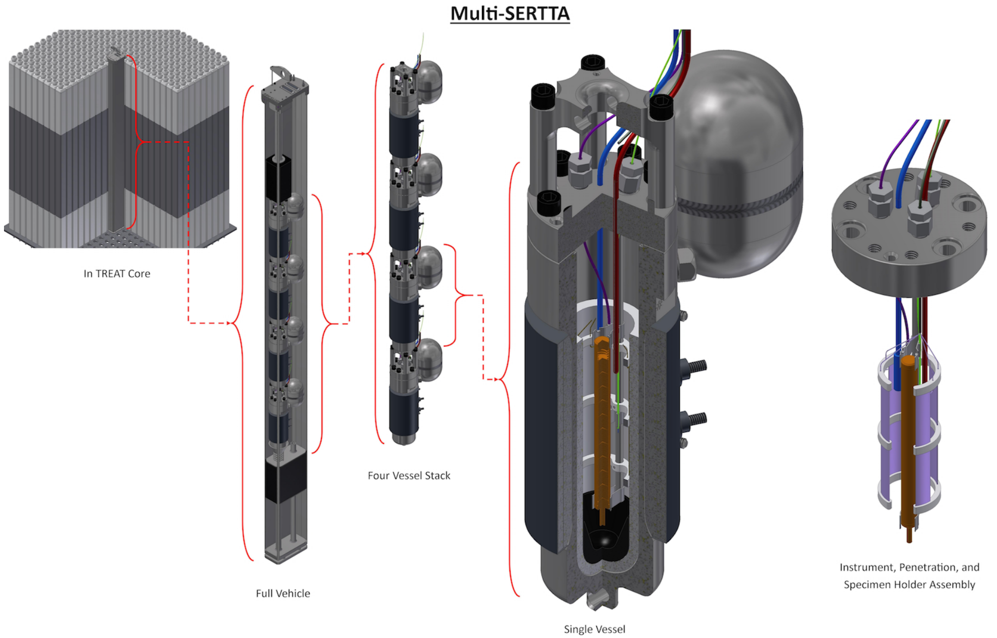
INL/MIS-17-43729

Idaho National Laboratory

Modeling of the Multi-SERTTA Experiment with MAMMOTH

Javier Ortensi, Ph.D. P.E.
R&D Scientist
Nuclear Science and Technology
Idaho National Laboratory

www.inl.gov



Idaho National Laboratory

Overview

- M8 Report
  - INL/EXT-17-42415: FY 2017 Modeling of the M8 Calibration Series using MAMMOTH.
- Purpose
- Codes
- Models
- Results
- Conclusions
- Future Work

Purpose

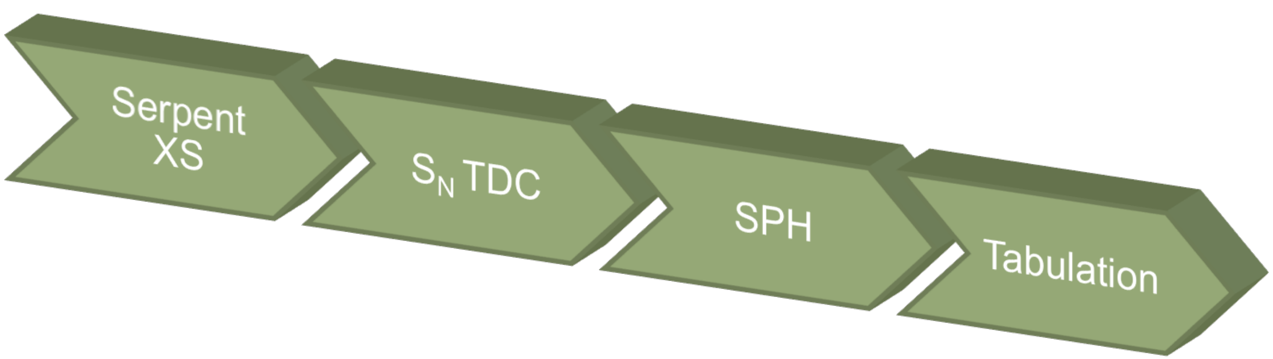
- Initiate the modeling of the Multi-SERTTA experiment with coupled multi-physics methods:
  – Safety case in FY-17 (temperature-limited), and
  – Control rod clipping case in FY-18 (shaped).
- Address operational concerns (long term):
  – How to optimize the use of TREAT reactor.
    - Timing of CR motion.
    - Power and Transient coupling factors.
- Address experiment concerns (long term):
  – How to improve the experiment design:
    - flux collars,
    - control rod effects on experiment …
  – Provide a design tool with time dependent data in the experiment region.

CODES

- Serpent Monte Carlo (v2.1.28)
  - Cross section preparation
  - Reference solution
- MAMMOTH / Rattlesnake
  - Transport discretizations
    - CFEM Diffusion, S_N, P_N
    - DFEM Diffusion, S_N (need better sweeper)
  - Equivalence methods
    - Superhomogenization
    - Discontinuity factors (under testing)
  - Larsen-Trahan tensor diffusion coefficient
  - Time integration
    - MOOSE integrators
  - Improved quasi-static (IQS)

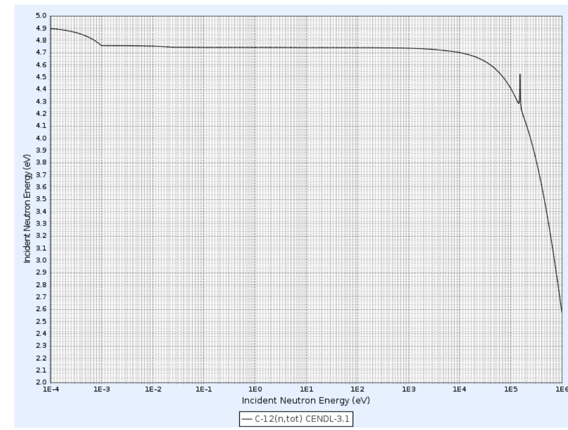
Cross Sections - Preparation

- Goal is to perform transient diffusion calculations when/where possible:
  - performance, needed for designers and operations,
  - ability to perform “multi-scheme” and “multi-scale” simulations coupling diffusion to high order solutions for experiment.
- Full core Monte Carlo to generate base cross sections.
  - Isotropic diffusion coefficient
- Full core S_N Larsen-Trahan source problem for tensor diffusion coefficients in optically thin regions.
- SPH correction on coarse mesh as an equivalence procedure.

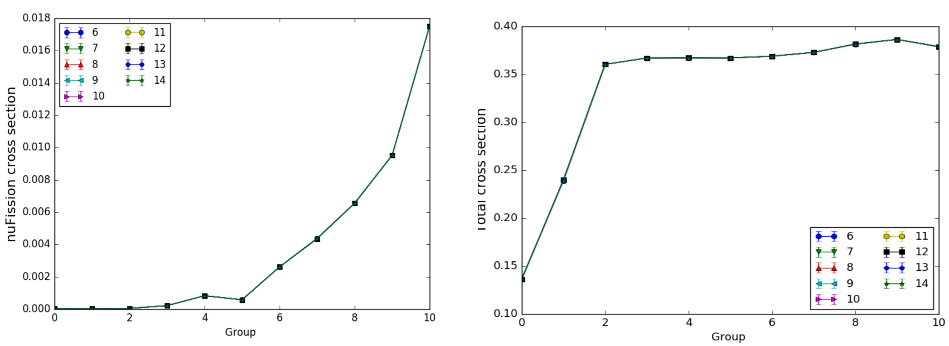


Cross Sections - Lessons Learned

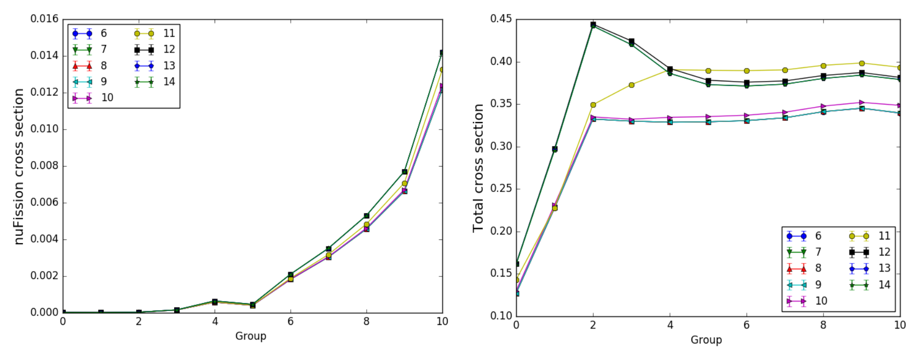
- Homogenized cross sections are invariant across the core for standard fuel elements and reflectors:
  - No significant resonance absorbers.
  - Graphite cross sections.
  - This is not the case for the LEU core.



- CR elements contain spectral zones near the CR tip and various material discontinuities.
- Just need flux tallies for SPH.

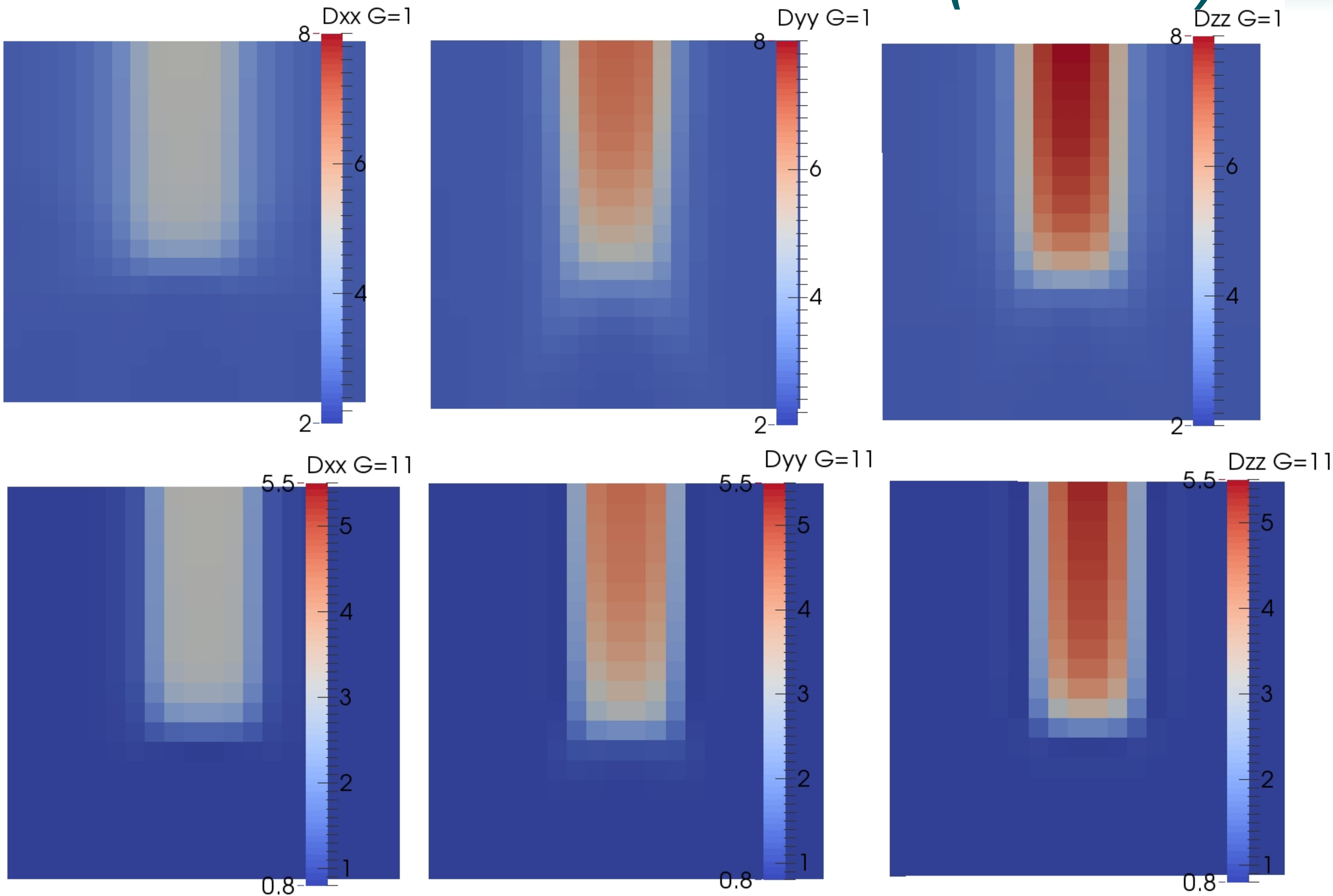


Std. Fuel Element



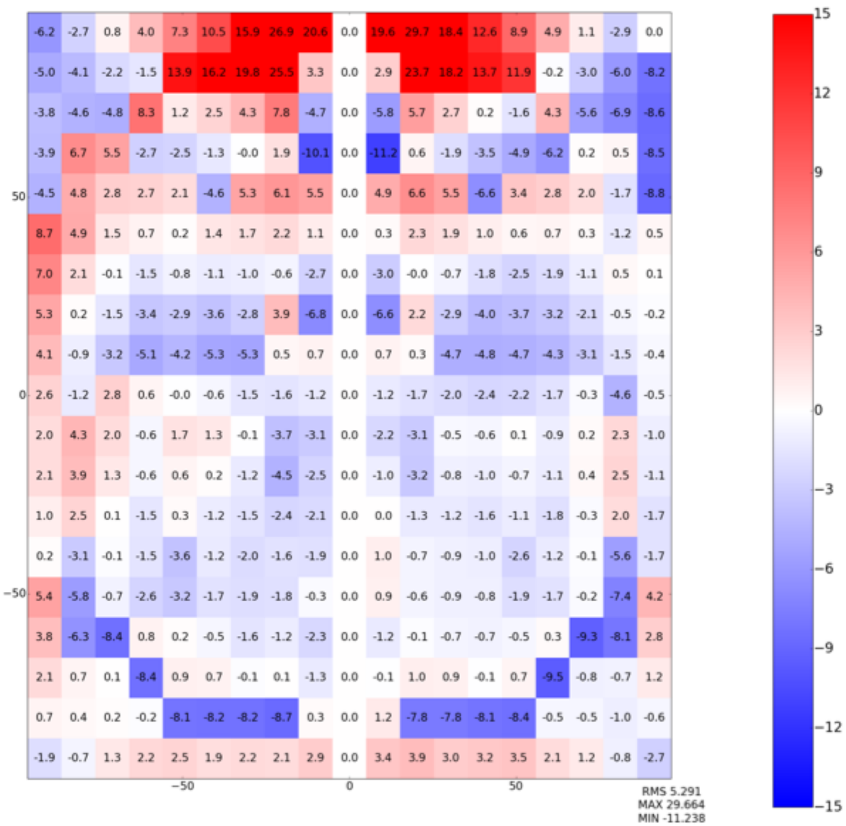
CR Fuel Element

Cross Sections - TDC in TREAT Slot (mid core)



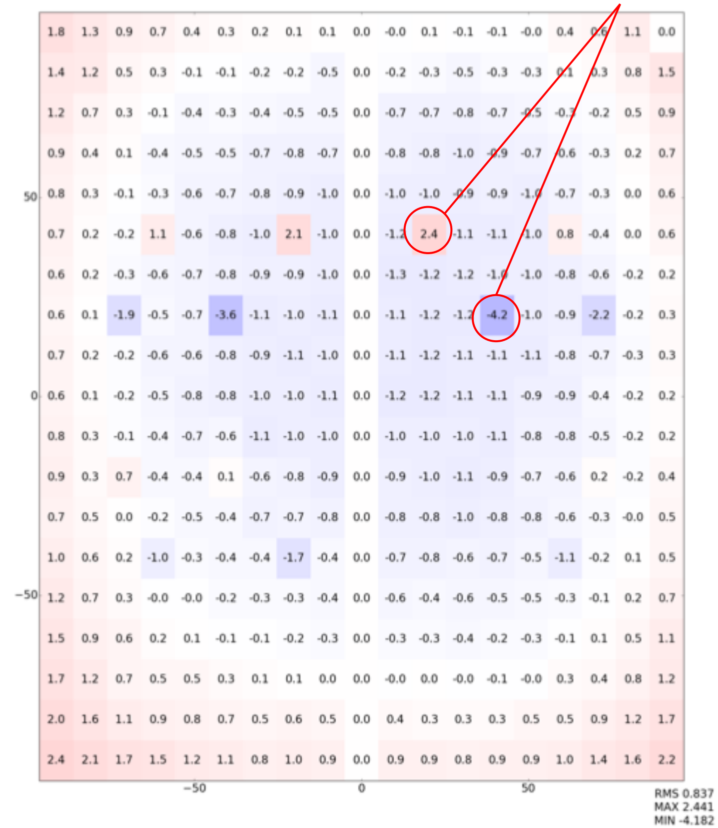
Cross Sections – SPH Equivalence

- Current work with M2CAL.
- Started by grouping similar fuel elements by location.
- SPH improves dramatically with spatial resolution.



Diffusion

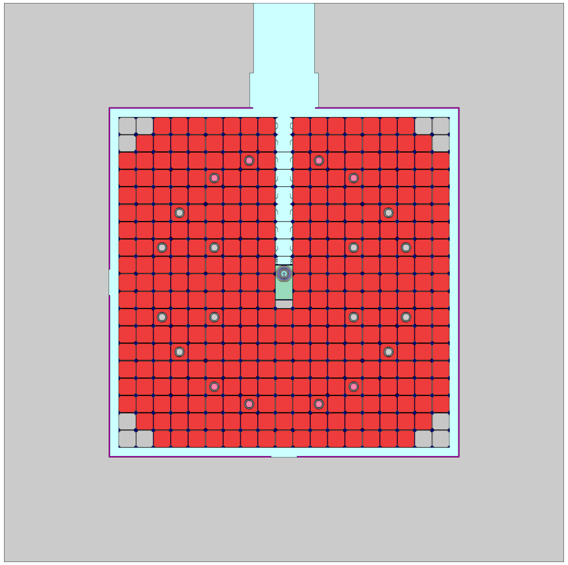
CR grouping

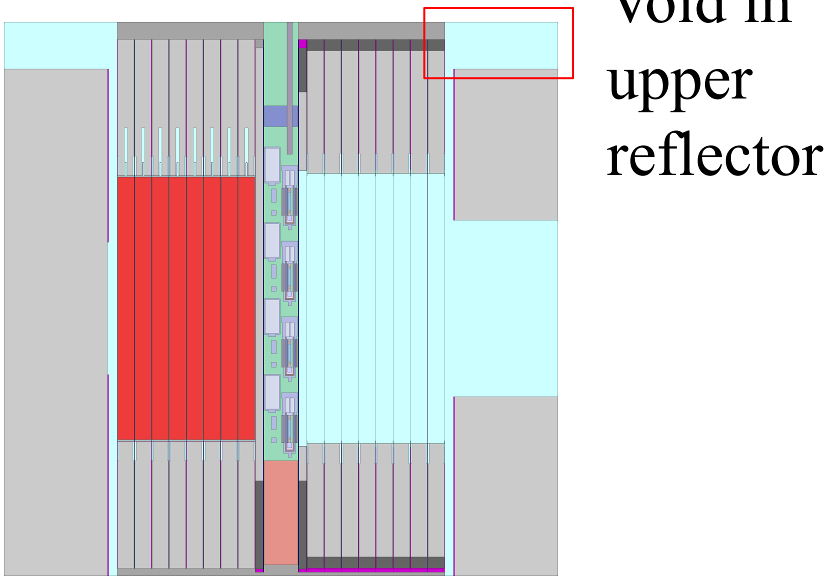


TDC-SPH Diffusion

SERPENT Core Model

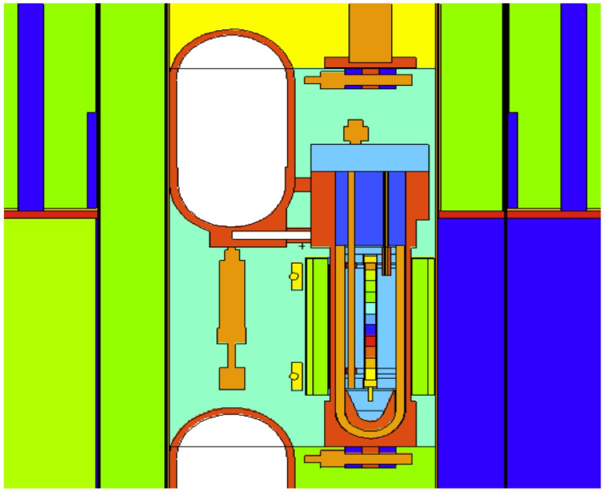
- No graphite thermal column or shield (~6% tilt across the core).
- Isothermal temperature to generate cross sections.
- Core functionalization of cross sections $\Sigma(T_{core}, CR)$
  - T_{core} = 300, 400, 500, 600 K
  - Transient rods in/out.
- Save MC source points for each core state at the experiment boundary.

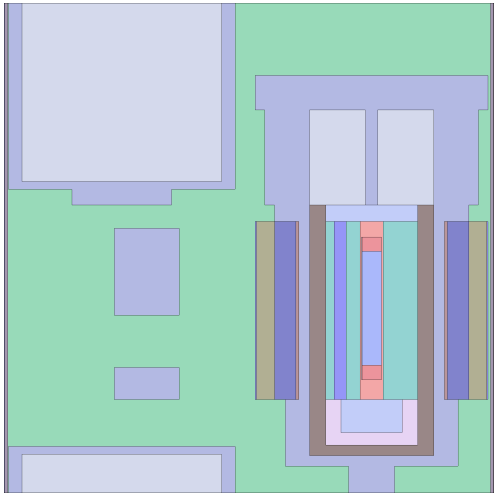


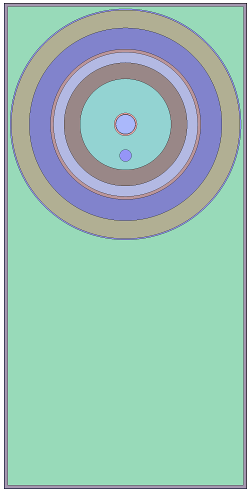


SERPENT Experiment model

- Use a simplified model of the experiment.



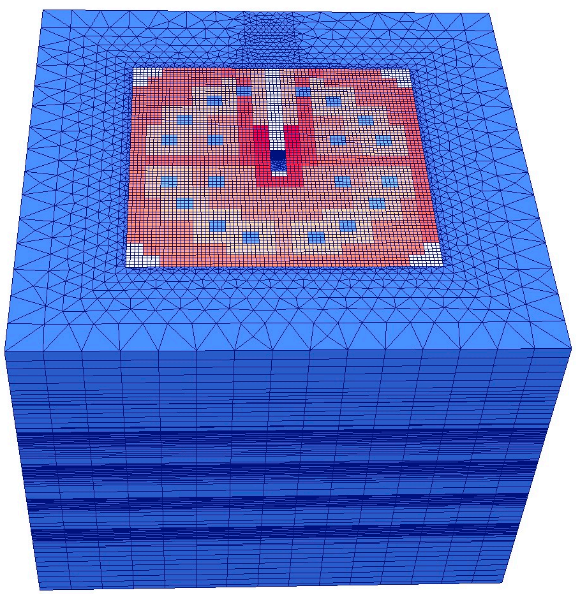


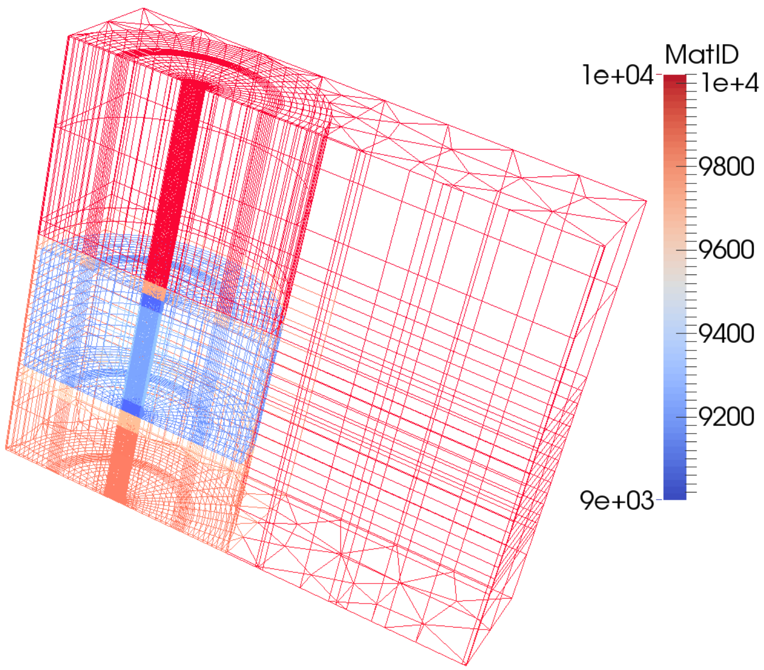


- Perform branch calculations on the vehicle with boundary fixed source points.
- Experiment functionalization of cross sections $\Sigma(T_f, T_{core}, CR)$
  - T_{core} = 553.15 to 2500 K at every 200K.
  - No moderator temperature dependence.

MAMMOTH Model

- Extruded unstructured mesh.
  - Includes hodoscope penetration.
  - SERTTA modules have heterogeneous rodlets and surrounding materials.
  - Adiabatic fuel model in core and SERTTA fuel pellets.





Steady State calculations - core

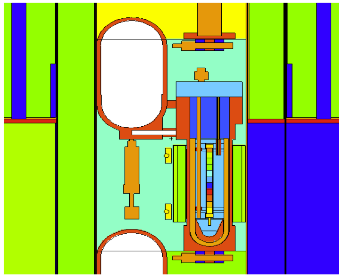
- Core liner and hodoscope hole best homogenized with some reflector regions.

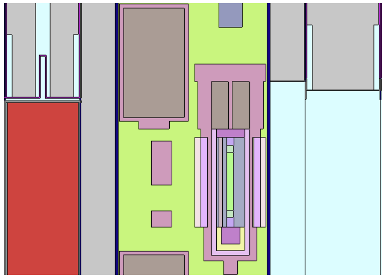
Temperature $[K]$	CR	Serpent	TDC-SPH Diffusion	TDC-SPH Diffusion*	pcm difference	pcm difference*
293.6	in	0.98779	1.00686	0.99140	1930.5	365.0
293.6	out	1.01309	1.03336	1.01443	2000.4	132.6
400.0	out	0.98925	1.01000	0.99051	2097.3	127.5
500.0	out	0.96886	0.98979	0.96601	2160.4	-294.2
600.0	out	0.95059	0.97550	0.95144	2620.8	89.1

	Source rate	Absorption rate	Leakage rate	Integral flux
Serpent	8.4602E+16	7.3712E+16	1.0892E+16	5.3900E+19
Diffusion	8.9687E+16	7.5645E+16	1.4041E+16	5.5245E+19
TDC-SPH	8.3007E+16	7.3840E+16	9.1664E+15	5.3852E+19
TDC-SPH*	8.4864E+16	7.3704E+16	1.1160E+16	5.3911E+19
Diffusion	6.01%	2.62%	28.92%	2.50%
TDC-SPH	-1.89%	0.17%	-15.84%	-0.09%
TDC-SPH*	-0.37%	0.04%	-3.14%	-0.02%

Steady State calculations - SERTTA

- Different between MCNP and Serpent results with current flux collar design.
- Unit 2-4 are consistent, which points to Unit 1.
  - Checked CR positions.
  - Found differences in slot geometry.
  - Voids in upper reflectors.

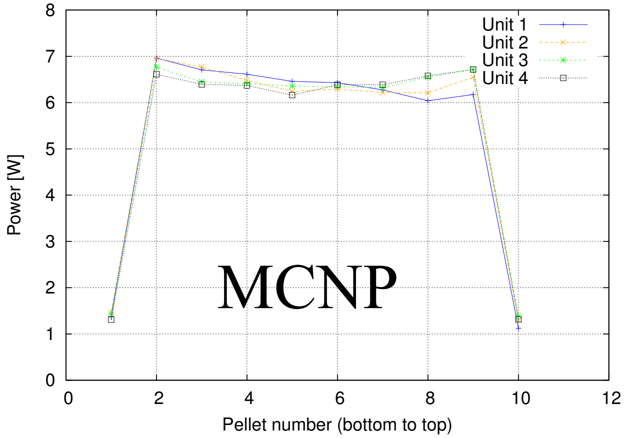


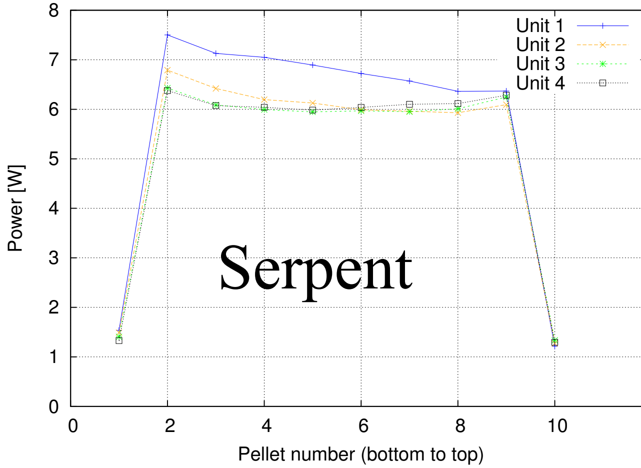


PCFs

Code	Unit 1	Unit 2	Unit 3	Unit 4
MCNP	1.1381	1.1394	1.1438	1.1369
Serpent	1.2029	1.0907	1.0715	1.0799

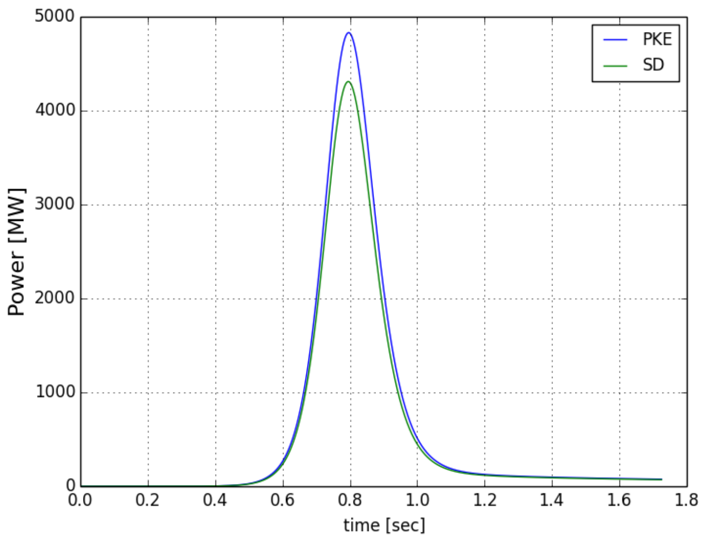
- Mammoth vs Serpent
  - Rodlet powers ~0.6%.
  - Pellet powers ~1.5%.

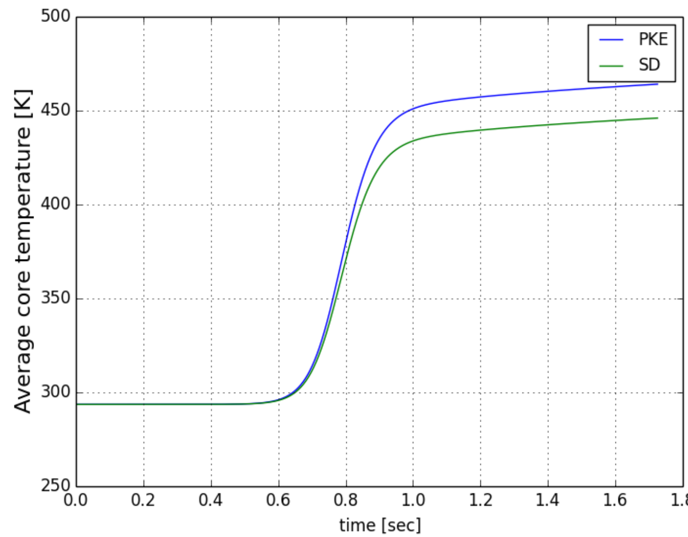




Results - PKE vs Spatial Dynamics for Core

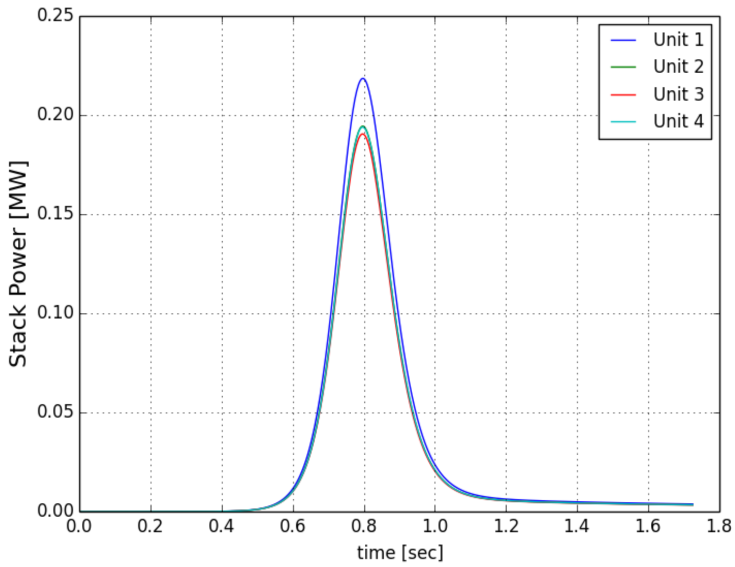
- 44 msec period ~2.685% Δk/k.
- Comparison of calculations:
  - 440 MW, 0.195 sec pulse width for a 2.634% (Relap-5 PKE).
  - 483 MW, 0.177 sec pulse width for a 2.685% (Mammoth PKE).
  - 431 MW, 0.177 sec pulse width for a 2.685% (Mammoth SD)
- PKE overestimates power and energy deposition by 12%.
- Compare PKE feedback model vs IQS?

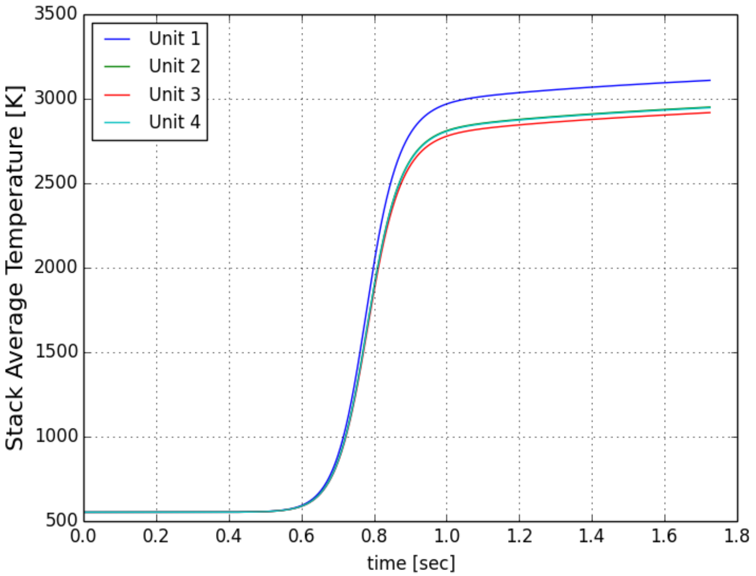




Results - Spatial Dynamics Experiment

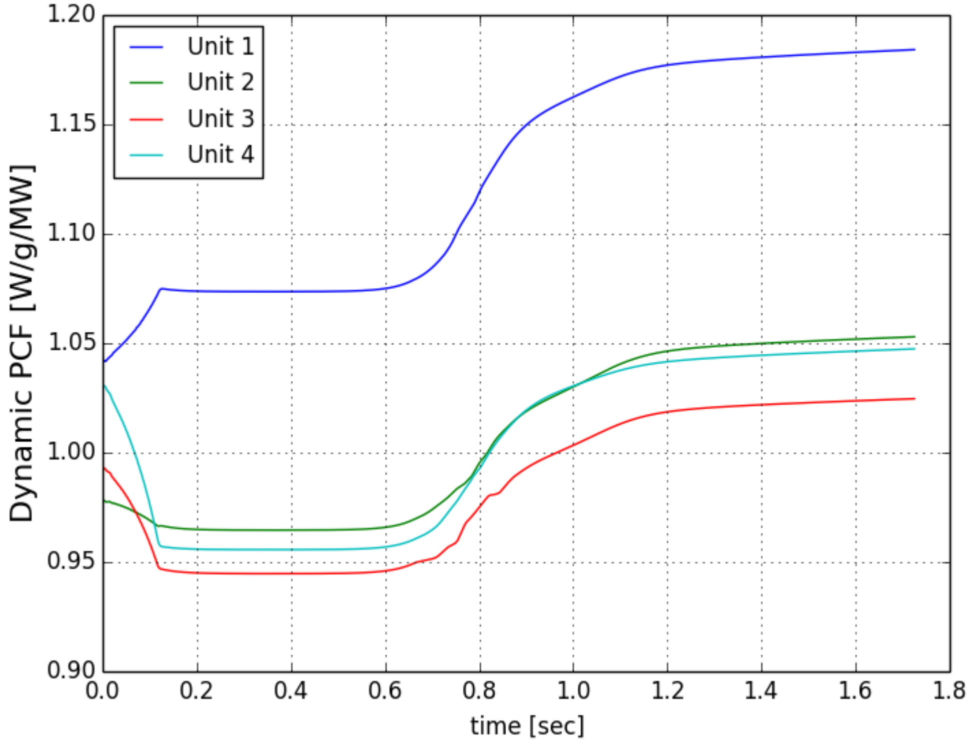
- Just as in steady state Unit 1 has different energy deposition.
- PKE overestimates energy deposition by 6%.
  - Might imply that 6% are transient effects (not known at this point).



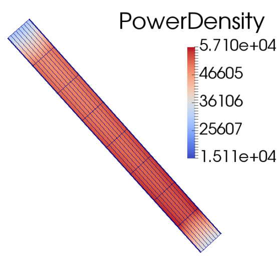


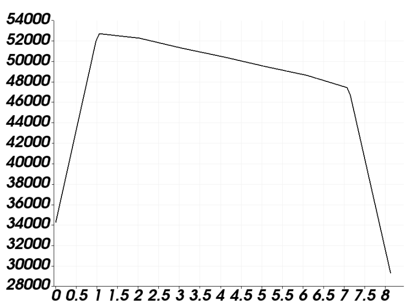
Dynamic Power Coupling Factor (DPCF)

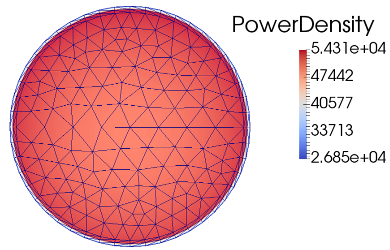
- As CR moves, the neutron distribution shifts to the top of the core:
  - higher PCF in Unit 1,
  - lower PCF in Units 3 & 4.
- Shaped transient will insert CR at point of peak energy deposition rate.

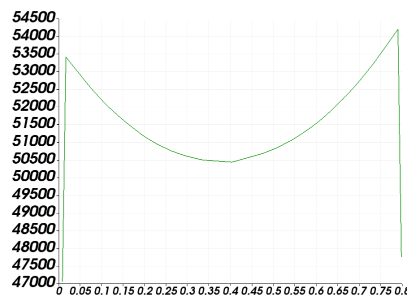


Unit 1 at 0.8 sec Power [W/cc] and Temp. [K]

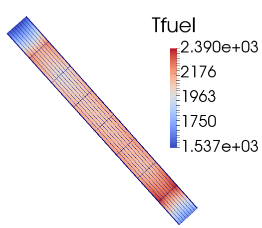


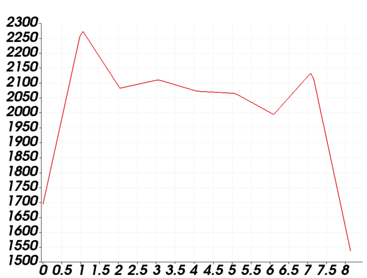


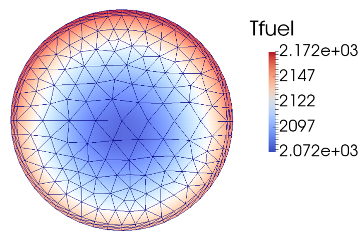


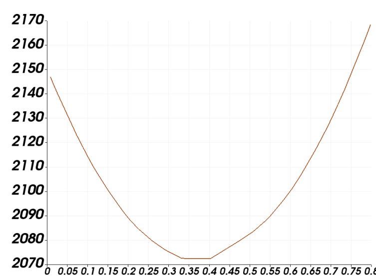


- 6% variation in the radial power profile.
- Visualization issues at periphery.





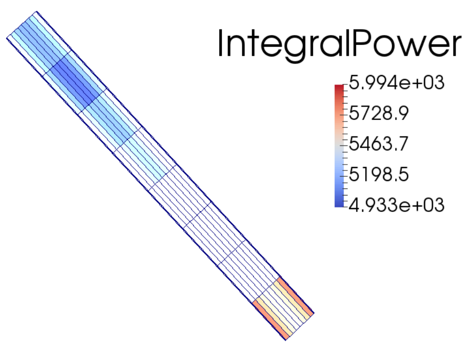


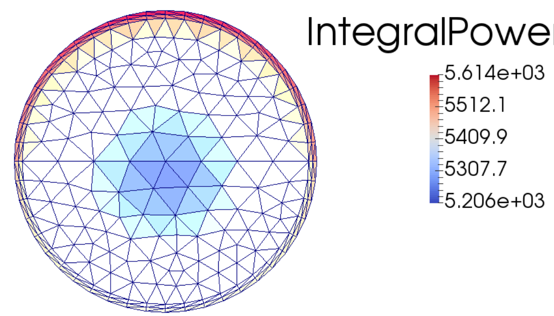


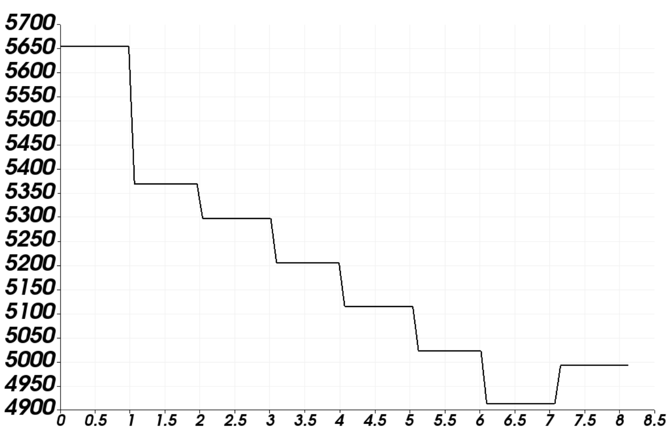
- ~100 K ΔT from center to periphery.
- Axial and azimuthal dependency in the temperature distribution should flatten with the conduction model.

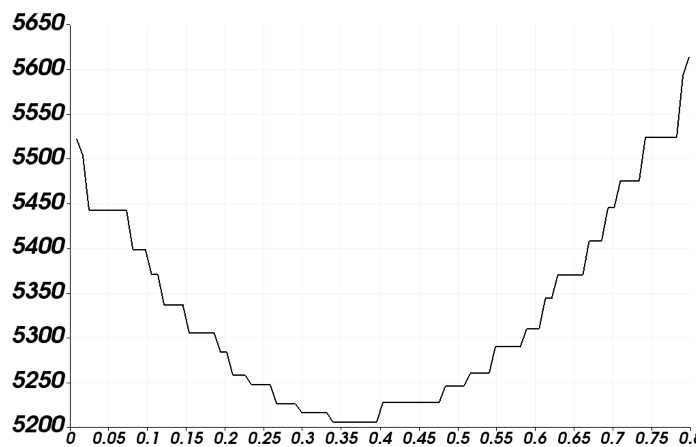
Unit 1 Integrated Power [J] at 0.8 sec

- Currently shows axial (12%), radial (6%) and azimuthal effects (2%).









Conclusions

- Modeled the safety case for MSERTTA with PKE and spatial dynamics multi-physics simulation.
- MAMMOTH produces rodlet powers that are within 0.6% of Monte Carlo & pellet powers that are within 1.5%.
- Results show good agreement with Relap-5.
- PKE overestimates power by 12% compared to SD.
- Subtle transient effects are apparent at the beginning of the reactivity insertion in the experimental samples due to the control rod removal.
- Additional differences due to transient effects are observed in the experiment powers and enthalpy.

Current Work - Comparison SPH/DF

- SPH does not preserve leakage.
- 3x3 supercell with CR in center.
- Symmetry of the problem:
  - 15 partial currents
  - 15 DFs

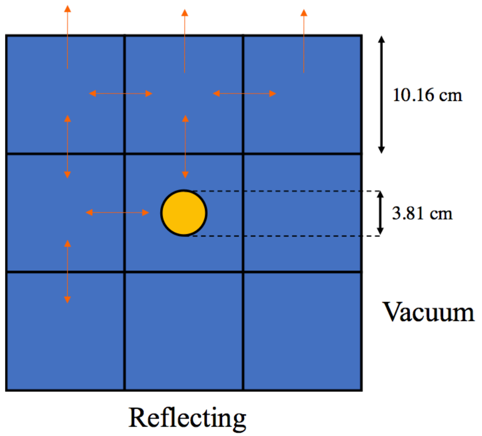


Table 2: Error in eigenvalue and power with vacuum boundary conditions for the right and top boundaries.

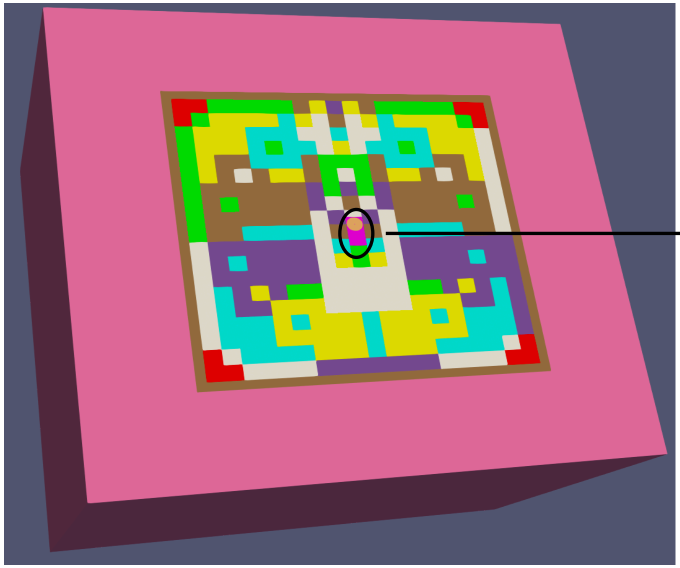
	Eigenvalue	Error (pcm)	RMS	Max	Min	Range
SERPENT	0.19418	($\pm 2\sigma$=1.8 pcm)				
No DF/BCf	0.18101	1317	5.90%	16.95%	-2.40%	19.35%
DFs/BCfs	0.19418	0.0	0.033%	0.059%	-0.046%	0.104%
SPH	0.19003	415	0.026%	0.034%	-0.014%	0.048%

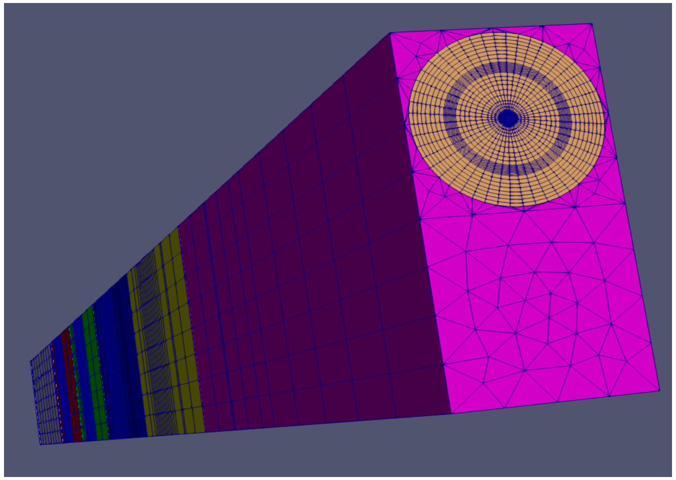
due to statistical error only

- Note: BCf = Boundary Coefficient (equiv. of DF on boundary)

Current Work - Multi-scheme calculations

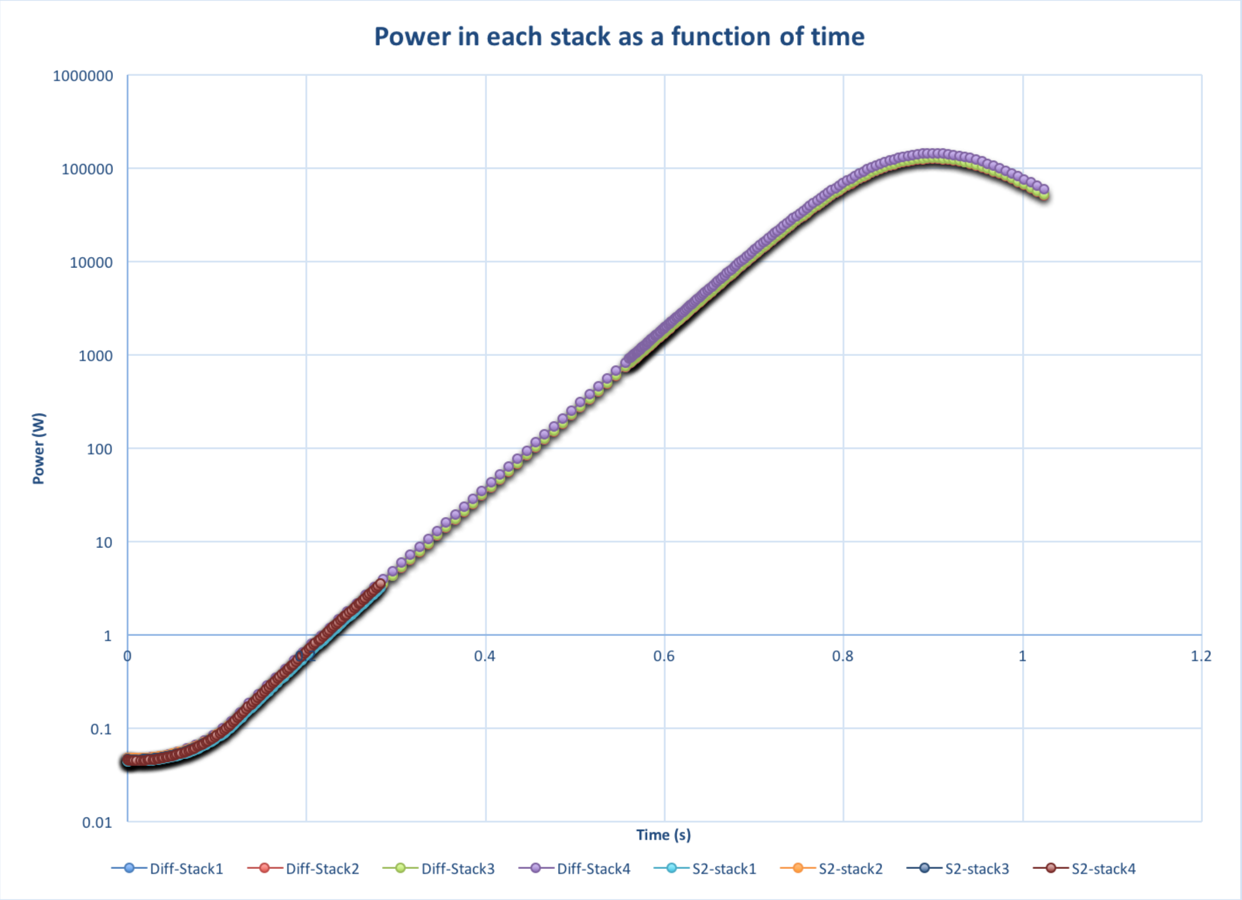
1. **Simultaneous**, run a full-core calculation with (SPH-corrected) diffusion and transport simultaneously in separate domains.
2. **A posteriori**, run the experiment region with time dependent B.C.:
   - The experiment design can be changed without having to re-run the full-core calculation.
   - Store the solution around the experiment region in full core calculation.
   - Solve higher order transport scheme in the experiment region.





Current Work - Multi-scheme calculations

- Power profile in the experiment.
- Shown: full-core diffusion, SAAF-S2 in experiment region



Future Work

- Improve CR models:
  - Add additional CR axial regions
  - CR cusping treatment
- Better equivalence:
  - More SPH resolution or discontinuity factors, BCfs
- Integrate workflow:
  - mesh generation + XS preparation from single input (experiment),
  - standard cross section set for the core.
- Re-run Multi-SERTTA:
  - work with experiments group to resolve unit 1 differences,
  - shaped transient (with CR clipping),
  - couple to BISON, Relap-7, and
  - more transport solutions.

Contributors to NEAMS TREAT M&S

- Staff
  - Lead Technical – Javier Ortensi
  - Analysis Support – Ben Baker, Rick Gleicher
  - Code Support – Yaqi Wang, Sebastian Schunert, Vincent Laboure (Postdoc)
  - Experiments – Nick Woolstenhulme, John Bess, Connie Hill
- Students
  - Tony Alberti (Oregon State University)
  - Alexandre Laurier (Ecole Polytechnique de Montreal)
  - Colby Sorrel (North Carolina State University)
- NEAMS Interface
  - Mark DeHart, Deputy Director for Reactor Physics Modeling and Simulation

INL

Idaho National Laboratory

Region Tensor Diffusion Coefficients (TDC)

- Need to define diffusion coefficient in near-void regions for TREAT while MIT completes Cumulative Migration Method work.
- Selected Trahan's region-wise definition.
  - Define a tensor diffusion coefficient

$$\left[\underline{\underline{D}}\right]_{i,j} = \frac{1}{4\pi}\int_{4\pi} d\Omega_i \Omega_j f$$

  - Obtain f from auxiliary transport problem without scattering or fission

$$\vec{\Omega}\cdot\nabla f_g + \Sigma_{t,g} f_g\left(r,\vec{\Omega}\right) = 1$$

- Use one of the Rattlesnake's S_N transport solvers to solve the auxiliary problem:
  - 2nd order SAAF-S_N with void treatment
  - 1st order S_N

Coupling Factors

- Historical operations lacked detailed 3D kinetics capabilities for experiment design and execution.
- Those operations relied on a “Power Coupling Factor” and “Transient Correction Factor” (TCF)
- Measurements were performed using both fission wires and fuel pin(s) representative of the fuel to be tested in a transient.
- PCFs were determined for both wires and fuel pin(s)
- PCF = power per gram of test sample, per unit of TREAT power
  - PCFs were expressed in different units – the form of the expression was irrelevant as long as used consistently:

$$\frac{fissions/g_{U_{235}}}{MJ_{core}}, \frac{J/g_{U_{235}}}{MJ_{core}}, \frac{fissions/g_{fuel}}{MJ_{core}}, \frac{J/g_{fuel}}{MJ_{core}}$$

  - Typically PCFs were measured at a low-level steady-state (LLSS) power, 80-100 kW.

Coupling Factors

- Because of core changes during a transient (principally rod motion and changes in the neutron spectrum due to non-uniform temperature increases), the PCF changes with time.
- A TCF was used to correct for those changes to obtain an effective PCF for a fuel experiment.
- To determine a TCF, it was assumed that there is a proportionality of fissions in both test fuel pins and fission wires:

$$\frac{PCF_{pin,transient}}{PCF_{pin,LLSS}} = \frac{PCF_{wire,transient}}{PCF_{wire,LLSS}}$$

- Rearranging:

$$PCF_{pin,transient} = PCF_{pin,LLSS} \cdot \frac{PCF_{wire,transient}}{PCF_{wire,LLSS}}$$

- Or,

$$PCF_{pin,transient} = PCF_{pin,LLSS} \cdot TCF.$$

Coupling Factors

- For the actual transient, a relationship between core energy and energy in the experiment was assumed as:

$$E_{pin} = E_{core} \cdot PCF_{pin,LLSS} \cdot TCF,$$

- Note that fuel pins were never subjected to a transient – only fission wires
- To measure $PCF_{wire,transient}$, for high power transients without wires melting:
  - Fission wires (usually a zirconium-uranium alloy) were typically LEU
  - HEU wires could be used but had to be enclosed in a filter
- Hence, measurements were performed for
  - $PCF_{pin,LLSS}$
  - $PCF_{wire,LLSS}$
  - $PCF_{wire,transient}$
- And TCF was calculated as $PCF_{wire,transient}/PCF_{wire,LLSS}$