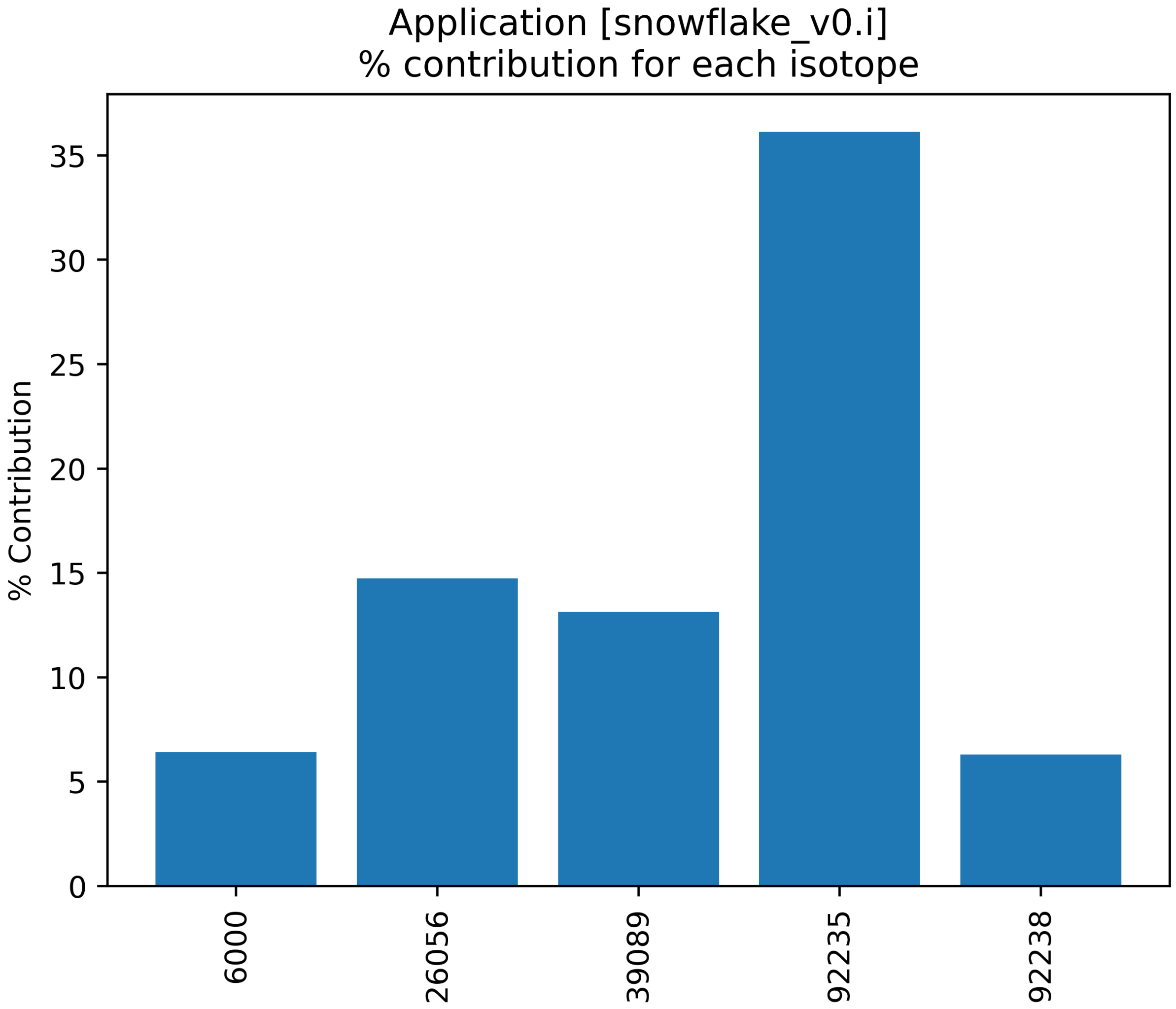
- Added fuel and heat pipes to the outer region
- Added Snowflake microreactor unit cells to the inner region

Table III. Deimos-like experiment similarity coefficients with Snowflake microreactor

	Snowflake, 300 K C_k	Snowflake, 1200 K C_k	Snowflake, 300 K E_k
Deimos V32	96.26%	94.17%	98.78%

Nuclear Data Uncertainty Contributors





Conclusions

- Planned experiment for 2024
  - Will validate MCNP criticality, heat conduction, kinetics, and multiphysics simulations
  - Deimos will act as a testbed for future advanced reactor experiments
- Deimos would be a unique benchmark that covers a new region of nuclear data sensitivities and uncertainties in both the ICSBEP and the IRPhE
- Deimos can be modified to maximize similarity i.e. capture nuclear data uncertainties in experiment for advanced reactor concepts

Acknowledgements

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