NEAMS Reactor Physics HTGR/FHR Capabilities

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May 8, 2025

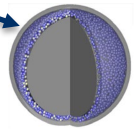
NEAMS Reactor Physics technical area develops and deploys codes for modeling neutral particle transport and nuclide depletion/decay

- **Neutral particle transport**: Interaction of neutrons/gammas with reactor materials
- **Transmutation**: Time evolution of isotope inventories due to irradiation and decay; and decay-induced neutron and gamma source
- **Coupled Transport and Transmutation:** Time evolution of flux (power), isotopes, and decay source
  - Steady-state operation (days, months, years)
  - Transient scenarios (seconds, hours, days)
  - Spent fuel management (years)
- Changes in geometry, temperature, and density influence change in reactor physics
- Strategically prioritize, coordinate, and develop 3 codes: Griffin, Shift, and MPACT

- **MPACT** is the direct whole-core reactor physics code integrated into **VERA** for high-fidelity light water reactor simulation
- **Griffin** is a flexible MOOSE-based reactor physics application for multiphysics simulations of advanced reactor designs
  - Range of mesh-based MG deterministic solvers
  - On-the-fly cross section processing is integrated for both fast and thermal systems, including TRISO based systems
  - Depletion/decay using built-in depletion solver
  - Transient analysis using point kinetics, improved quasi static method, and spatial kinetics.
  - MOOSE framework enables ease-of-coupling to other MOOSE-based codes
- **Shift** is a Monte Carlo radiation transport code designed to scale from supercomputers to laptops.
  - Continuous-energy nuclear data on exact geometry (CSG)
  - State-of-the-art methods for eigenvalue, shielding, depletion, and sensitivity/uncertainty on CPU/GPU systems
  - Shift provides MG cross sections for subsequent multiphysics simulations with Griffin for all non-LWR reactor systems

Technology Specific Needs for Pebble Bed Reactors

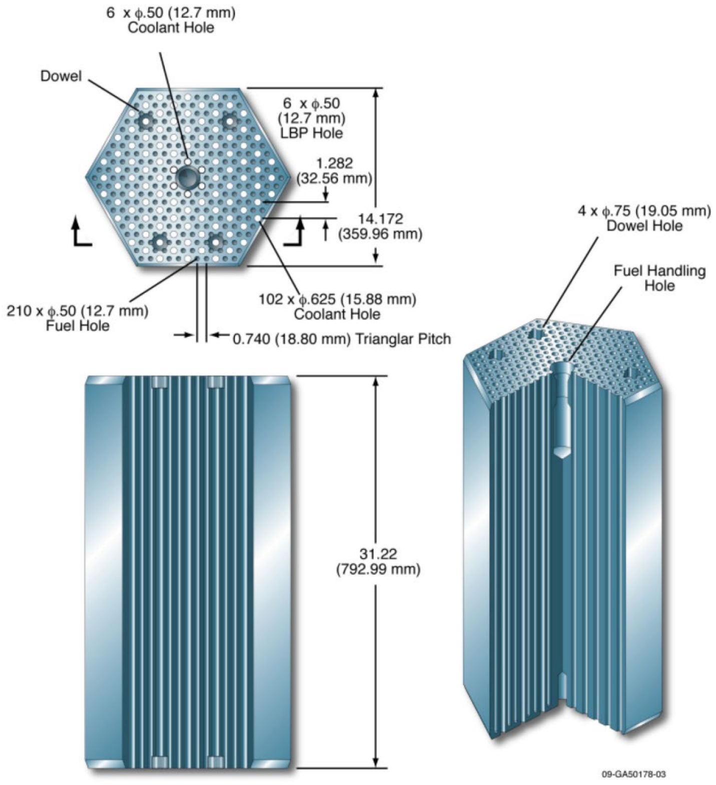
- Steady state
  - Critical height
  - Equilibrium core
- Time dependent
  - Running-in
  - Transient analysis
- Feedback mechanisms
  - Temperature fuel, moderator, reflector
  - Coolant density and composition changes
- Spherical fuel forms



David Reger, et al., Discrete element simulation of Pebble Bed Reactors on graphics processing units, Annals of Nuclear Energy, Volume 190, 2023.

Technology Specific Needs for HTRs

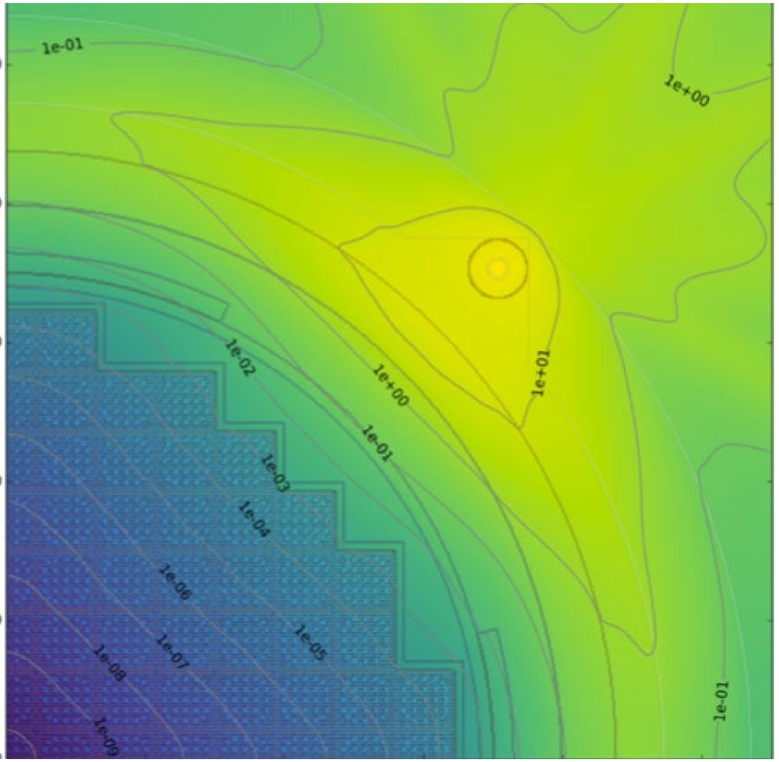
- Steady State
  - k_{eff}
  - Depletion, shuffling
  - Equilibrium core
- Time dependent
  - Transient analysis
- Feedback Mechanisms
  - Temperature fuel, moderator, reflector
  - Coolant composition changes
- Cylindrical fuel forms
- Asymmetric pins (BPs, etc.)



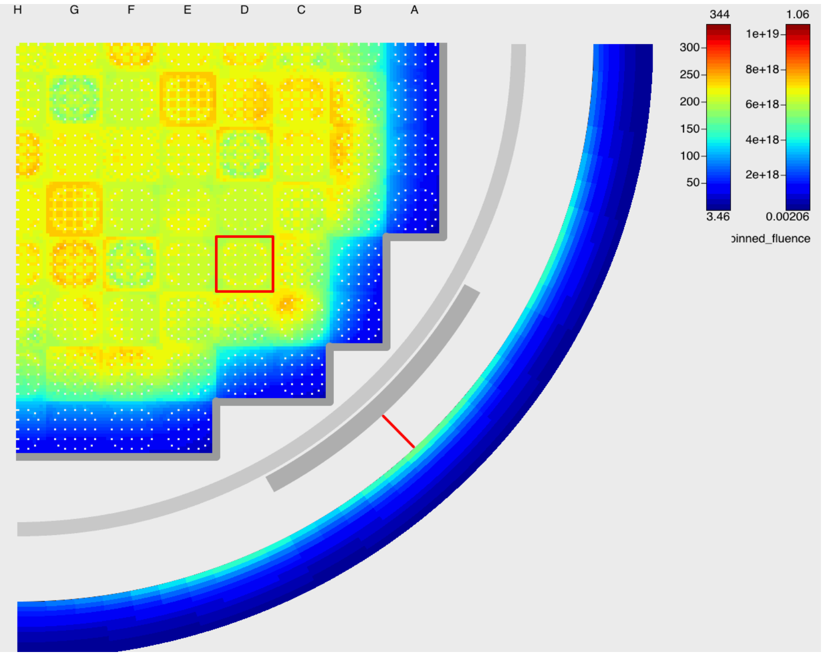
J. Sterbentz, et al., High-Temperature Gas Cooled Test Reactor Point Design, INL/EXT-16-38296, 2016.

Technology Specific Needs for both

- Gamma heating of reflectors and steel components
- Fluence calculation in structures and components
- Shielding and detector response (source calculations)



Harris power plant adjoint flux for ex-core detector response from Shift



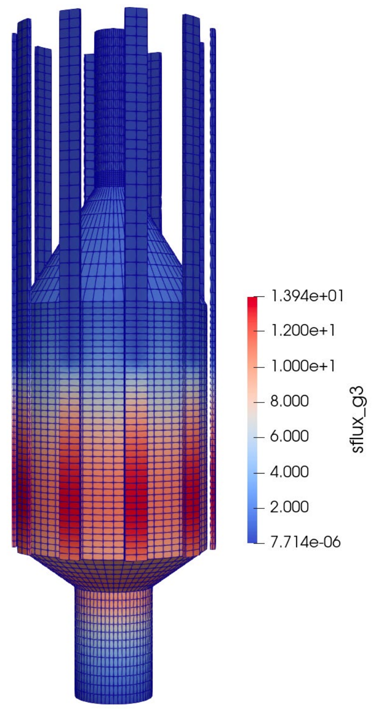
Shift WBN1 vessel fluence and normalized core flux over 15 cycles

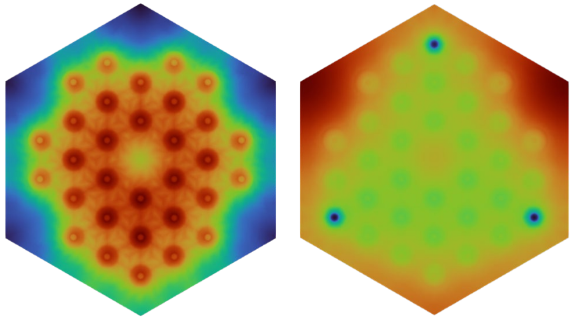
Griffin Capabilities for PBRs and HTRs

Flexible high-performance radiation transport code designed to scale from laptops to supercomputers

State-of-the-art methods and algorithms

- Flexible geometry / resolution
- Depletion (CRAM)
- Coupling to thermal-fluids thermo-mechanics
- On-line cross sections with DH treatment



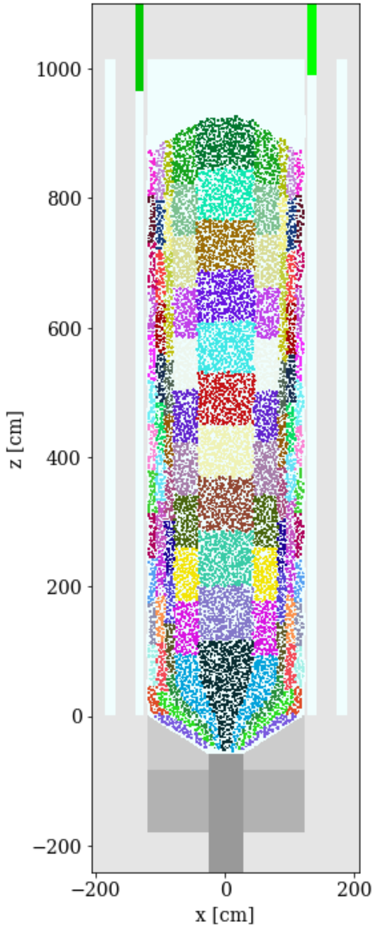


Shift Capabilities for PBRs and HTRs

Flexible high-performance radiation transport code designed to scale from laptops to supercomputers

State-of-the-art methods and algorithms

- GPU/CPU
- hybrid variance reduction
- shielding methods
- depletion via ORIGEN
- sensitivity/ uncertainty



Shift GC-PBR depletion

Top RD&D Priorities - Griffin

- Griffin broad group cross section preparation FY25 (NO, AOO, DBA, BDBA)
  - leakage correction
  - neutron self-shielded XS for for HTRs
  - neutron-gamma self-shielded XS for all PBRs and HTRs
- Deep penetration problems and detector response (NO, AOO)
  - Solver improvements for SN + CMFD acceleration
  - Adjoint flux generation for Shift (shielding)
- Improvements to low order methods (SPH, GET) FY25 (AOO, DBA, BDBA)
  - Improve SPH convergence with reflector zones
  - Determine SPH correction effects on the reactor kinetics solutions

NO – Normal Operation
AOO – Anticipated Oper. Occur.
DBA – Design Basis Accident
BDBA – Beyond DBA

Top RD&D Priorities - Shift

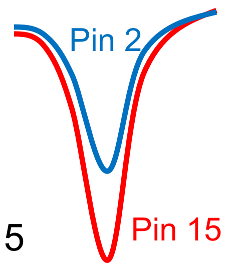
- Cross section preparation (NO, AOO, DBA, BDBA)
  - Integrate microscopic cross section generation with overlay CSG tally
  - Enable more accurate scattering matrix moments
- Generate a MOOSE-based workflow for FW-CADIS with Shift (NO, AOO)
  - Enable Griffin-Shift calculations for detector response and deep penetration problems
  - Compute weight windows from Griffin generated adjoint fluxes (biasing parameters)
- Shift multiphysics (NO, AOO, DBA, BDBA)

Online Cross Section Generation Capability of Griffin

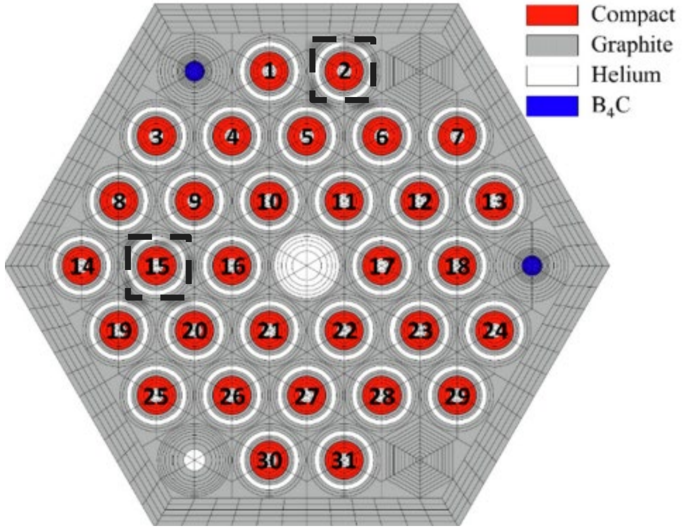
Introduction to Self-Shielding API (SSAPI)

$$\sigma_g = \frac{\int_{E_g}^{E_{g-1}} \sigma(E)\phi(E)dE}{\int_{E_g}^{E_{g-1}} \phi(E)dE}$$

- Purpose
  - To perform fully heterogeneous transport calculation for flux solution without needing to generate cross sections by a user
  - To generate cross sections in a downstream code for two-step approach
- Objective
  - Determine region-dependent self-shielded multigroup cross sections by performing self-shielding calculation.
- Method
  - TRISO Dancoff factor for region-dependent shadowing effect
  - Two-stage on-the-fly slowing down method

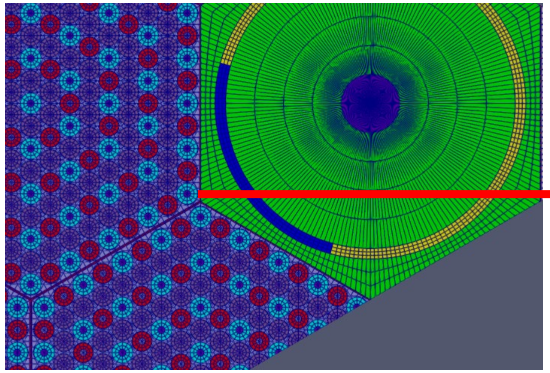


Shadowing effect in pin 2 < pin 15
= less shielded spectrum in pin 2 than pin 15

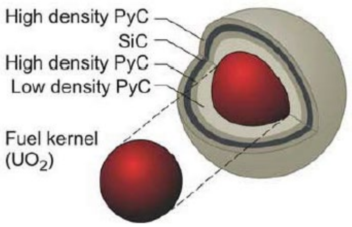


SSAPI Capabilities

Prismatic-type Fuel Rod Design



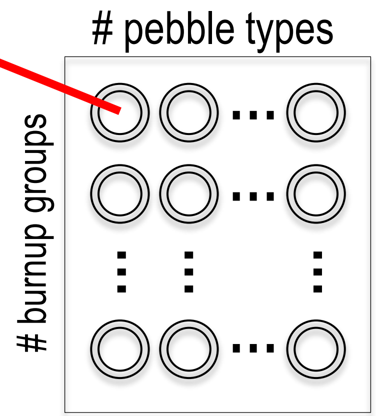
TRISO particle



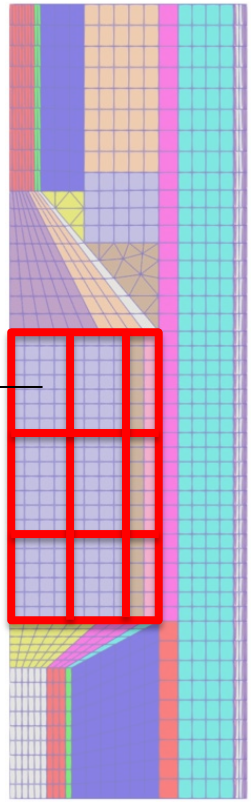
- TRISO double-heterogeneity treatment
- High temperature treatment (resonance up-scattering)
- On-the-fly Doppler broadening
- Multiphysics coupling (Doppler, coolant density)
- Macro- and micro-cross section edits for two-step procedure
- Support pebble-bed cross section generation with depletion
- Support shell-type fuel (HTTR annular compact, FHR pebble)

Pebble-bed Design

Pebble ensemble per fuel type per burnup level



Spectral Zone

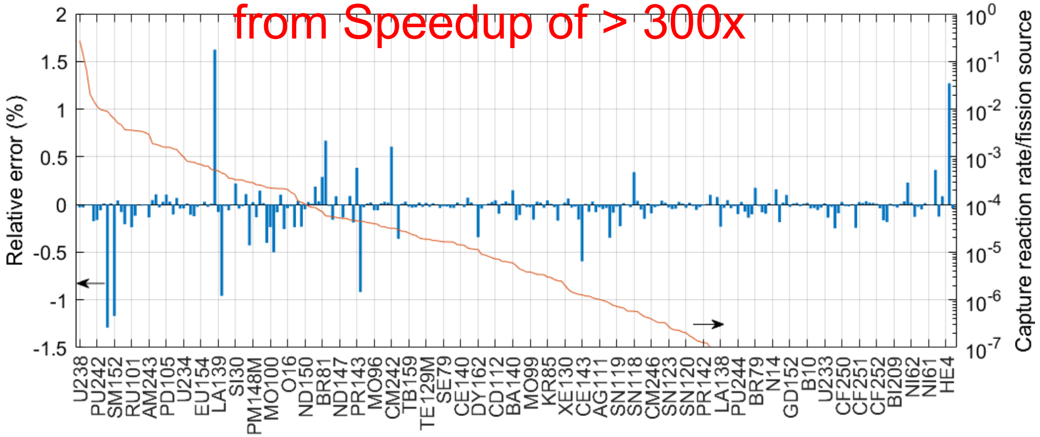


Pebble-bed Core

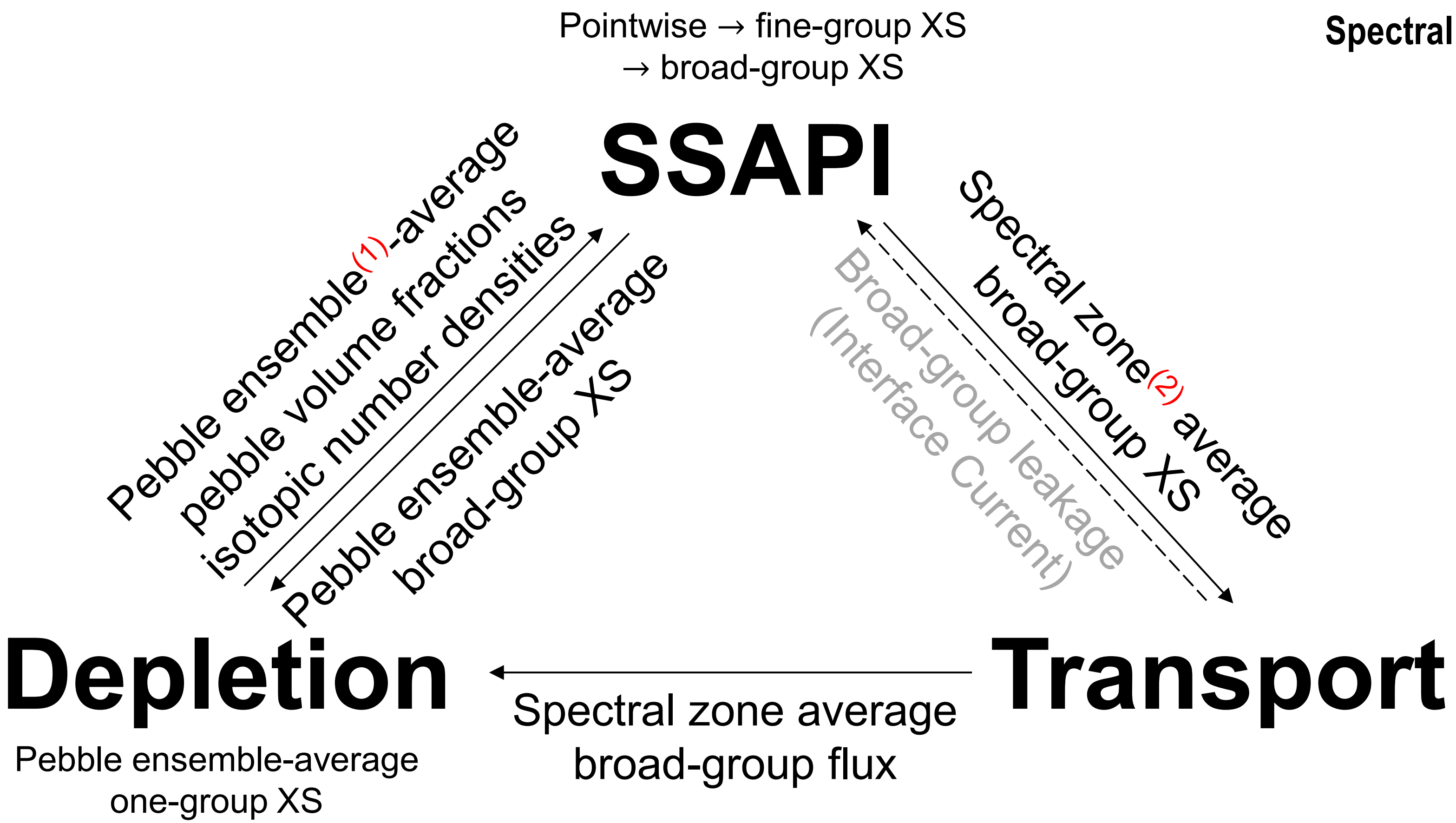
Verification Efforts

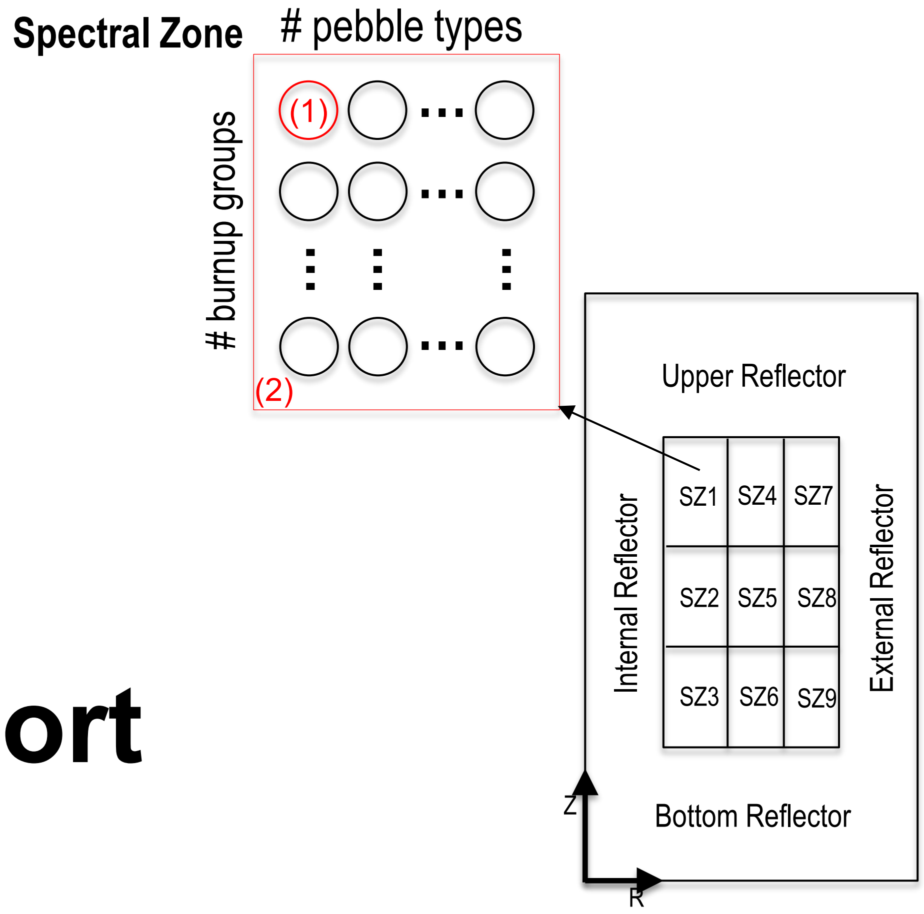
- Accuracy (FY21 – 24 Accomplishments)
  - Griffin uses the most advanced resonance self-shielding theory in terms of accuracy.
  - Verified against Serpent for VHTR, HTTR, EMPIRE, gas- and salt-cooled PBRs.
    - Generally eigenvalue error < 200 pcm, power error < 2%.
    - Temperature reactivity coefficients < 5%
- Performance (FY24 Accomplishment)
  - Optimization + New method
  - Total speedup: > 300x
  - Pebble-wise (fuel rod-wise) self-shielding calc. ~ 0.4 seconds per processor
  - Supported by MPI parallelization

No Loss of Accuracy in Absorption Reaction Rate from Speedup of > 300x



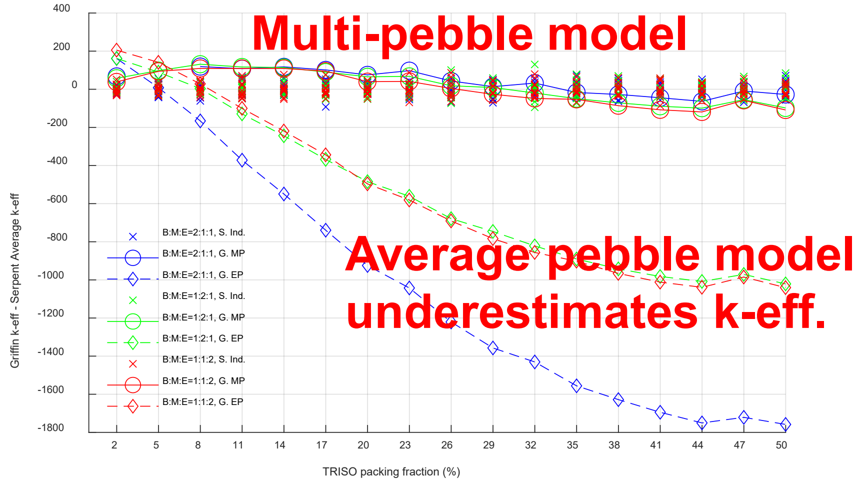
Coupled SSAPI, Transport, and Pebble Depletion





Multi-pebble Model

- Issue in Average Pebble Model used by Legacy Tools
  - Composition averaging leads to wrong self-shielding effect.
  - Major impact: Overestimation of ^{240}Pu capture up to +15% → Underestimation of eigenvalue up to -1.5%.



- Implementation of Multi-pebble Model in Griffin
  - Pebble interactions are considered by coupled balance equations in different pebbles and coolant based on collision probability.
  - Confirmed excellent agreement against Serpent results.

Balance on Pebble Surfaces

$$J_x^- = E_{c\to x} V_c F_c + \sum_y T_{y\to x} J_y^+$$

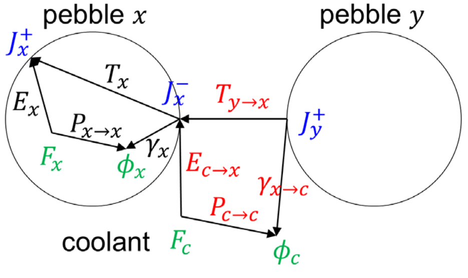
$$J_x^+ = \sum_i E_{x,i} V_{x,i} F_{x,i} + T_x J_x^-$$

Balance in Pebble

$$V_{x,i}\Sigma_{x,i}\phi_{x,i} = \sum_j P_{x,j\to i} V_{x,j} F_{x,j} + \gamma_{x,i} J_x^-$$

Balance in Coolant

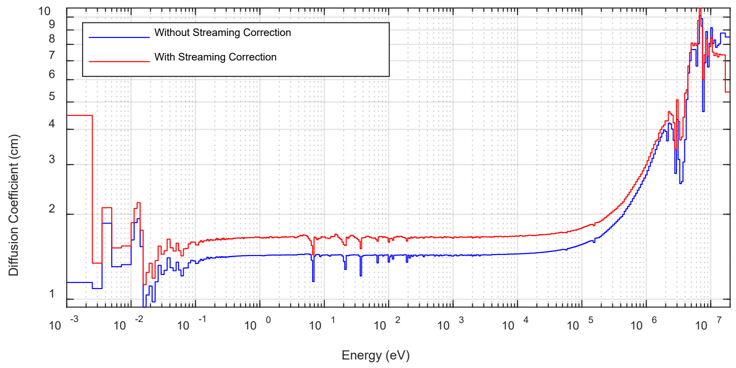
$$V_c\Sigma_c\phi_c = P_{c\to c} V_c F_c + \sum_x \gamma_{x\to c} J_x^+$$



$$F_x = Q_x + \Sigma_{s,x}\phi_x$$

Streaming Effect for Gas-cooled PBR

- Presence of 40% Gas Region in a Pebble-bed
  - Affects the mean neutron migration area.
  - Conventional homogenization underestimates diffusion coefficient.
    - Effect: power tilt and eigenvalue overestimation (up to a few %)



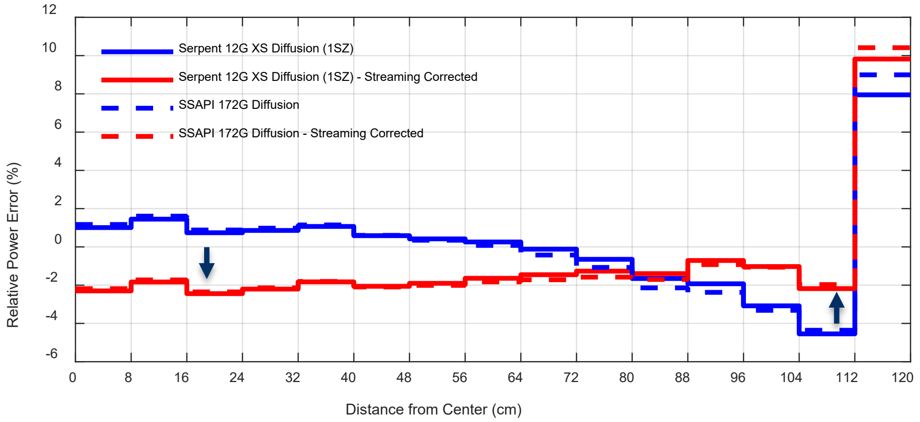
- P. Benoist method for better diffusion coefficient
  - Works for both transport and Diffusion calculations.

$$\bar{D}_g^{\mathrm{Corr}} = \frac{1}{3}\frac{\sum_k V^k \phi_g^k \sum_j \frac{P_{k\to j,g}}{\Sigma_{\mathrm{tr},g}^{j}}}{\sum_k V_k \phi_g^k} = \frac{1}{3\bar{\Sigma}_{\mathrm{tr},g}^{\mathrm{Corr}}}$$

- Good agreement in k_{eff} and power distribution

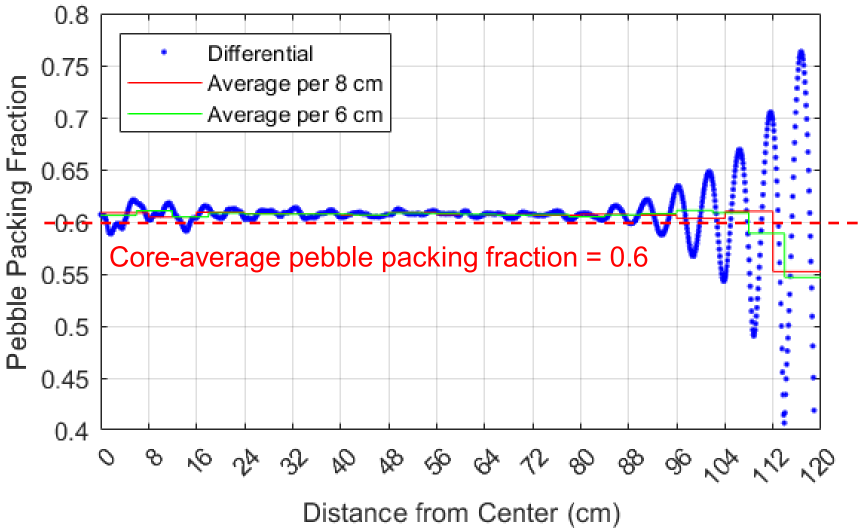
k_{eff} error (pcm) of Griffin w.r.t. Serpent

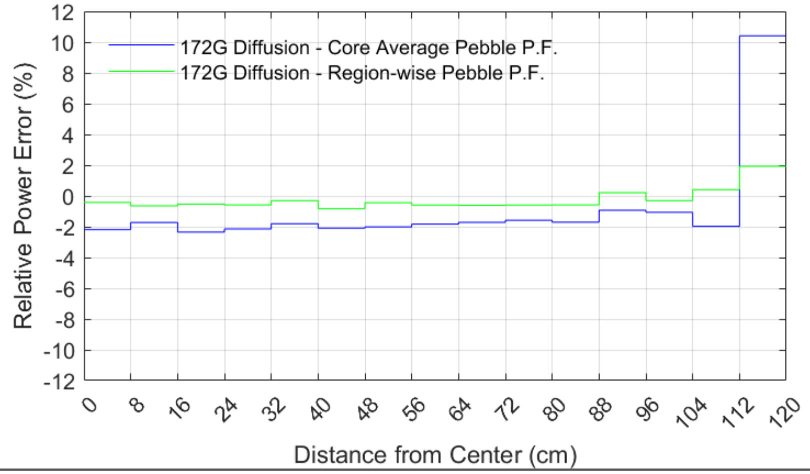
XS Generation Code	Diffusion			Transport (P1)		
	No Str. Corr.	Str. Corr.	Str. Effect	No Str. Corr.	Str. Corr.	Str. Effect
Serpent XS 12G	+486	+125	-361	-	-	-
SSAPI	+285	**+15**	-269	+337	**+8**	-329



Region Dependent Pebble-bed Porosity

- Region-wise Pebble Packing
  - Less packed near the wall by -8% and more packed in the inner side by +1.2% than nominal average
- Error Caused by Using Core-average Porosity
  - Power error by the same error in pebble porosity
- Measure in Griffin
  - User provides a txt file that contains pebble locations.
  - Griffin calculates region-dependent porosity.
- Excellent agreement of power distribution in the final solution (less than 2%).





Conclusion

- Developed an advanced on-the-fly cross section generation methods for GCR/FHR.
- Biggest advantage
  - Elimination of user's burden to generate cross sections, particularly more valuable for PBR depletion calculations.
  - No interpolation error from tabulation approach, especially for complicated Multiphysics scenarios.
- Future works
  - On-the-fly leakage correction for reducing computational burden without loss of accuracy.
  - Support pebble-bed running-in calculation
  - Coupled neutron and gamma transport
  - Two-step process for core calculation with homogenized assembly
  - Depletion for prismatic-type reactors

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