NETS 2026

Accelerating SNP Development with Radiation Source Approximations for Far-Field Environment Modeling

Eleni Mowery

Nuclear Engineering Intern, AMA

Corey Smith (AMA), Benoit Forget (MIT), Jarvis Caffrey (MSFC)

April 30th, 2026

ANS® American Nuclear Society

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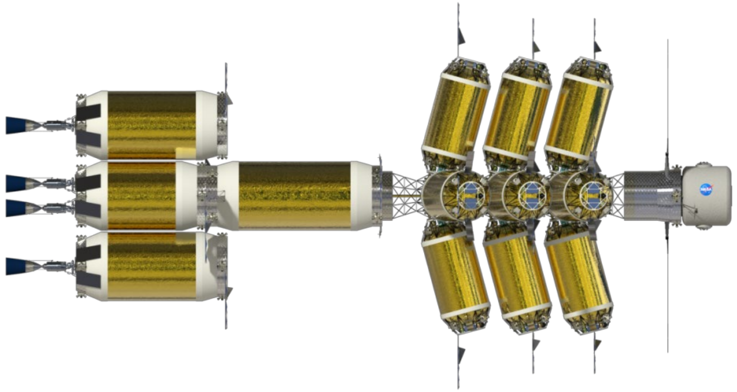
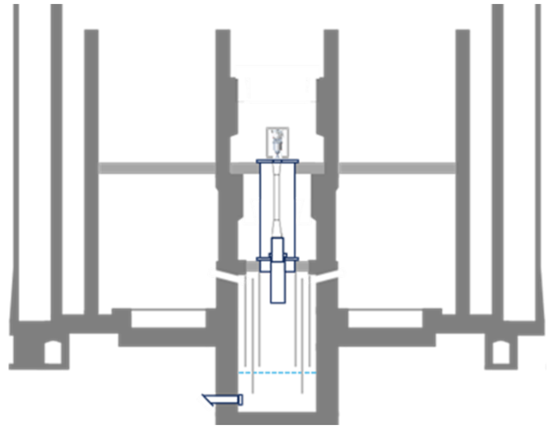
Motivation for Space Nuclear Systems

Modeling radiation environments outside of SNP reactors is a critical to informing system design and fulfilling regulatory requirements

Photon and neutron flux from the core causes:	Quantifying these effects is critical for the design of:
Heating of ex-core systems (e.g., propellant tanks)	Materials selection, propellant tank placement and design, heat rejection systems
Damage to sensitive components (e.g., photovoltaics, sensors, micro-electronics)	Electronic component selection and requirements, spot-shielding placement and mass
Human radiation exposure	Reactor and shield design and mass
Displacement damage to materials	Materials testing requirements



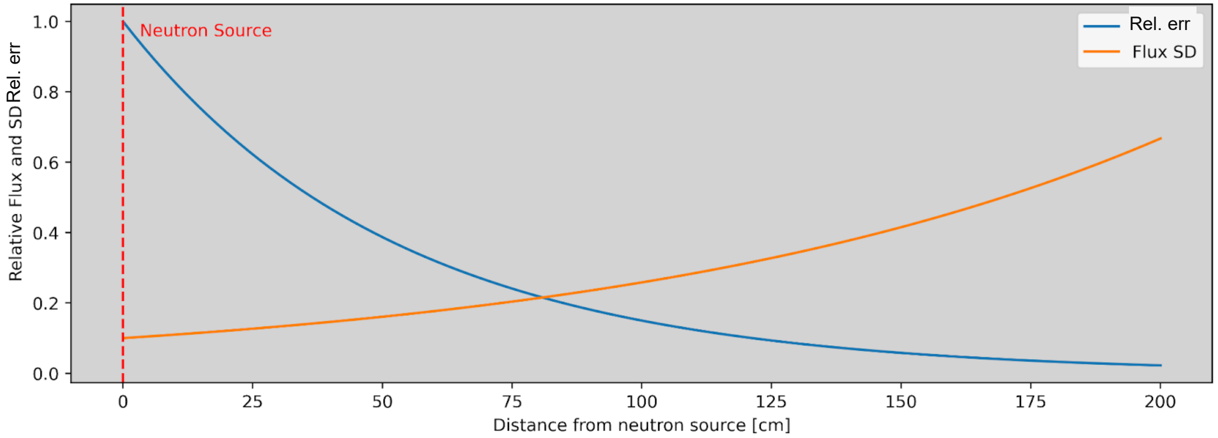
For ground testing and in-space operation of SNP reactors, flux fields must be quantified through regions far from the active reactor core(s).



Primary Challenge: Computational Inefficiency

- **Monte Carlo methods are the most accurate for modeling radiation transport to analyze heat deposition, dose, and localized damage effects**
- **Consequently, uncertainty on these quantities is inversely proportional to the number of particles simulated in a region**

  → Monte Carlo methods become increasingly inefficient with distance from the active core



Neutron attenuation through a solid graphite slab

The goal: Maintain the accuracy of a Monte Carlo approach in far-field regions without the significant computational inefficiency.

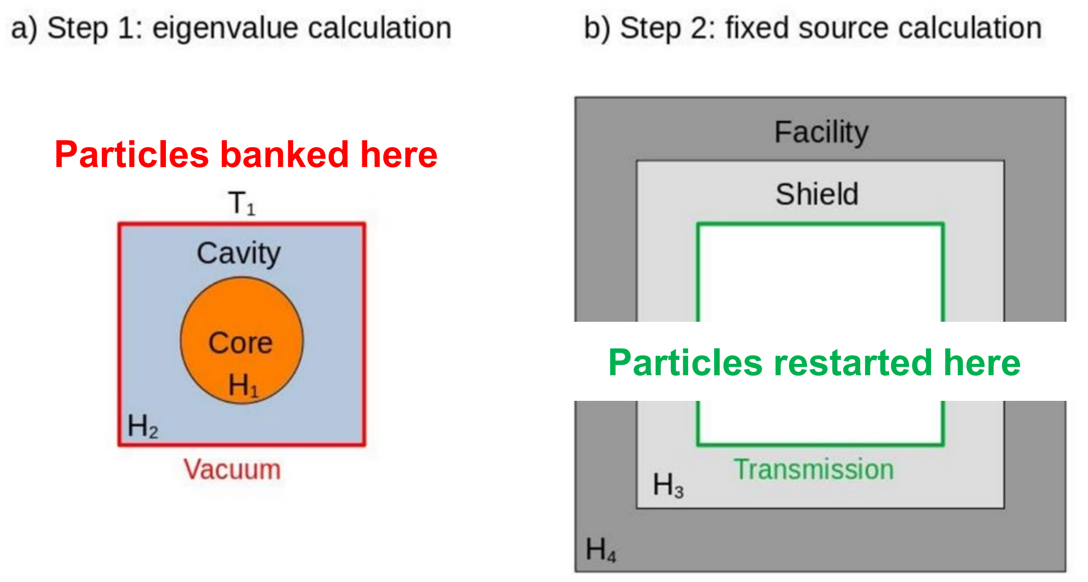
Solution: Surface Source Banking (SSB)

- **Particles are "banked" during an eigenvalue case, and restarted during a fixed source case**
- The particles can be restarted on different geometry, allowing **a clean interface between CAD and CSG geometry**
- **This can significantly accelerate ex-core transport**

- **This work →** Overcome the primary limitations associated with SSB:

No metric to tell when a source is properly defined	Oversampling bias limits future simulations limited to number of particles originally banked
Stationarity criterion implemented to indicate when sources have converged (reached "stationarity") to a desired resolution	Sources verified to have reached stationarity can be used to develop a set of parameters to generate new particles (**"analytically defined"** sources)

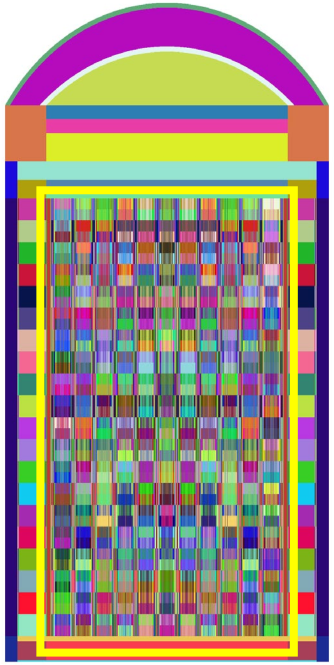
- This capability is contained entirely within an AMA code package, ASG1.0



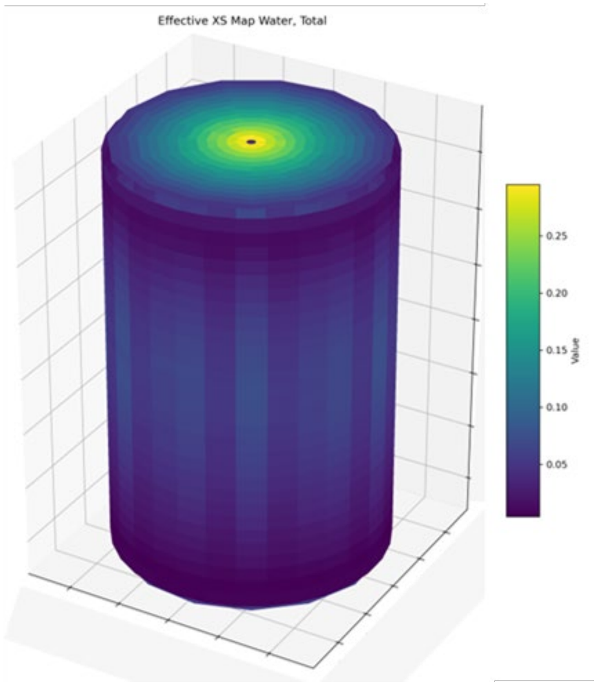
Generic Two-Step Approach [1]

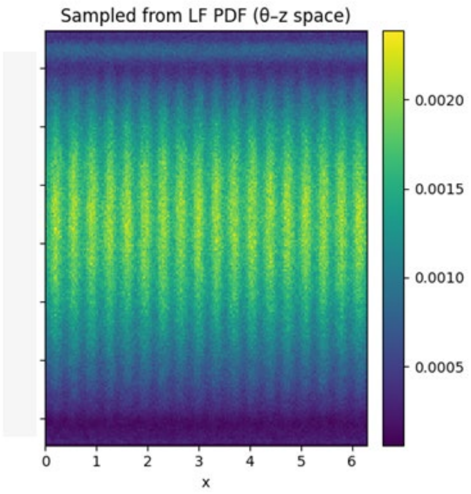
Process Overview

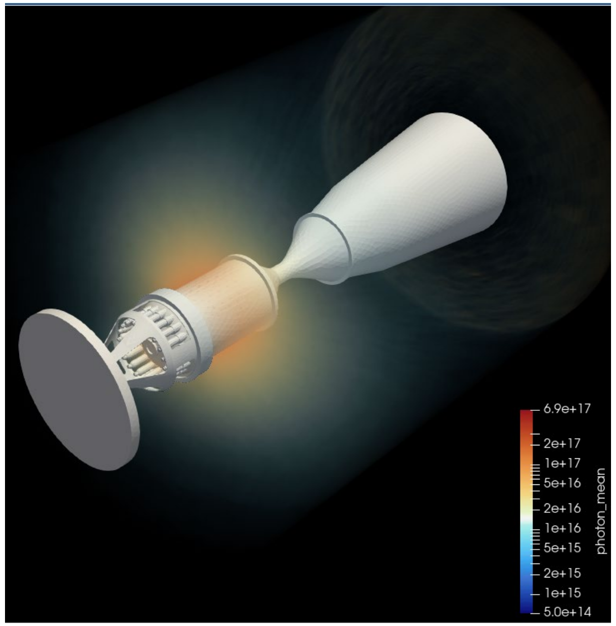
Eigenvalue Case for Source Banking → **Source Bank Validation** → **Validated source bank used to generate parametrized source** → **Integrated parametrized source with ex-core geometry**



Banking Surface







Source Generation (x1 per reactor): Create a parameterized source

Use the parameterized source (as many times as needed)

Source Bank Validation

Particles sampled from the parametrized source have two compounding sources of error:

- **The original source bank's degree of representation of the reactor core**
- **The accuracy of the bank's analytical reconstruction**

Validation reduces the first source of error.

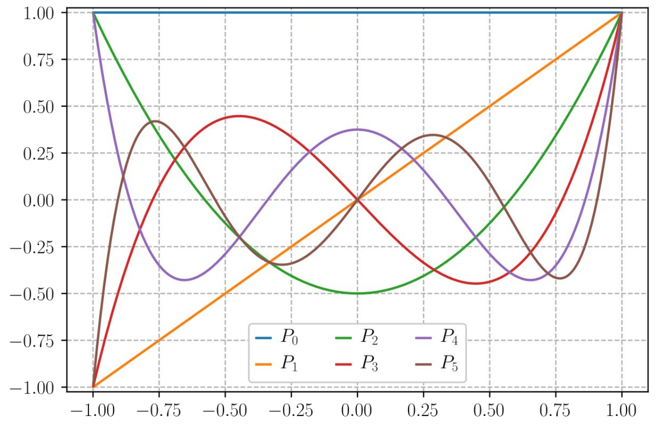
ERRs of the banked flux are a useful validation technique: one value that can quantify finer features of energy spectra and spatial particle distribution

- The specific reaction rate to be calculated with can be tailored to the application of interest

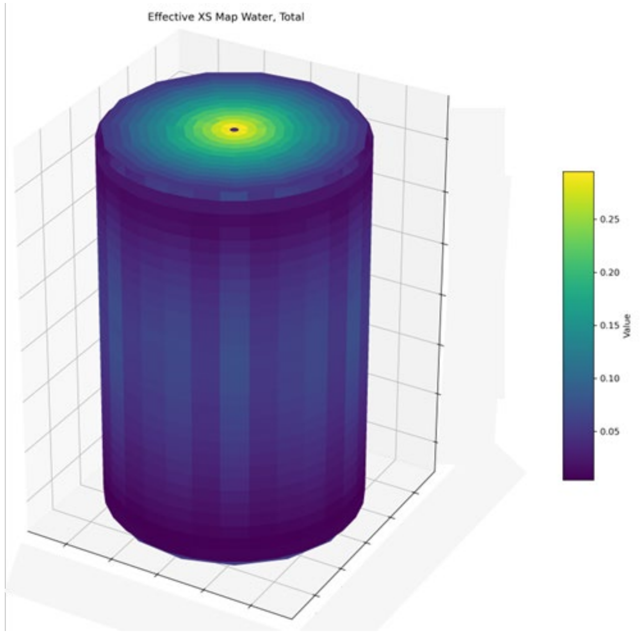
$$R_{ij} = \begin{cases} \frac{1}{N_{\text{total}}} \sum_{E_k \in \mathcal{E}_{ij}} \sigma(E_k), & \text{if } N_{ij} > 0 \\ 0, & \text{if } N_{ij} = 0 \end{cases}$$

Convergence of coefficients to adequate tolerance → source is ready to use

The first 6 Legendre polynomials, used to reconstruct reaction rates in linear dimensions

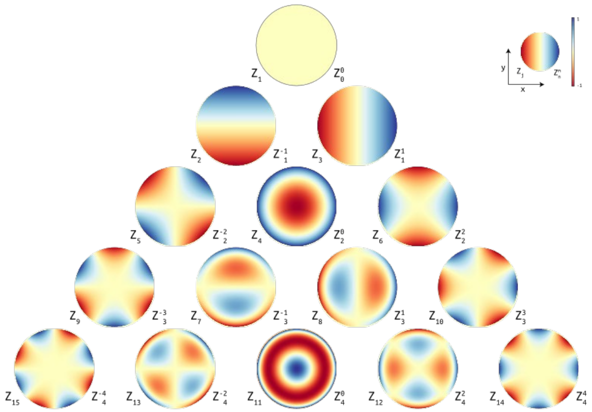


Spatially-dependent reaction rate of banked particles with water



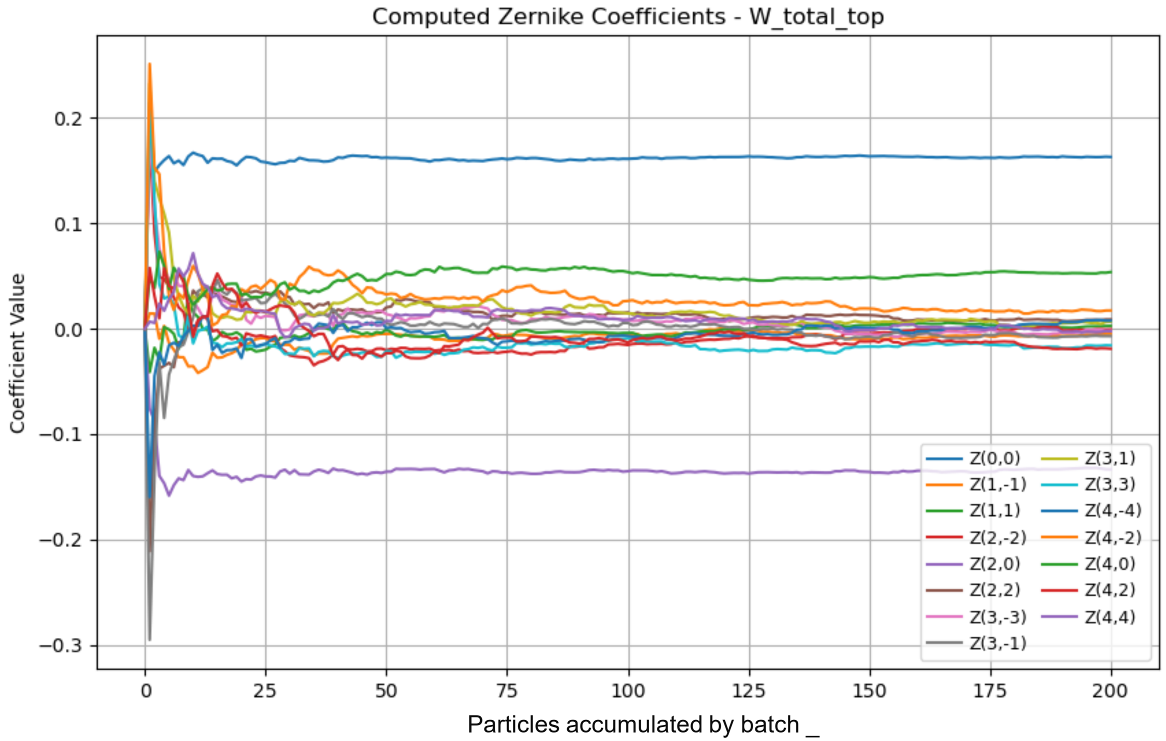
Source Bank Validation: Example

Radial and angular Zernike degrees



Eff. total reaction rate of top cap with W

Convergence of coefficients as particles accumulate in the bank



Tungsten chosen here as a high-Z material (presence of resonances requires higher particle counts to converge on reaction rates) that will be likely be used for photon shielding in in-space applications

Analytical Source Defintion: All of phase space…

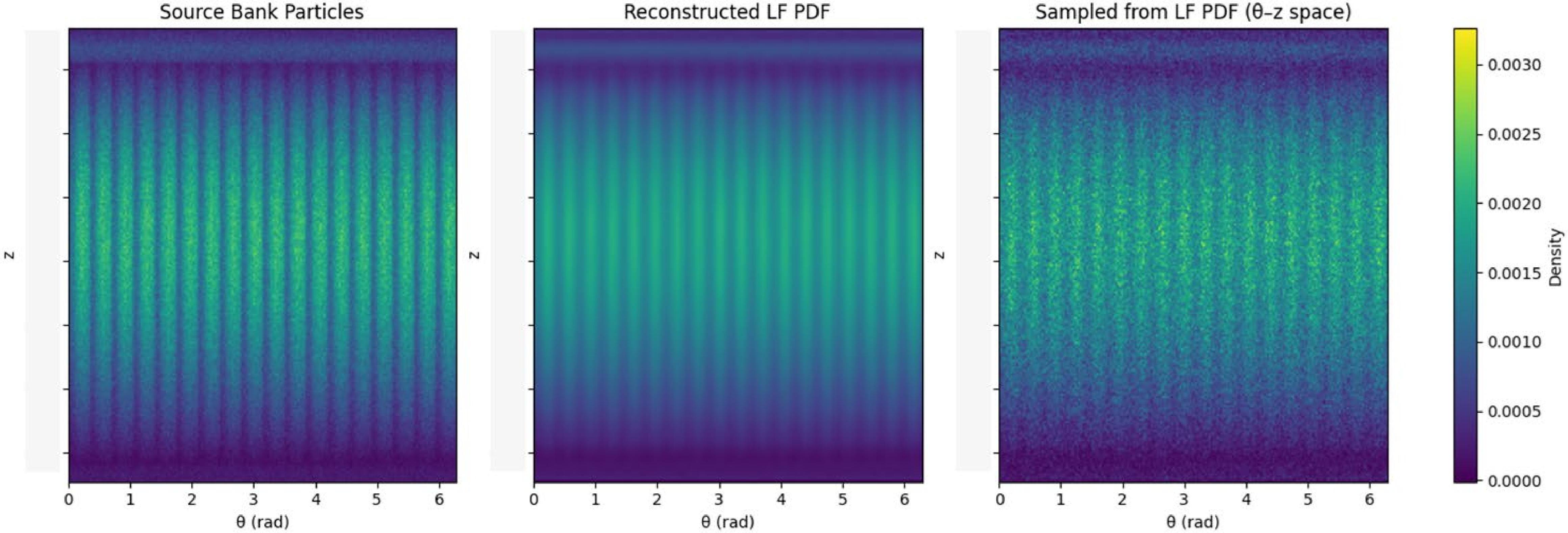
The first step in analytically reconstructing a particle source is to find particle density for each species as a function of space.

First particle location is sampled from the density distribution

$$S(E,\Omega,\vec{r}) = \boxed{\rho(\vec{r})} \cdot \boxed{p_E(E\,|\vec{r}) \cdot p_\Omega(\Omega\,|\,\vec{r})}$$

Then the energy and trajectory distributions are a function of position

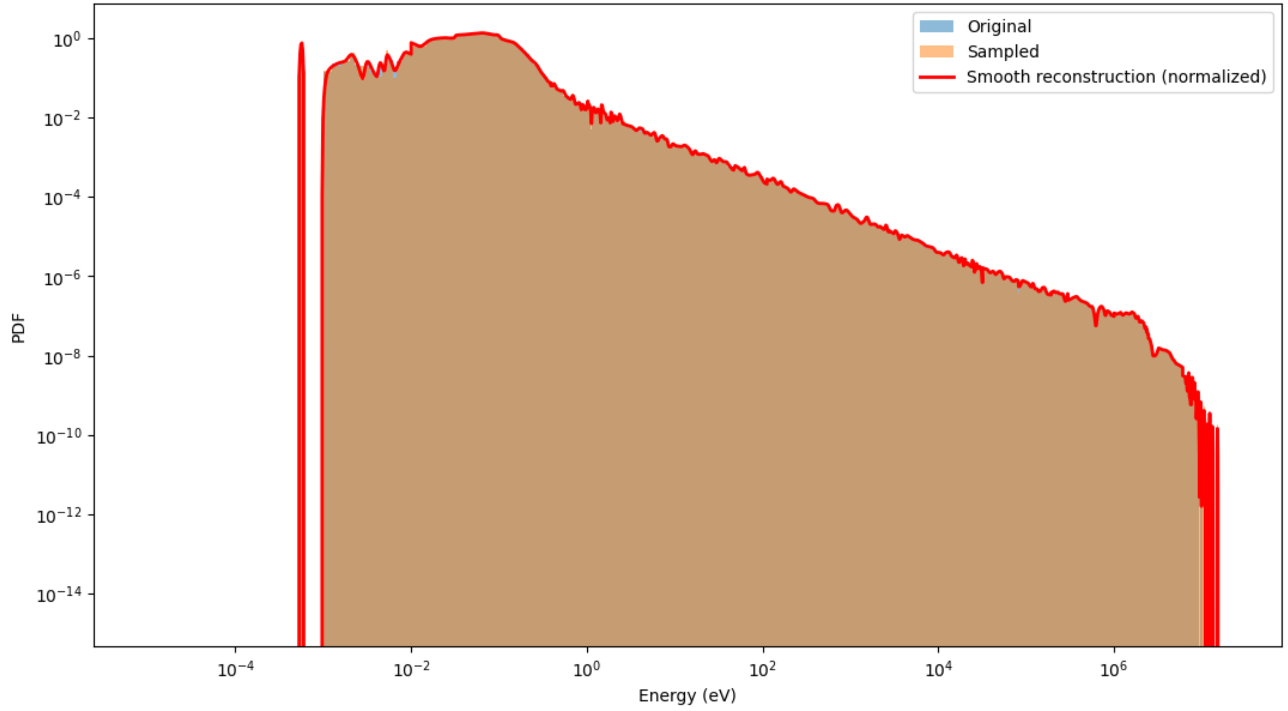
This is done with orthogonal basis sets:

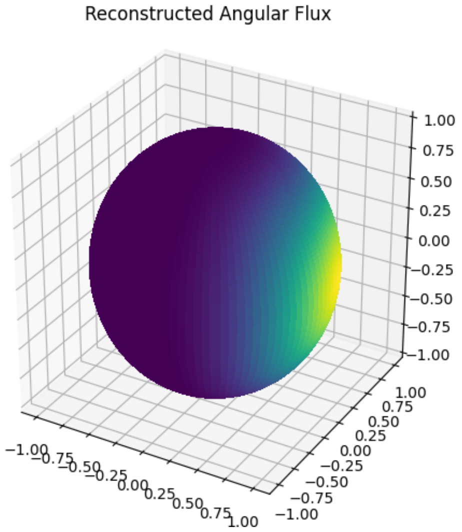


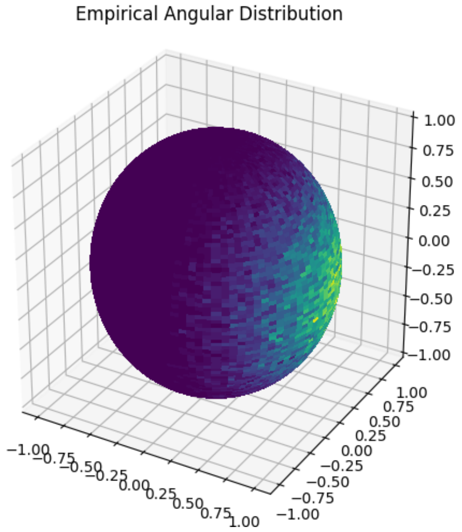
Analytical Source Defintion: All of phase space…

Then, the surface is divided into a mesh, not exceeding the resolution of the mesh used to analyze the original banked source stationarity.

Within each mesh cell, the energy and trajectory distributions of the particles are reconstructed:







These distributions are then tied together into a sampling routine that can be passed into OpenMC as a list of parameters to use with a CompiledSource object to generate new particles.

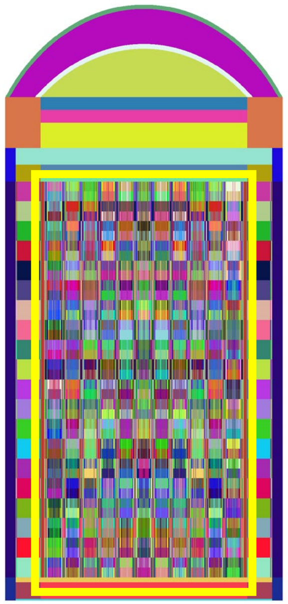
Tying it together: ASG1.0

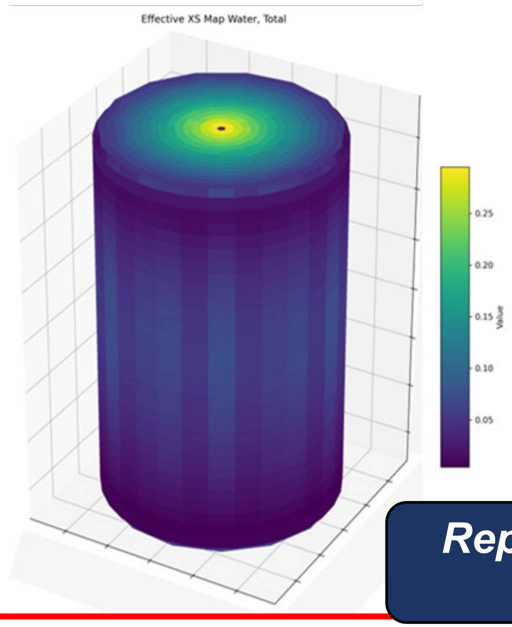
AMA's tool ties source banking, validation, parameterization, and use into one tool

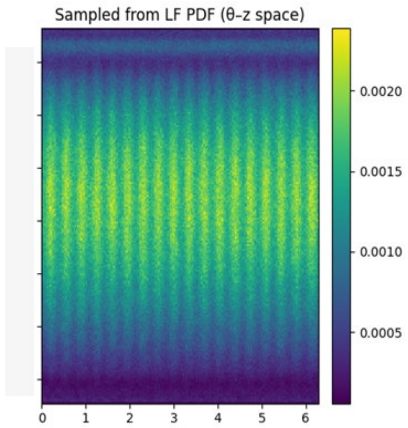
- **Source Generation:** Input geometry and material files for the core → output validated, parametrized source
- **Source Use:** Input ex-core geometry and fixed source simulation settings → output flux + dose field

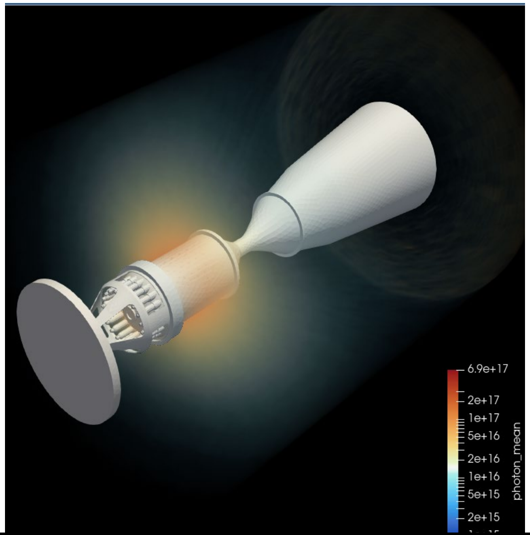
Source Generation is time-intensive but only needed once per reactor geometry. Source Use takes minutes.

Eigenvalue Case Source Banking → **Source Bank Validation** → **Validated source bank used to generate parametrized source** → **Integrated parametrized source with ex-core geometry**





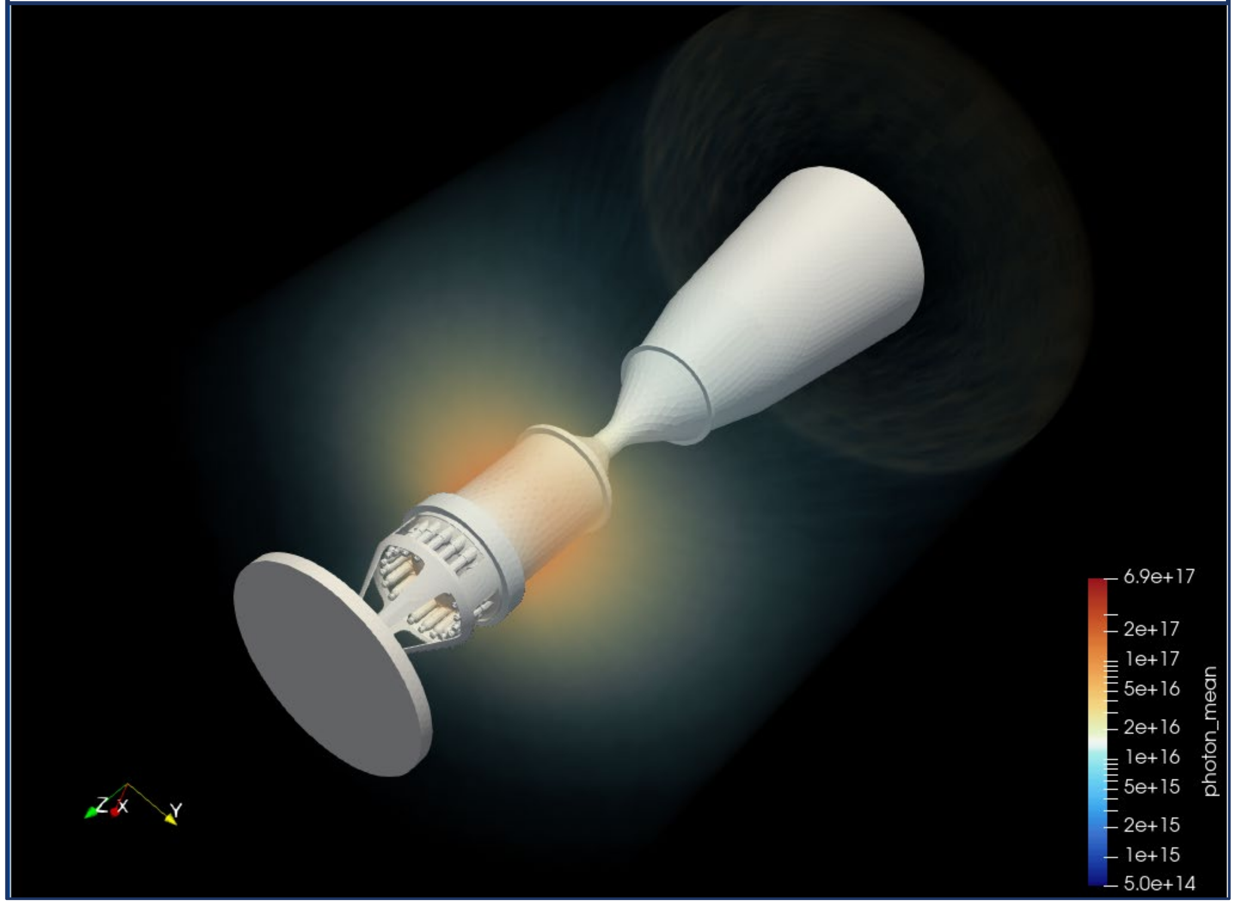




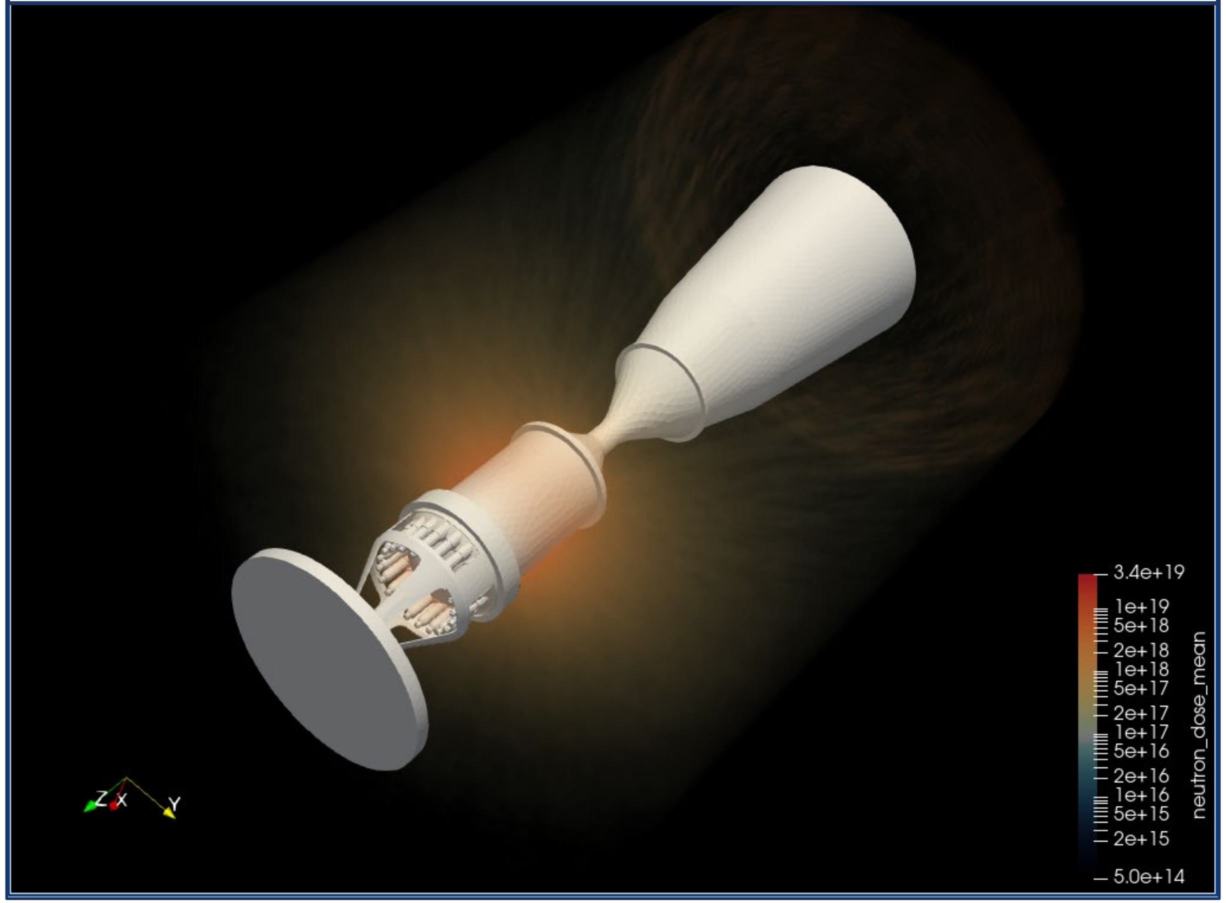
Repeating the Source Use stage allows for rapid optimization of ex-core components

Use Case: NTP Engine Flux Fields

Photon Flux

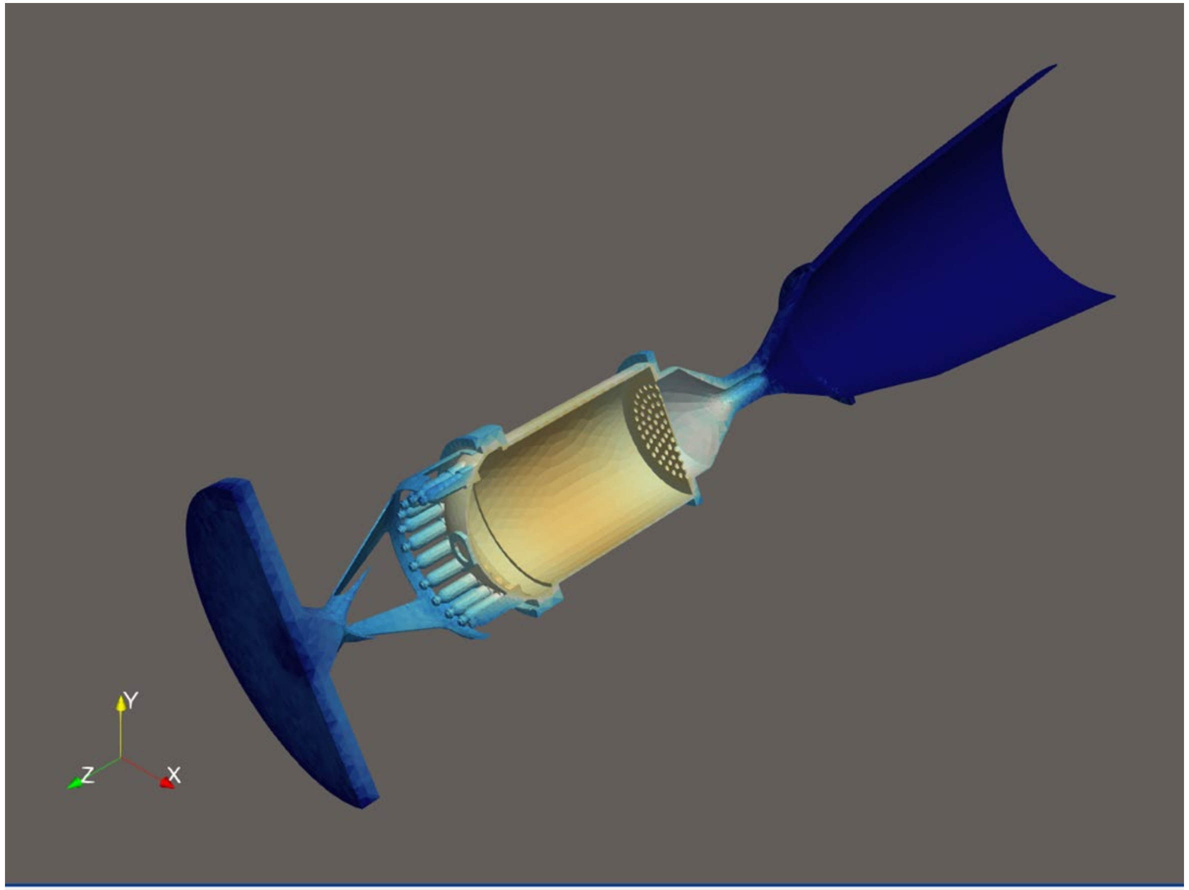


Neutron Dose



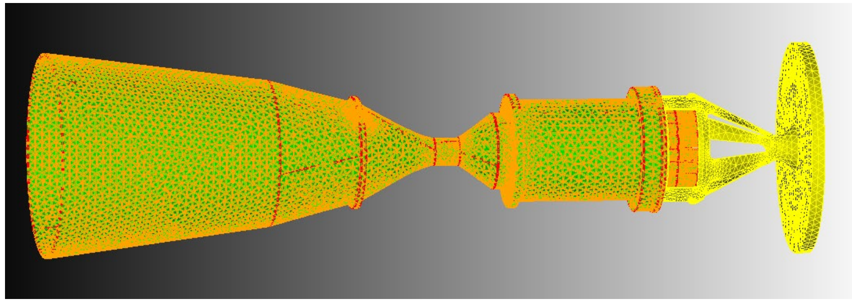
By default, flux and dose fields around (and accounting for) ex-core geometry are returned as a .VTK

Use Case: Radiation Damage



Mesh tallies allow for analysis of heat deposition and tracking of radiation damage (DPA) to structures around a reactor in an easy-to-visualize manner.

A note on meshing:
Conversion of CAD-based engine geometry was done for this case with CUBIT [4], which has a plugin that allows for direct translation of the geometry into a format compatible with OpenMC / DAGMC.



Using CAD-based geometry for the ex-core structures also allows for dose to be tracked within the structures using mesh tallies. These can also be viewed as a .VTK output.

Summary and Forward Work

- **Surface source banking → analytical / parametrized source generation is a promising means of accelerating ex-core radiation field modeling**
  - Modeling radiation fields far from a reactor can be very computationally intensive and inefficient → few particles in the core survive to areas of interest
  - Cutting out fission can accelerate ex-core transport simulation by a factor of 2+ per particle simulated, purely because fission is computationally intensive to model
  - This factor increases significantly if relatively few particles produced via fission survive to the regions of interest → this is almost always the case
  - **The effects of varying ex-core geometry (shielding) can be iterated on without the need for repeating core transport**
- **Using a source bank to generate an analytical source can even further extend the utility of this method: arbitrarily many particles can be created and simulated**
  - These particles can be generated to bias certain areas
  - No risk of oversampling bias
- **More work to be done on "proving out" source generation against pure source banking:**
  - How much deviation between a banked and generated source is acceptable?
  - For shielding cases: does backscattering bias [1] create meaningful heating tally error?
  - Application of MAGIC-based weight windows for applications where absorption is significant

Questions?

Eleni Mowery

eleni.t.mowery@ama-inc.com

etmowery@umich.edu

References

[1] L. Charlot, M. K. M. Jaradat, M. Elkamash, G. L. Giudicelli, A. Abou Jaoudé, E. Shemon, S. Kumar, and J. Dorville, "New Virtual Test Bed Capabilities: Virtual DOME Model and New Updates to Repository," Tech. Rep. OSTI 2478528, Aug. 31, 2024.

[2] E. T. Mowery, "Evaluating the use of surface source banking to accelerate Monte Carlo transport simulations of far-field particle fluxes," B.S. thesis, Dept. Nucl. Sci. Eng., Massachusetts Institute of Technology, Cambridge, MA, May 2025.

[3] *Under review:* Full journal paper on ASG process.

[4] Sandia National Laboratories, *Cubit* 17.4, Albuquerque, NM, 2024.

Acknowledgements

This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) Project

Contract No. 80LARC23DA003